FORMATION OF SINKHOLES ALONG THE SHORE OF THE DEAD SEA — SUMMARY OF THE FIRST STAGE OF INVESTIGATION

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INTRODUCTION

Hundreds of sinkholes formed along the Dead Sea (DS) coast during the past ten years. They began appearing at several locations since the 1980's (Arkin, 1993). Sinkholes also occur in the eastern Jordanian side of the DS (Taqieddin et al., 2000), although only in its southern part. Sinkhole dimensions reach up to about 10 meters in depth and 25 meters in diameter. They represent danger both to life and property, disrupt life in the area, and aversely affect building and development. The formation of the sinkholes is a dynamic process continuing to the present day, and which their resultant development at unexpected sites.

The preliminary study aimed at an understanding and recognition of the subsurface geological mechanisms leading to the formation of the sinkholes, and to map the risk zones and develop tools for reducing the scale of the phenomenon. This research incorporates fieldwork and geophysical methods. Boreholes were drilled in order to obtain geological and hydrological data and to verify certain of the data obtained by the geophysical methods. The combination of field and aerial photograph studies, together with data obtained from the subsurface, allowed the preparation of a preliminary conceptual hydrogeological model that presents most of the factors involved in the formation of the sinkholes.

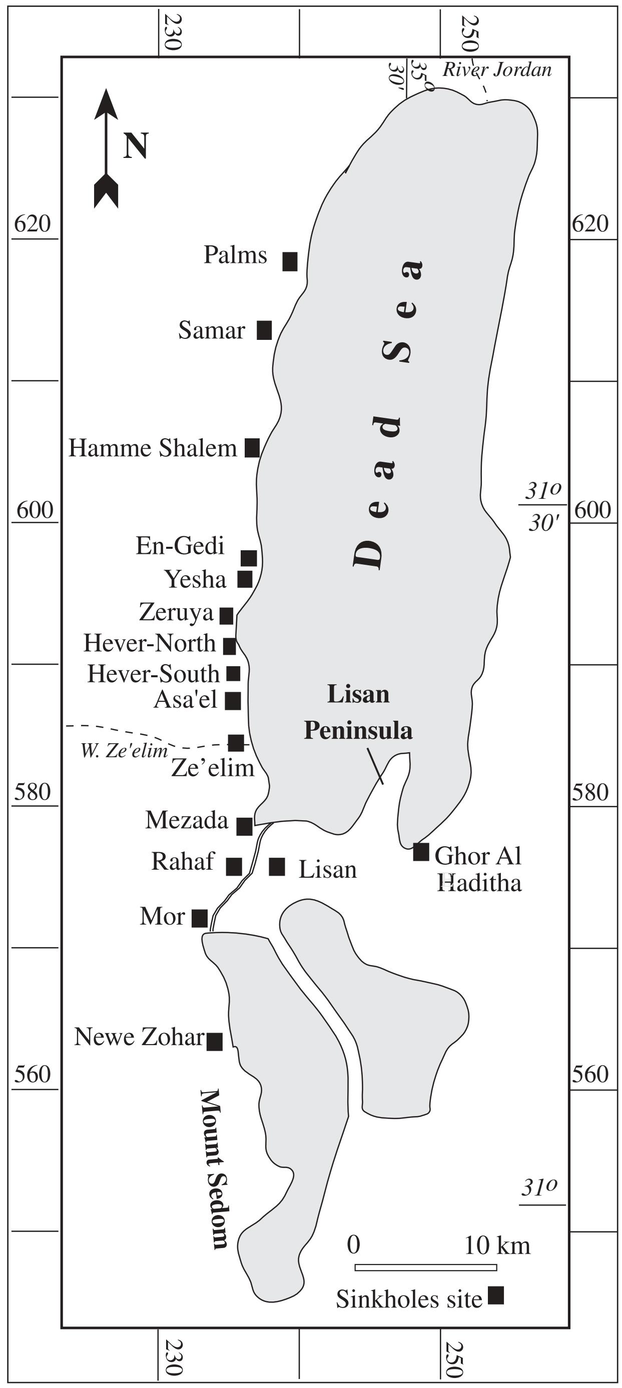

Figure 1. Sinkhole sites along the Dead Sea shore.

EVOLUTION OF SINKHOLE SITES

Earlier studies (Raz, 2000; Itamar and Reizmann, 2000) showed that the sinkholes are not randomly scattered on the Dead-Sea shores, but tend to occur in clusters. Some twenty sites containing sinkholes are presently known and most of these are presented in Figure 1. In order to monitor sinkhole development, the present study included mapping of their spatial and temporal occurrence at selected sites. Most of the mapping was carried out using ortho-rectified aerial photographs from different time-series, and in part using field differential GPS. These data sets were incorporated in

Figure 2. Two types of sinkhole appearances: (a and b) sinkholes on mud plains at the Hamme Shalem site and (c) sinkhole on alluvial sediments at the Hever South site.

the geographical information system (GIS) that was recently built for this project. This system enables a more quantitative assessment of the development of the sinkholes.

The development of sinkholes is presented for two sites (from December 1996 until July 2001): Hamme Shalem, located about 2 km south of Mitzpe-Shalem, and Hever North, located about 4 km south of Ein-Gedi (Fig. 1). The former site is located on a mud plain (Fig. 2) which consists of alternating clays and aragonite layers and the latter is located on the edge of an alluvial fan consisting coarse clastic sediments (Fig. 2).

The sinkholes at Hamme Shalem site are distributed along a distinct lineament with a trend similar to that of the main tectonic features of the DS rift as noted by Raz (2000) and Abelson (2001) (Fig. 3). Although only a few sinkholes covering a limited area were present at the Hamme Shalem site until 1999, a significant growth in their extent occurred during the following years. The recent sinkholes fill gaps between the older ones, and reach beyond them to the north and south. The clear orientation of the sinkholes is preserved. The development of sinkholes at the Hever North site is somewhat different, where they were located along two, less well-defined, lineaments (Fig. 3). Since 2001 these lineaments were obscured and the sinkholes occur in a non-oriented cluster.

The temporal differences between these two sites can be assessed by comparing several sinkholes parameters, such as their number and area which they cover (Fig. 4). The number of sinkholes present at a given time is a problematic parameter for assessing the sinkholes development since often several small sinkholes merge into one big sinkhole. The total area of the sinkholes seems to better represent the sinkholes development (Fig. 4). It can be seen that Hamme shalem site has total area of sinkholes greater than Hever north site. Another interesting observation is that the abrupt growth in sinkholes total area starts at different times: during 1999 at Hamme Shalem, and during 2000–2001 at Hever north. These differences are probably related to the local geologic and hydrogeologic conditions of each site.

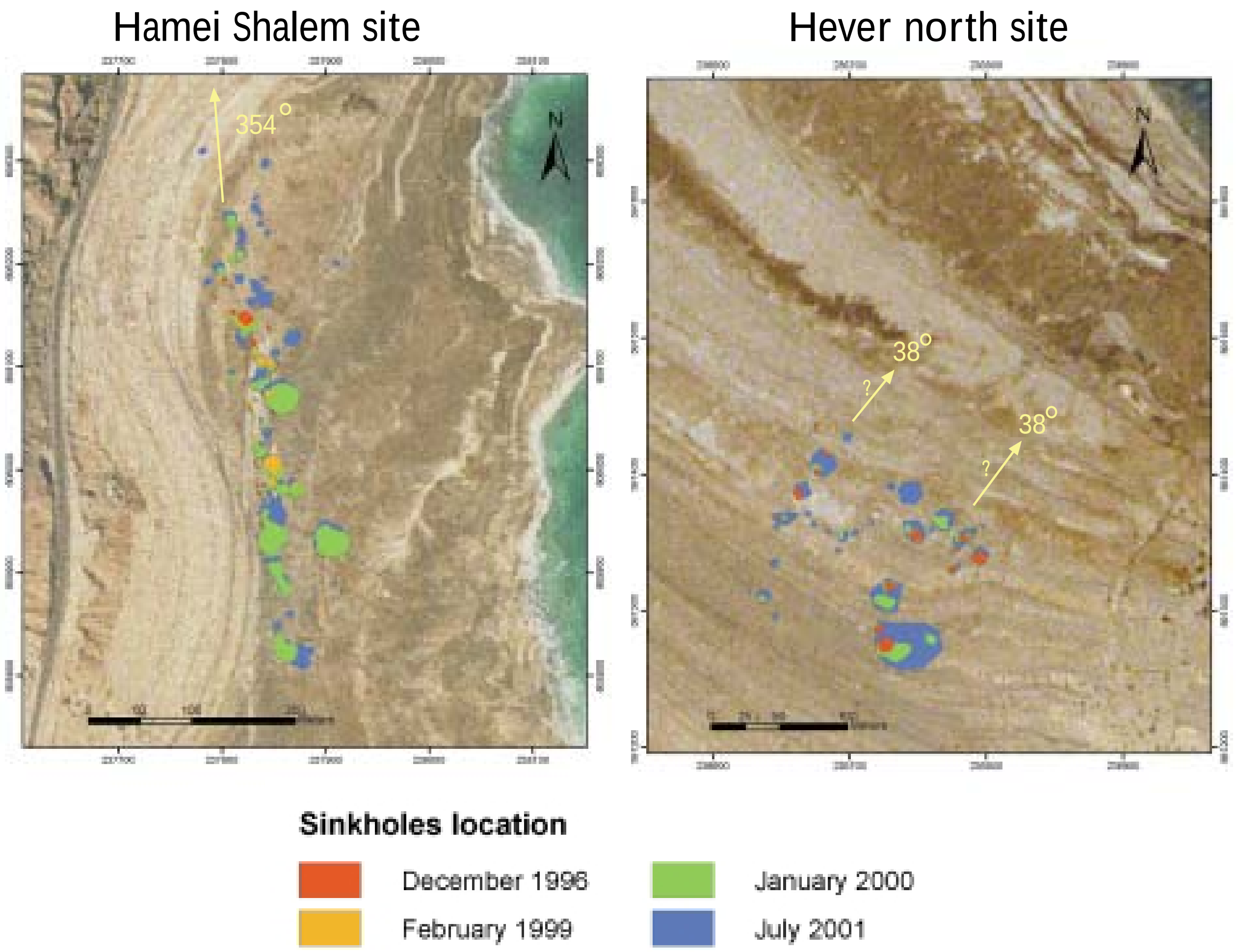

Figure 3. Development of sinkholes at two sites as mapped on air-photos. The general sinkhole orientation is marked by yellow arrows.

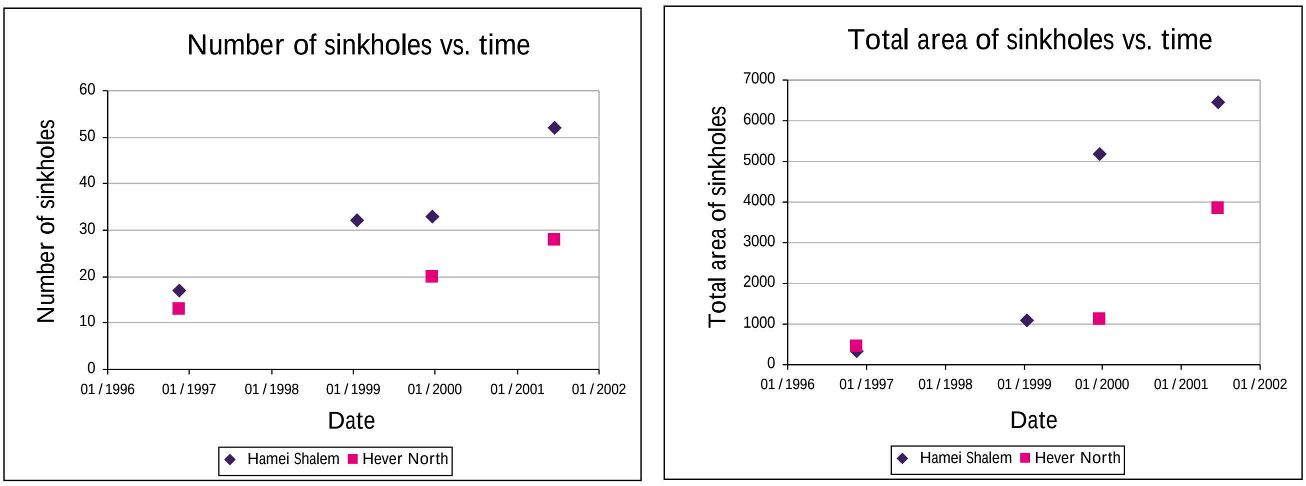

Figure 4. Development of sinkholes at two sites in terms of the number of sinkholes and total area.

GEOPHYSICAL AND DRILLING RESULTS

Geophysical methods such as seismic refraction allowed the recognition of a salt layer, which is an essential condition for the formation of sinkholes on the surface. The subsurface extension of the salt layer has yet to be mapped. In the northern part of the Dead Sea area, no evidence was found for the salt layer in the subsurface, and no sinkholes were observed on the surface.

The borehole in the Nahal Hever alluvial fan (Hever 1) is located among the sinkholes about 1 km south of the Hever North site. It encountered an 11 m thick salt layer at a depth of 24 m (Fig. 5), as predicted by the geophysical data. The age of the salt layer was found to be ~10,000 years, similar to the salt layer in the Zeelim area (Yechieli et al., 1993). Another borehole (Hever 3) drilled 40 m to the south of Hever 1 to a depth of 37 m, did not encounter the salt layer. At the depth interval of 23–29 m, a cavity was found at the same stratigraphic level as the salt layer in Hever 1 (Fig.5). This observation strongly supports the hypothesis that dissolution within the salt layer results in sinkhole formation.

MECHANISM OF THE SINKHOLES' FORMATION

It has been suggested that the rapid formation of sinkholes in the last few years is related to the rapid drop of the Dead Sea level during the past decades (Arkin, 1993; Arkin and Gilat, 2000, Wachs et al., 2000). This drop resulted in rapid and drastic changes in the hydrogeological conditions in the near-shore subsurface. During the past thirty years the sea level dropped by some 20 m (~80 cm/year). As a result, the regional groundwater level has dropped (Yechieli et al., 1995), as expected. The drop of sea level is accompanied by a retreat of the shoreline and in a reduction in the size of the surface area, accompanied by a change in the location of existing springs, and in the appearance of new springs along the shoreline. In the subsurface, the drop in groundwater level is accompanied by changes in the location of the fresh-saline water interface, which also retreats toward the center of the basin.

As a result of the drop in the Dead Sea level and the

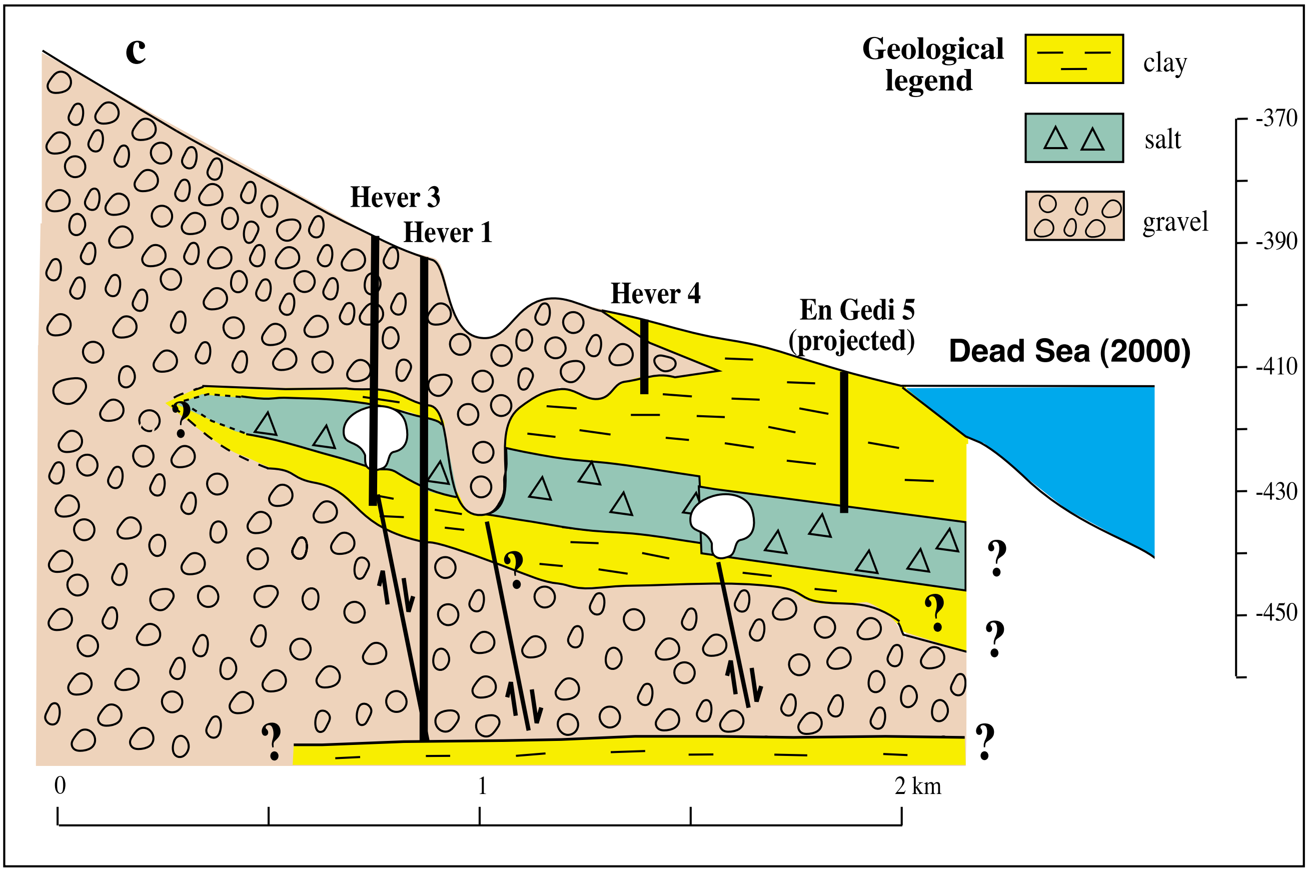

Figure 5. Geological cross-section in the Hever South site.

change in the location of the interface, the subsurface salt layers come into contact with groundwater which is under-saturated with respect to halite. The water probably flows through conduits such as faults or joints. This water dissolves the salt that results in the initial development of caverns within the layer. With time, the ceiling of the caverns collapse, followed by the collapse of the overlying unconsolidated sediments into the empty spaces. Temporary ceilings may be present in relatively consolidated layers within the sedimentary section. The process ends in the formation of sinkholes on the surface. It should be noted that the dissolution of rocks is the major cause of sinkhole formation in many parts of the world (e.g., Martinez et al., 1998; Galloway et al., 1999; Beck and Herring, 2001). Another effect of the decrease in water level could be a drop in hydrostatic pressure in the subsurface within pre-existing cavities, which could also be responsible for the formation of sinkholes.

The system of evaporation ponds in the southern basin of the Dead Sea used by the Dead Sea Works Co., apparently presents different conditions that require special consideration. The water level in the ponds is higher today than that of the Dead Sea level of the 1980's. Moreover, the nature of the hydrological relationship between the pond water and the regional aquifer that occurs at greater depth is not clear and is currently under study. It is also possible that another process is responsible for the sinkhole formation in this area, which could coincide with the process of the dissolution of salt.

SUMMARY AND RECOMMENDATIONS

The observations from the present study lead to the conclusion that the formation of the sinkholes and the collapse of the infrastructure over a wide area resulted from the dissolution of a subsurface salt layer. Mapping of the salt layer and quantification of the hydrogeological processes is, therefore, the key to dealing with the problem. These studies, combined with engineering solutions at single sites, are expected to allow some development of the area. At present, it is not possible to indicate sites along the Dead Sea shore which are considered safe and where the potential for sinkhole formation is unlikely. It appears that areas close to the cliffs and in the northern part of the Dead Sea are safer, based on the assumption that the salt layer is either absent or limited in extent.

The future plans include three main components to be carried out in conjunction:

1. Identification and mapping of risk areas;
2. Monitoring of the events in time and space;
3. Examination of methods to reduce the process of dissolution of the salt layer.

Using geophysical tools, field data, and the hydrogeological model, will allow the preparation of micro-zonation maps. These maps will identify and classify endangered areas. It is also recommended that monitoring of the events should be carried out both in space and time using aerial photographs and satellite imagery. InSAR measurements have shown certain relationships between sinkholes and gradual subsidence (Baer et al., 2001, Abelson et al., in prep.).

It may be possible to reduce the scale of the phenomena by removing the waters undersaturated with respect to salt. This may reduce the rate of dissolution of the layer, prevent the formation of new caverns within it, and/or reduce the rate of the development of those that already exist. The reduction in the rate of dissolution may be possible by the introduction of saturated water into the salt layer.

In addition to the specific recommendations, it is necessary to examine the subject of the lowering of the Dead Sea level in its widest sense, including aspects related to the environment and ecology, raw material for industry, tourism and nature protection, infrastructures, and water resources. All aspects regarding the advantages and hazards of retaining the present water balance should be compared with those that could result from a change in the balance by a Mediterranean- or Red Sea–Dead Sea Canal. This should include an examination of the processes and a quantification of their technical and economic significance, and requires a multidisciplinary team. The implementation of the sea-to-sea canal project should be considered very seriously before implementation.

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