Dead Sea sinkholes – an ever-developing hazard

Y. Arkin · A. Gilat

Abstract Sinkhole development along the western shore of the Dead Sea became a major concern in 1990 with the appearance of a series of holes 2–15 m diameter and up to 7 m deep in the Newe Zohar area. One of these sinkholes, below the asphalt surface of the main road along the western shore of the Dead Sea, was opened by a passing bus. Repeated infilling and collapse of these holes indicated the extent of this ongoing process and the significance of this developing hazard. Since then sinkholes have developed in other areas including Qalia, Ein Samar, Ein Gedi and Mineral Beach.
Three main types of sinkholes have been recognized. Gravel holes occurring in alluvial fans, mud holes occurring in the intervening bays of clay deposits between fans and a combination of both types at the front of young alluvial fans where they overlap mud flats. Fossil, relict sinkholes have been observed in the channels of some old alluvial fans. Sinkhole development is directly related to the regression of the Dead Sea and the corresponding lowering of the regional water table. Continuation of this process widens the neritic zone enveloping the sea and increases the sinkhole hazard of the region.

Key words Sinkholes · Piping · Gravel holes · Mud holes · Environments · Case histories

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Introduction

Sinkholes are defined as circular depressions in a karst area of subterranean drainage measured in meters or tens of meters. They are commonly funnel shaped (Bates and Jackson 1980) and according to the literature can develop within a matter of days in different geologic settings (carbonate, loess, evaporite, alluvial fan, etc.). In Israel sinkholes associated with karst phenomena have been recognized in central Israel, and the Negev (Arkin 1980; Arkin 1984; Arkin and others 1985; Schick 1963). However, those of the Dead Sea area are a unique occurrence. The first appraisals of this local process were made by Arkin (1993), Arkin and Michaeli, (1995) and Gilat (1999). Past geophysical surveys (Neev and Emery 1967 and Shtivelman and others 1994) including seismic and ground penetrating radar, have not verified speculation that these sinkholes are associated with karst in large subsurface salt bodies.
It is rare in our times to be able to follow the progress of a new active geological process. Lynch (1849), in one of the first recorded scientific expeditions to the Dead Sea, presents a sketch of the northern end of the sea with indications of a sinkhole (Fig. 1). The regression of the Dead Sea gives us this opportunity to study the consequences of such a phenomena. The major one is the formation of a mudflat enveloping the sea and creating an area of major environmental hazards. The present paper describes and evaluates the sinkhole phenomena and mechanism of development of this recent hazard in this area. Three main types of active and progressive sinkholes are recognized. These are gravel holes occurring in alluvial fans, mud holes occurring in mudflats, and a third type made up of elements of both conditions in the overlapping areas between mudflats and alluvial fans.
To understand the mechanism of development of the sinkholes it is necessary to review the recent changes which have occurred in the Dead Sea basin and catchment area (Fig. 2).
The Dead Sea in the central part of the Jordan-Arava Valley within the Syro-African Rift System is the lowest place on the surface of the earth. Stages in development of this segment of the rift system can be summarized as follows: Initial rift development began in the Oligocene and was followed by formation of elongated sedimentary basins of mainly clastic and some volcanic elements in the Miocene. This was followed by intermittent marine

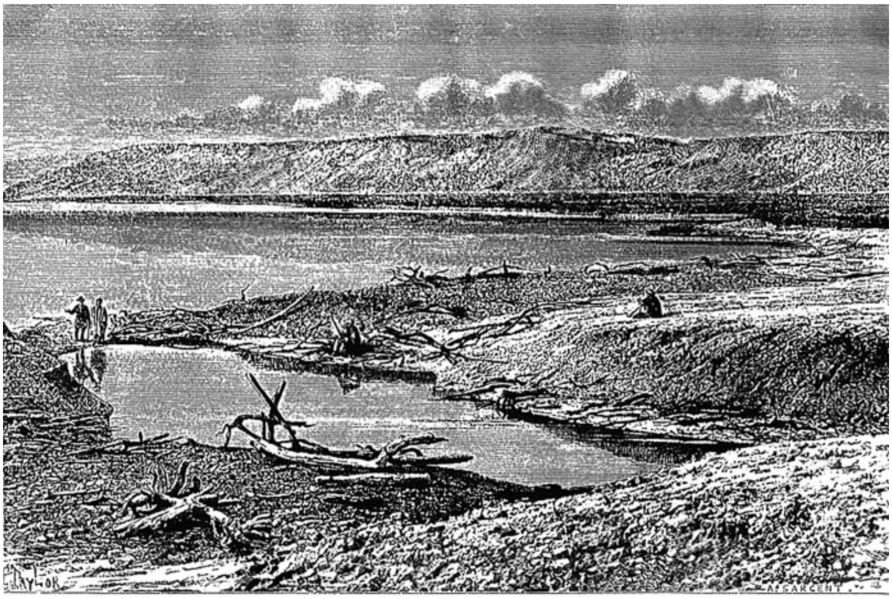

Fig. 1
Sketch of the northern end of the Dead Sea from Lynch (1849)

incursions into the rift with marine and clastic deposition. Salt lakes and evaporite deposits were formed during Plio-Pleistocene times creating the precursor lakes of the present day Dead Sea. Clastic, evaporite and lacustrine sediments continue to be deposited during the Pleistocene and today. Evaporite and clastic deposition continues today with regression of the sea and the formation of an enveloping muddy hazardous strip surrounding the sea.

The Dead Sea is a N-S rectangular pull-apart graben, 8–10 km deep (Garfunkel 1981) having a maximum length of 80 km and width of 17 km shaped like a pot. The handle represents the southern shallow basin of a maximum water depth of 3 m and the bowl, the northern deep basin with a maximum water depth of 700 m. The southern basin today comprises the Dead Sea Potash Works and the Jordan Potash Co. The northern basin today has a water level of –413 m below Mediterranean Sea level and is continuing to recede (Fig. 2).

The total catchment area of the sea is 43000 km^2 (Fig. 2) with an annual average rainfall of over 1000 mm in the north, 50 mm in the south, 600–800 mm in the west, and 200–600 mm in the east. The main contributors are the perennial Jordan and Yarmuk Rivers from the north and the ephemeral Nahal Arava and Nahal Zin from south. Other ephemeral streams contribute smaller seasonal amounts of water from the east and west. The annual average evaporation of 1.80 m reaches a maximum during the month of August.

The sea occupies base level with no natural outlet and existed in the past as a self-regulating hydrological system. Old water levels (Fig. 3) fluctuated according to climatic conditions within an overall equilibrium of balanced inflow and evaporation. The inflow of freshwater from the Dead Sea catchment basin mainly through the Jordan River, was the controlling factor in this balance. Since the beginning of the century, when water levels were measured in 1917 by the Palestine Exploration Fund (PEF) till the 1930s, the Dead Sea level fluctuated around a topographic elevation of about –392 m below Mediterranean Sea Level (Underhill 1967). However, an upset in the natural conditions caused by large-scale development projects in Israel and the Hashemite Kingdom of Jordan during the past forty years has resulted in a dramatic recession in sea level. Since then the ongoing diversion of fresh water for agricultural purposes has reduced the inflow into the sea by about 75%. This, together with prevailing high monthly evaporation, has resulted in the regression of the sea to its present day level of –413 m below Mediterranean Sea Level. It is the upset of this delicate balance between inflow and evaporation that has caused the development of the muddy strip surrounding the sea.

These unique conditions are directly related to the physical and chemical composition of the waters of the sea, which are a Ca/Cl brine having a range in salinity of 288–332 g/l and density of 1.160–1.223 g/cm^3 (Neev and Emery 1967).

Various aspects regarding geographic setting, sea level changes, and physical and chemical processes can be found in the studies of Masterman (1913), Neev and others (1967), Belfori (1976), Rich (1978), Sauer (1978), Maugh (1979), Arkin (1982), Weiner (1985), Yechieli and others (1993), Shehanowicz-Firtel and Bowman (1998).

The present study covers the western shore of the Dead Sea and the areas where sinkhole development occurs today are shown in Fig. 2.

Sinkhole types

Two types of alluvial fans (Fig. 4) that spread out from the major wadis of the western border mountains of the Dead Sea rift are recognized (Arkin and others 1975; Bull 1977; Hooke 1975).

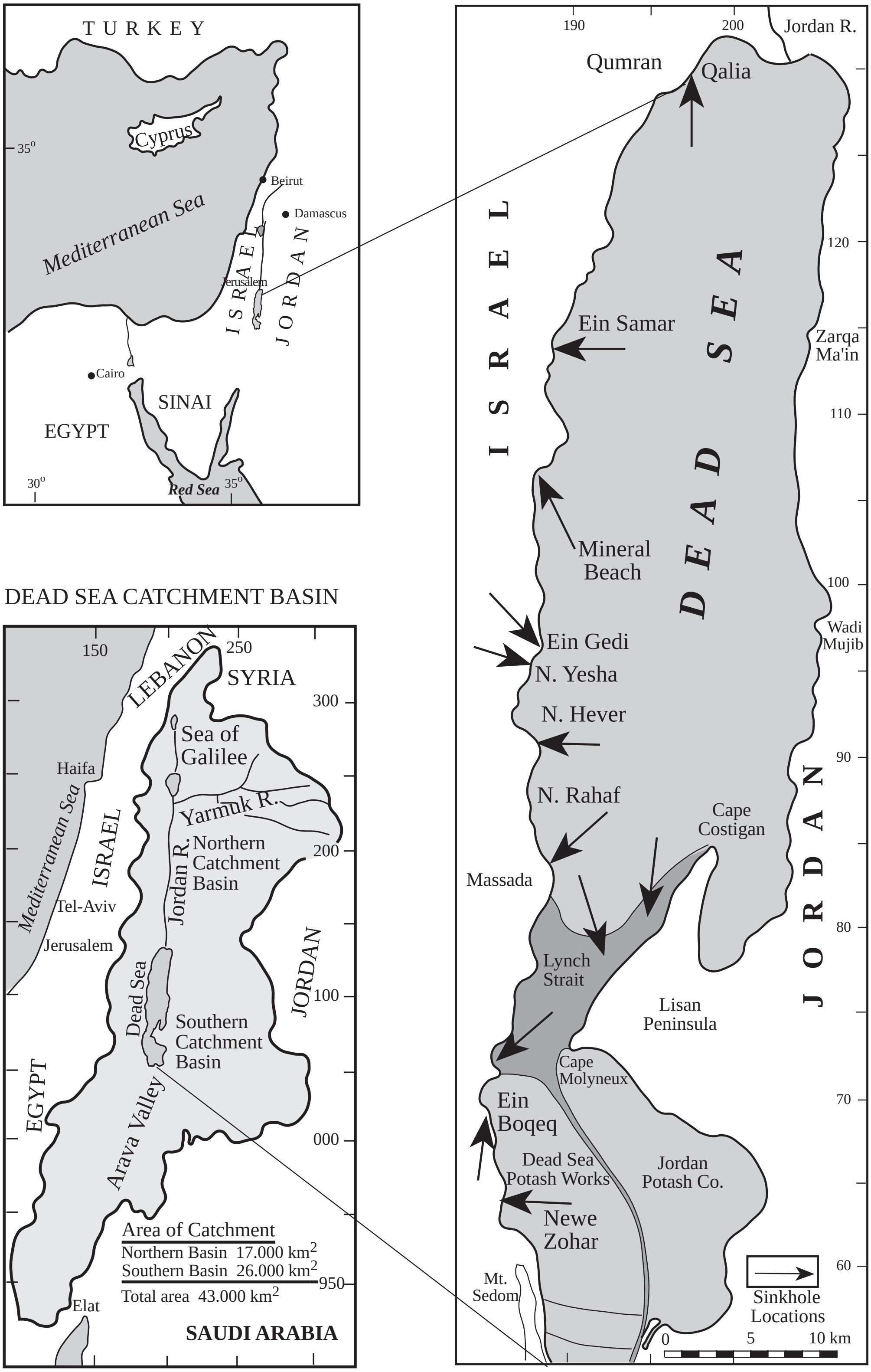

Fig. 2
Location maps

a) "Young fans" with no central channel and surface slopes that are generally greater than 15°. Surface flow, resulting from floods, spreads out over the fan in numerous shallow flow paths with minimal erosion. Subsurface flow occurs in a similar manner along individual flow paths which are recognized by iron oxide stains.
b) "Old fans" with a central erosional channel, in the form of a deep canyon with walls over 20 m high, that crosses the fan from its apex to the toe. Surface slopes

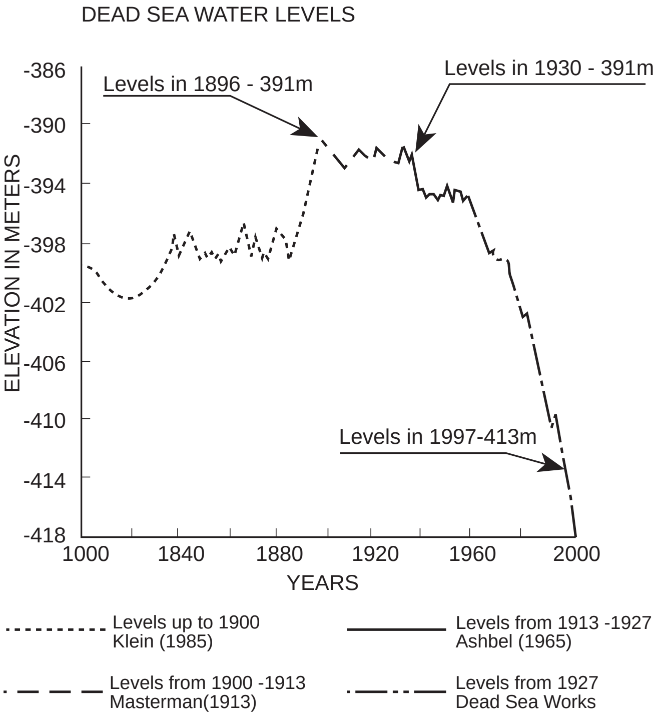

Fig. 3
Water Levels

on these fans range from 5–15°. The eroded fan material is carried along the channel during floods and deposited at the toe forming a new, smaller fan at the mouth.

Sinkholes appear in distinct hydrogeologic environments; at the toe of young alluvial fans, in mudflats between the fans and in the overlapping areas. They fall into three groups according to the sediment composition and location of gravel holes and mud holes and a combination of these two.

Fig. 5
Typical gravel hole, Ein Gedi caravan park

Gravel holes

Gravel holes (Fig. 5) form in the frontal areas of young alluvial fans (Fig. 4). They are typically funnel shaped with a surface diameter ranging from 1 m to over 30 m. The funnel pipe diameter is smaller, ranging from 0.5 m to several meters depending on the size of the sinkhole. The pipe depth depends on the depth of the subsurface flow and may not exceed 15 m in length. Small diameter holes (<0.5 m) and concentric fractures appearing at the surface indicate the presence of a growing active gravel hole (Fig. 6). Spills and slumping that may partly fill the pipe are washed out as water continues to move along the subsurface flow path. A typical vertical section con-

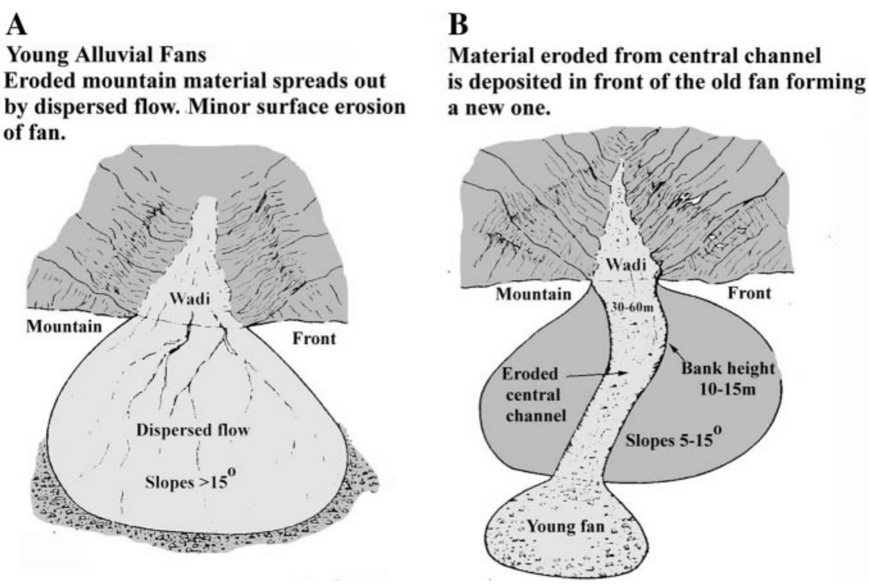

Fig. 4
Young and old alluvial fans

Fig. 6
Concentric fractures formed as subsidence begins

sists of coarse and fine conglomerates, pebble beds and in some areas, clay lenses. Pre-existing unique flow lines can be recognized in the conglomerate beds by iron and limonite stainings deposited by the flowing water.

Fine material is washed out along the flow path in places where the flow changes from laminated to turbulent and a hollow is formed. Resettlement of the gravel, and continued washing out of collapsed material, destabilizes the roof of the hollow causing further collapse. The process continues in an upward direction forming a pipe. As the pipe approaches the surface sudden collapse occurs forming a funnel shaped hole (Fig. 7).
Relict "fossil" gravel holes are seen in the walls of the central channel of old fans (Fig. 8) indicating an earlier period of piping and sudsidence.

Mud holes

Mud holes are developed in clay sequences deposited in the intervening areas between alluvial fans (Fig. 9). In these areas there appears to be an association with mineral and hot water springs and seepages as in the Mineral Beach and Ein Samar sites (Figs. 9 and 10). The mud holes at the surface range in size from 3–20 m diameter and generally up to 6 m deep. Some contain brine 0.5–2.0 m deep, ranging in total dissolved salts from 157.3–379.3 g/l. The brine color varies from blue, brown, red to colorless, sometimes milky, with a strong smell of

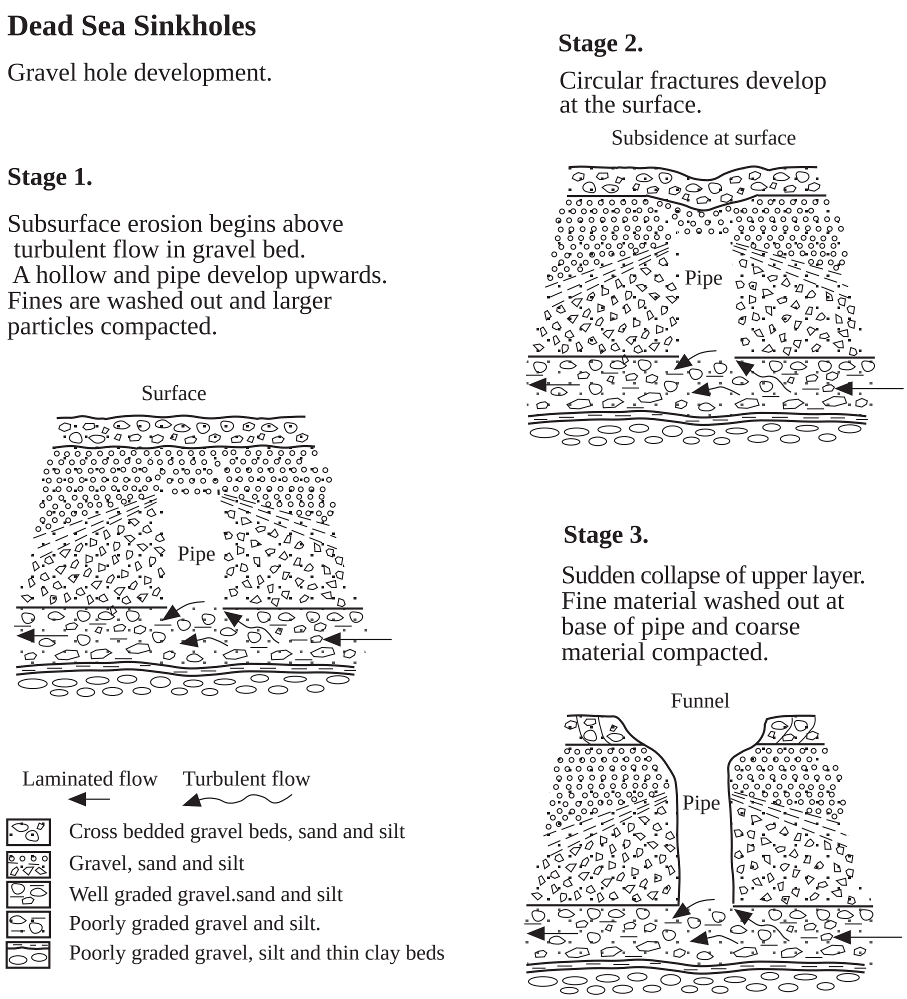

Fig. 7
Stages in development of gravel holes

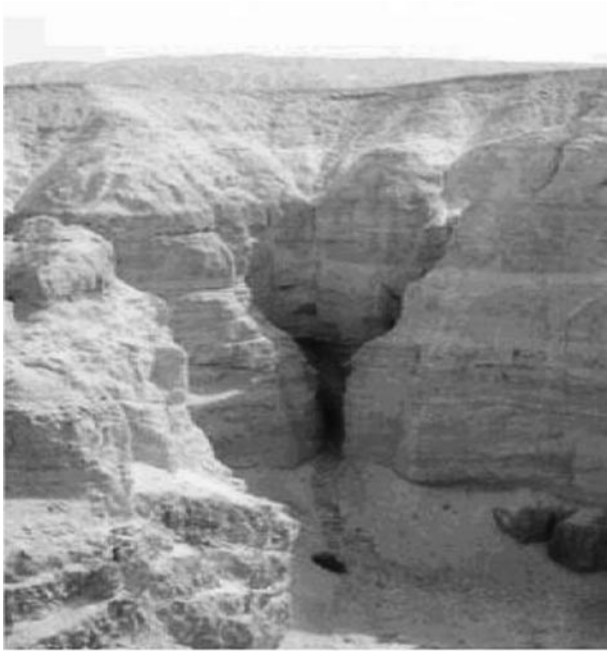

Fig. 8
Relict fossil sinkhole in central channel of Newe Zohar alluvial fan

Fig. 10
Typical mud hole at Ein Samar. Note reeds and brine

H_2S and temperatures ranging from 28° to 42 °C. Within the clay sequence (Fig. 11) in some areas there appear permeable layers of gravel and/or recrystalized salt (Yechieli and others 1993). In the subsurface these layers may become the focus of mud hole development. Where such layers occur above the regional water table, and exposed at the surface, as the sea recedes, springs and seepages are revealed.

At the surface the circular holes expand as slumping of the walls follows the formation of concentric fractures (Figs. 10 and 11). Stages in the piping process are shown Fig. 12. In some areas these mud holes coalesce forming a channel-like depression up to 100 m long.

Fig. 11
Laminated clay and evaporite, and conglomerate section in mud hole partly filled with brine. Note convolutions in clay bed

Fig. 9
Mud holes and seepages at Mineral Beach

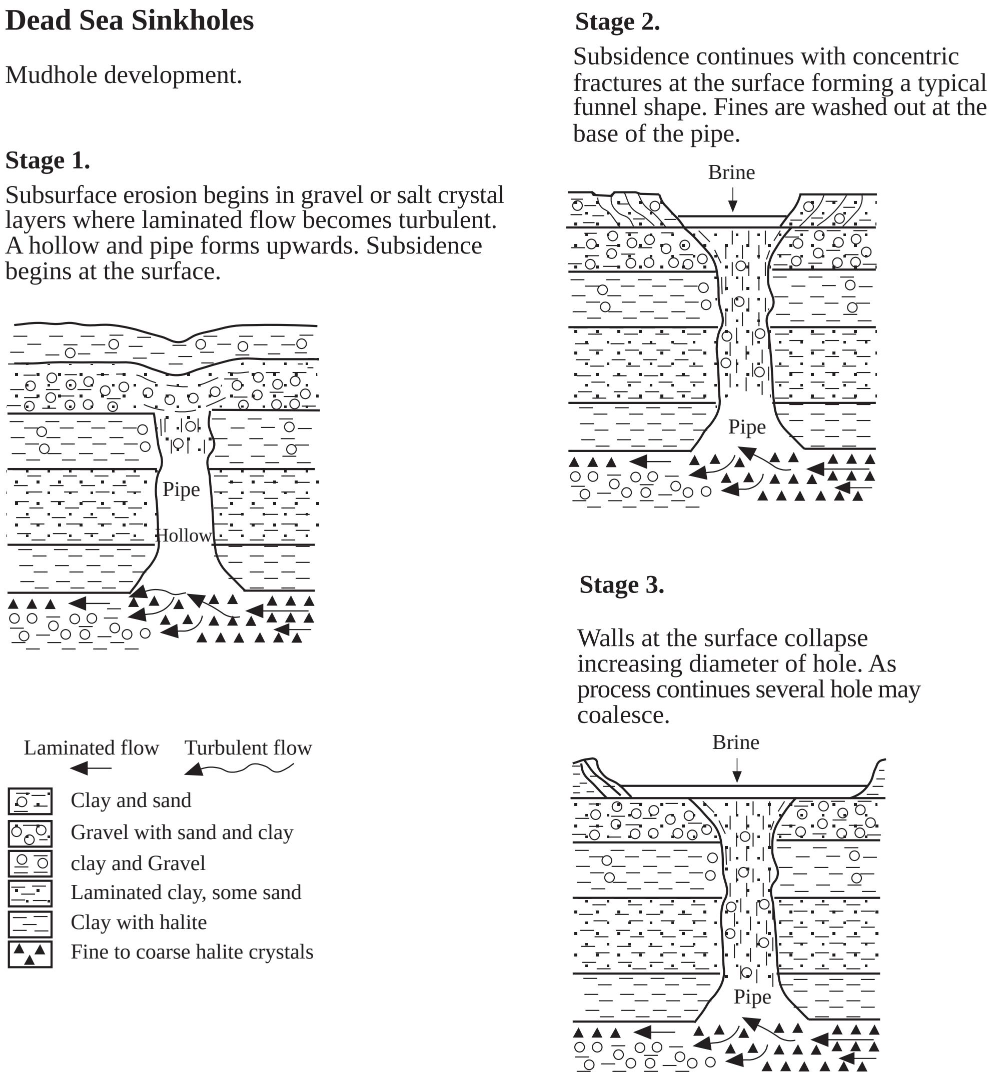

Fig. 12
Stages in mud hole development

Case histories

The areas of direct concern of this natural hazard in Israel are in the developing infrastructure along the shores of the Dead Sea. To date eight areas of sinkhole development have been recognized along the western shore. Sinkholes similar to those described below in a clay sequence are known to be developing along flow lines in the mudflats of the Lynch Straits. The following presents the case histories, of two sites on alluvial fans, the second of which is still under investigation.

Fig. 13
Gravel hole in the main road at Newe Zohar, western side of the Dead Sea

Newe Zohar Sinkholes

In 1991 a sinkhole developed in the asphalt layer of the main road along the western side of the Dead Sea near the entrance to Newe Zohar (Fig. 13). The hole was opened by a bus traveling northwards, revealing a circular hole of about 3 m diameter and 5 m depth in a gravel sequence consisting of conglomerate layers of 1–2 m thick of components of various sizes. Discussions with local authorities revealed that this phenomena began towards the end of the 1980s. The sinkhole in the road, as well as others, were filled with gravel and the road repaired. These sinkholes continued to reappear at the same locations, generally after seasonal floods. A detailed survey of this phenomena in the Newe Zohar area was then requested to serve as a basis for remedial works (Arkin 1993).

Geological and geomorphological mapping of the site, in the field and on aerial photographs, defined a line of sinkholes along a subsurface flow line in the frontal area of the Newe Zohar alluvial fan (Fig. 14). The holes ranged in diameter from 3–5 m, and depths up to 5 m. In some sinkholes the floor was wet. In the gravel hole in the road (Fig. 13) a continuous flow of water was seen at the base. Three boreholes were made around the sinkhole in the road. Rock mass characteristics and granulometric distribution of the gravel were examined to determine the characteristics of the subsurface flow layer. The gravel

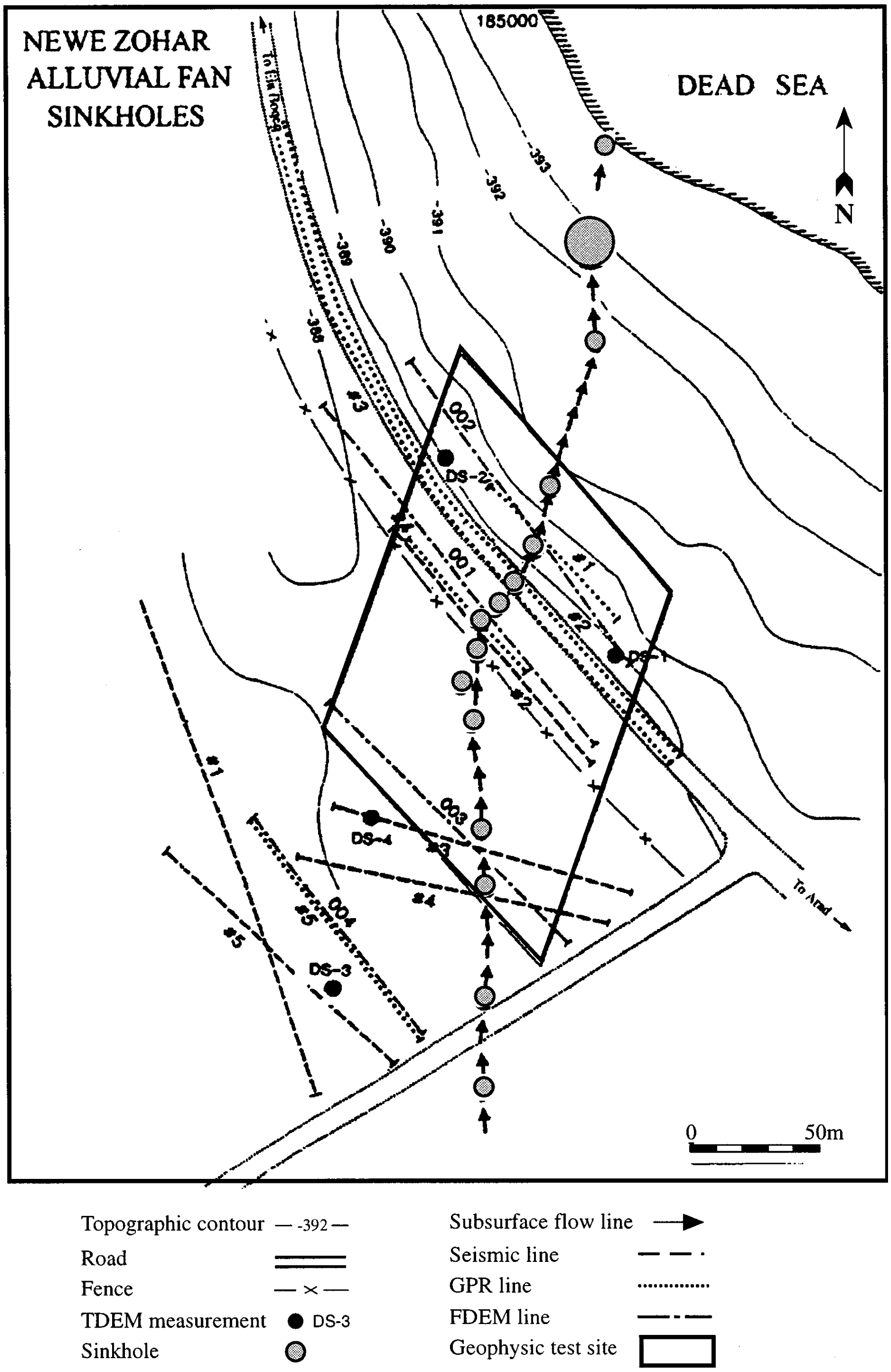

Fig. 14
Newe Zohar Alluvial fan sinkholes

beds were found to be well graded, consisting of limestone, dolomite and flint pebbles and cobbles up to 60 mm across in a matrix of silt and clay. In two boreholes lenses of silty clay up to 1.5 m thick were found. These layers represented part of a typically unconsolidated alluvial fan sequence. The water level in the boreholes was found to range from 1.0–1.8 m above Dead Sea level. A trench was dug at the point where the flow line crossed the road and showed that the width of the flow line was greater than 3 m. Beyond this the gravel was dry.
The remedial solution involved constructing a bridge in the form of an "n" across the flow line allowing the natural flow to continue and the road to pass over it. Since then new sinkholes have developed along the flow line both upstream and downstream of the road. Geophysical methods including seismic refraction, electromagnetic and ground penetrating radar surveys were carried out over the site to evaluate their use in revealing developing sinkholes in the subsurface. The results are discussed below.

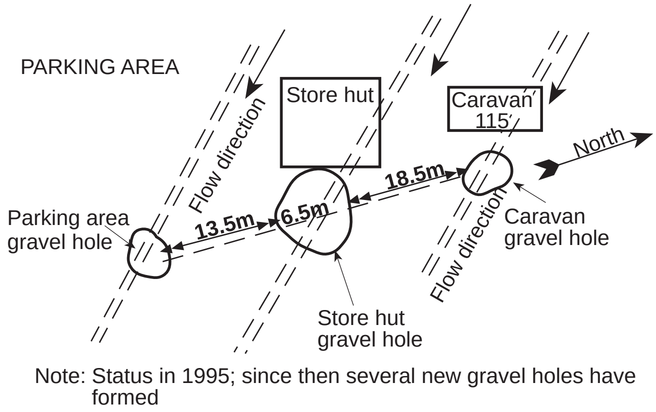

Fig. 15
Ein Gedi sinkholes

Fig. 16
Store hut gravel hole in the Ein Gedi caravan park

Ein Gedi Caravan Park sinkholes

The caravan park at the toe of the young alluvial fan extends from the older Nahal Arugot fan in the Ein Gedi area. The old fan has a typical central erosional channel from which the material was washed out during floods to form the young fan at its toe.
The fans consist of cobble, pebbles and boulders of varying sizes, as well as sand silt and clay lenses eroded from the Cretaceous source rocks of limestone, dolomite, marl and sandstone. For the most part these sediments form unconsolidated horizontal or slightly dipping beds towards the Dead Sea. Cross-bedding, ripple marks, flow channels and other sedimentary structures are evident throughout. Some layers are partly cemented by silt or clay and secondary deposits of aragonite, gypsum or salt. This central channel has been redirected northwards to divert flood waters away from the agricultural and holiday areas on the young alluvial fan. However this action has not diverted the subsurface flow within the fan which continues to flow in a south-easterly attitude to the Dead Sea. Camping, parking and beach front areas have greatly disturbed the original topography of the young fan.
In 1995, five sinkholes developed in the park; two between the caravans and two in the date plantation opposite the gas station. On September 3, another large sinkhole, 6.5 m diameter and 8–9 m deep, developed in the caravan park. These catastrophic developments initiated a geological site investigation to determine the extent of the hazard and possible remedial actions. The first group of sinkholes (Arkin and Michaeli 1995) are along discrete subsurface flow lines (Fig. 15). The gravel hole alongside the store hut (Fig. 16) has since expanded in diameter undermining the hut. In 1998, a detailed ground penetrating radar survey at the site (Kofman 1998) indicated the presence of additional, developing gravel holes which as yet have not reached the surface. These also appear to be aligned along subsurface flow lines. Since then existing sinkholes have continued to be active increasing in diameter. An examination of aerial photographs from 1972 before major development works began showed no indication of sinkholes. Only detailed analysis of relatively undisturbed topography maps with a contour interval of 5 m, prior to development, indicated the presence of old channels which in some cases could be recognized within the low coastal cliffs on the beach front of the young alluvial fan. These channels have been revealed as the level of the Dead Sea receded. The subsurface flow lines are comparable to these channels. The mechanism of sinkhole development as described below is linked to continued regression of the sea and the increasing gradient of subsurface flow, increasing the potential of sinkhole development along these flow lines.

Discussion

Although this study is restricted to the western side of the Dead Sea it has applicability to other areas. Piping and subsidence phenomena occur above subsurface flow channels, in the vadose zone above the regional water table, at various locations along the western shore of the Dead Sea. The phenomena are related to the receding water level of the sea, the lowering of the regional water table and erosional processes associated with incoming extraneous waters. Yechieli and others (1993) in studying the effects of Dead Sea water level changes on the surrounding sediments calculated that a large amount of groundwater, some $680 \times 106\ m^3$, reaches the Sea. The response to this influx is rapid, usually occurring within a few days. This influx, however, has not altered the overall trend of regression of the sea level due to the imbalance between intake and evaporation. Regression of the sea level has uncovered some springs and seepages which continue to flow today and illustrate that groundwater continues to flow within the fans and in the adjacent bays. The migration eastward of the fresh-saline water interface as well as the increased gradient of subsurface fresh water flow create the environment for sinkhole development.

The mechanism of development (Moore 1976) of the various sinkholes is similar in that the piping process begins at specific loci of change from laminar to turbulent flow in a discrete horizon. Laminar flow within a natural media, depending on grain size distribution, grain shape and packing, generally follow Darcy's law (Todd 1959). Deviations from this may be found in unconsolidated sediments where steep hydraulic gradients or large diameter solution openings occur. Pebble clusters in a gravel bed have been shown to have a significant effect on the spatial and temporal response of the flow (Buffin-Belanger and Roy 1998). This effect is analogous to the change in flow from laminated to turbulent in the present case. Typical groundwater movement under most conditions occurs as a smooth flow at relatively slow velocity in which the water follows a path that is relatively straight and parallel. Sudden influx of extraneous water from a manmade or natural flood event, or dissolution of components in the permeable layer, causes a disruption of the flow. Heterogeneous mixing of the flow lines and head loss then result in the change from laminar to turbulent flow. Piping then begins as described above (Figs.7 and 12).

The gravel holes in the Newe Zohar and Ein Gedi alluvial fans are clearly seen to follow subsurface flow lines. Borehole and trenching at the Newe Zohar site delineated the discrete flow line (Arkin 1993). This observation is supported by the continued activity of individual holes, their expansion and the appearance of new holes on the fans particularly in the Ein Gedi area.

The clay deposits in the intervening bays between alluvial fans, where mud holes occur, consist of gray, brown, dark-green and black clays typically composed of detritic illite/smectite and kaolinite in similar amounts with minor palygorskite (Nathan and others 1992). Often very thin laminations of white aragonite, some gypsum and well developed salt cubes are present. These sediments represent a modern deposition of the Lisan Formation (Arkin and Starinsky 1981) possessing similar physical and chemical characteristics. They contain 60–70% water content which is a brine. The total dissolved salts range from as low as 40 g/l to Dead Sea water composition of some 320 g/l, depending on the amount of dilution by extraneous waters. These parameters give the clay an effective strength which dissipates on dilution of the porewater. Dilution breaks the ionic bonds of clay platelets causing an immediate loss of effective strength and subsequent mud flow (Arkin 1980). The loss of strength of the clay plays a major part in the process of mud hole development and in the later stages at the surface as the hole widens. The process of sinkhole development begins with piping at specific points along discrete flow lines in the permeable layers as laminated flow becomes turbulent, causing dissolution of salt and/or washing out of the fines. The surrounding clay loses effective strength and piping continues upwards to the surface forming a funnel shaped hole.

Permeable recrystalized salt and gravel beds, up to several meters thick and at depths below the regional water table occur in a near shore borehole DSIF (Yechieli and others 1993). However mud holes have not developed in this vicinity. Mud holes have occurred in a similar situation in the Lynch Straits which today is a naturally dewatered area separating the northern and southern basins of the Dead Sea due to the receding sea level (Fig. 2). This further indicates that the overall process of sinkhole development around the Dead Sea begins above the regional water table following the receding sea level.

Sinkholes similar to the mud holes described above are reported by Hoffman and others (1998) as circular and linear features occurring in alluvial deposits along the flood plain of the Santa Cruz River, Arizona USA. These holes are noted to be grouped along bands approximately paralleling the river and other flood plain subsurface drainage lines. The sediments consist of medium to coarse grained components with some clay and silt. Subsurface erosion of dispersive sediment along pre-existing cracks, resulting from desiccation and tension, developed during past water table decline setting the stage for sinkhole development. It is interesting to note that the main elements of lowering of the water table and subsurface erosion are in accordance with the above described mechanism. Furthermore Celik and Afsin (1998) report on similar bowl-shaped solution-subsidence features resulting from drawdown by extensive pumping of water from Lake Dipsiz, Turkey. They conclude that lowering of porosity by repacking of unconsolidated grains, as a result of groundwater level fluctuation, causes increased compaction and plays an important role in developing a bowl-shaped subsidence. Consolidation of conglomerate and/or sandstone is affected by the sudden increase of effective stress. Subsidence at the surface occurs a long

time after drawdown of the groundwater level and is retarded with increased depth of the aquifer. These features are in accordance with our contention that the Dead Sea sinkholes are a shallow phenomena developing along discrete flow lines well above the regional water table.
Geophysical surveys were carried out over the frontal area of the Newe Zohar alluvial fan to explore for the presence of sinkholes that have not as yet surfaced (Shtivelman and others 1994). The methods tested were seismic refraction, frequency domain electro-magnetic (FDEM), time domain electro-magnetic (TDEM) and ground penetrating radar (GPR). The following conclusions were reached Fig. 14).
Seismic refraction revealed a refractor representing the incursion of Dead Sea water level into the alluvial fan, ranging in depth from 5–10 m from the NE to SW. This level forms an aquiclude over which fresher water flows within the fan towards the sea, as revealed in the road sinkhole. No other refractors were found within the depth of 10–50 m. TDEM survey conclusively confirmed the existence of the above water level. Seismic velocities measured along the subsurface flow indicated distinct velocity anomalies in the vicinity of known sinkholes. FDEM anomilies can be correlated with the subsurface flow line. GPR only gave an indication of the presence of sinkholes to a depth of 4 m. A recent ground penetrating radar survey in the Ein Gedi area by Kofman (1998), using a range of 100–600 MHz antennas, indicated the presence of additional sinkholes that are in the process of development. These methods provide good support to surface mapping of areas of potential sinkhole development.
As sinkholes develop in time and space in relationship to Dead Sea water levels an important question remains. That is, can the phenomena be arrested? The above discussion indicates that sinkhole development will continue in the future with the regressing water level of the Dead Sea, in the mudflats and in the toe of young alluvial fans. The overall process could be reversed by raising the Dead Sea water level as proposed in the Mediterranean – Dead Sea Scheme (Arkin 1982; Weiner 1985).
Local remedial works such as infilling the gravel holes have been unsuccessful as the filled holes continue to be active. The construction of drainage structures allowing undisturbed subsurface flow have been successful at local specific sites. It is suggested here that large scale gabions (wire mesh cubes filled with large boulders) filling the holes and allowing the natural flow to continue, may be a practical local solution. However, remedial solutions for larger areas of sinkhole concentration have not as yet been devised.

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