Research Article

Multi- and inter-disciplinary approaches towards understanding the sinkholes' phenomenon in the Dead Sea Basin

Hilmi S. Salem[1]

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Abstract

Over the last few decades, thousands of sinkholes have developed at an increasing pace, with the majority along the western and eastern shores of the Dead Sea. Recent studies indicate that the number of sinkholes in the Dead Sea Basin (DSB) has reached more than 6000; each of them, on average, 1–10 m deep and up to 25–30 m in diameter. These sinkholes can open-up suddenly and swallow whatever exists above them, resulting in an area that looks like an earthquake zone. Sinkholes in the DSB are formed when a subterranean salt layer that once bordered the Dead Sea is dissolved by underground freshwater that follows the migration of the saltwater–freshwater interface, due to receding water level of the Dead Sea. Consequently, large areas of land are subsiding, causing the formation of sinkholes in the region. Also, based on the fact that the Dead Sea's region is tectonically and seismically active, as being greatly affected by the Dead Sea transform fault system, sinkholes can also be evolved as a result of tectonic and seismic activities. This paper presents multi- and inter-disciplinary approaches towards understanding the occurrence of sinkholes in the DSB, with respect to geomorphology, geology, geophysics, tectonics, seismology, limnology, climatology, biodiversity, and socioeconomics, as well as the steady decline of the Dead Sea's water level and the continuous shrinkage of its surface area and its water volume, at alarming rates. The occurrence of sinkholes in this region could be attributed to anthropogenic reasons and/or natural reasons.

Keywords Sinkholes · Dead Sea Basin · Water level's decline · Surface area's shrinkage · Anthropogenic causes · Naturally induced · Brine and freshwater · Tectonics and seismicity · Transform fault system

List of symbols

V_p	Compressional wave velocity
V_s	Shear wave velocity
V_p/V_s	Ratio of compressional wave velocity to shear wave velocity
k	Permeability (hydraulic conductivity)
φ	Porosity
τ	Tortuosity
ρ	Electric resistivity

Abbreviations

APC	Arab Potash Company
BP	Before present
BrO	Bromide oxide
DSB	Dead Sea Basin
DSF	Dead Sea fault
DSFS	Dead Sea fault system
DSTF	Dead Sea transform fault
ERT	Electric resistivity tomography
FDEM	Frequency domain electro-magnetic
GIS	Geographic information system
GPR	Ground-penetrating radar
HSL	Hyper-saline lake
InSAR	Interferometric synthetic aperture radar
JRV	Jordan Rift Valley
LiDAR	Light detection and ranging
MCASW	Multichannel analysis of surface waves
MODIS	Moderate resolution imaging spectro-radiometer

✉ Hilmi S. Salem, hilmisalem@yahoo.com | [1]Sustainable Development Research Institute, Bethlehem, West Bank, Palestine.

MRS	Magnetic resonance sounding
MSL	Mean sea level
NDSB	Northern Dead Sea Basin
O_3	Ozone
ODEs	Ozone depletion events
OL	Ozone layer
P-wave	Compressional wave (seismic, acoustic)
RS	Remote sensing
RSDSC	Red Sea–Dead Sea conveyance (project)
SDSB	Southern Dead Sea Basin
SITS	Satellite image time series
SMCE	Spatial multi-criteria evaluation
SNMR	Surface nuclear magnetic resonance
S-wave	Shear wave (seismic, acoustic)
TDEM	Time-domain electromagnetic
TDS	Total dissolved solids
TEM	Transient electromagnetic
TLS	Terrestrial laser scanner
USD	United States' Dollar

Units

BCM/yr	Billion cubic meters per year
°C	Degree Celsius
°C/yr	Degree Celsius per year
ft	Foot
g/l	Gram per liter
kg/l	Kilogram per liter
kg/m^3	Kilogram per cubic meter
km	Kilometer
km^2	Kilometer square
m	Meter
m^3	Cubic meter
MCM	Million cubic meter
MCM/yr	Million cubic meters per year
m/ka	Meter per thousand years
ms	Millisecond
m/s	Meter per second
m/s^2	Meter per second square
m/yr	Meter per year
mm	Millimeter
mm/yr	Millimeter per year
mol/l	Mole per liter
pH	Acidity–basicity indicator
Ω m	Ohm meter
%	Percentage

1 Introduction

A sinkhole, also known as sink, stream-sink, cenote, swallet, swallow hole, ponor, cavern, or doline, is defined as a geomorphological depression or hole in the ground, caused by some forms of collapse of the surface layers because of different reasons [112]. The morphology of sinkholes and their genetic mechanisms, spatial distribution, and associated risks are well known [15, 58, 98, 99, 113, 114, 122, 140, 192, 201, 202, 234].

Sinkholes can be formed when the land surface topography is changed, and it is vice versa, which means when sinkholes form, topography of the surface is changed. Karst is a topographic feature formed by the dissolution of soluble rocks, such as carbonates (limestone and dolomite) and salts (halite, gypsum, and anhydrite), which can be expressed in topography but can be a subsurface feature that is not visible on the surface of the Earth. Ground collapse and subsidence, and environmental contamination are hazards strongly associated to water, often encountered in a karst environment. Most of the sinkholes are caused by karstic processes, including the 'karstification process,' meaning that rocks are chemically dissolved as happened in carbonate rocks [63, 141]; the 'suffusion process' (or washing-out process), meaning that rocks are collapsing and subsiding as happened in sandstone rocks [41, 171, 225]; and 'dissolution process' as happened in salt rocks, similar to the case of the Dead Sea's salt layers [92–94, 191, 192, 196, 226]. The karstification and dissolution processes require soluble rocks; favorable climatic conditions; structural elements that act as conduits (such as faults, ruptures, fractures, flexures, fissures, etc.); and hydraulic gradient; as well as high porosity and permeability (hydraulic conductivity), which all facilitate water mobility, in the presence of soluble rocks. Therefore, the distribution of groundwater potentiometric heads, fluxes in space and time, and the other factors (mentioned above) are necessary parameters to understand, in order to predict and probably prevent karstic hazards.

Aside from the fact that sinkholes are naturally caused, humans are also responsible for the formation of sinkholes. Activities like drilling, mining, construction, broken water or drain pipes, improperly compacted soil after excavation works, or even heavy traffic (especially when there is void under the road) can provoke small to large sinkholes. Water from broken pipes can penetrate through mud and rocks and erode the ground underneath, causing sinkholes. Sometimes, heavy weight on soft soil can cause collapse of the ground, resulting in sinkholes. The sinkholes, resulting from these natural and anthropogenic processes, generally vary in size from 1 to 600 m (3.3–2000 ft) both in diameter and depth; some of which are even larger than that, as indicated below. They also vary in shape from soil-lined bowls to bedrock-edged chasms.

Sinkholes may form gradually or suddenly, and are found worldwide [61, 104, 131, 227]. They are found, for instance, in Europe (Czech Republic [69], Croatia [60], Serbia [217], Italy [58], Greece [216], the UK [195]; and Ireland [46]); in Africa (Egypt [127], South Africa [166], and Zambia

[182, 210]); in the Caribbean (Bahamas) [155, 224]; in North America (Mexico [32, 68], USA [100, 205, 218–220], and Canada [1, 119]); in Central America (Guatemala [36, 168, 169, 215]); in South America (Venezuela [235]); in Oceana (New Zealand [129], and Papua New Guinea [2]); and in Asia (Iran [86, 88, 156], India [177, 181, 194], China [121, 193, 204], Turkey [35, 62], Lebanon [8, 48, 65], and Oman [162, 222]).

In Oman, for example, there are the Wadi Shab and Bimmah sinkhole, the Dibab sinkhole, and the Teiq (Teeq, Taiq, Tayq) sinkhole. The Teiq Sinkhole, in Salalah–Dhofar, Oman, is one of the largest sinkholes in the world, where several perennial wadis (valleys) fall with spectacular water-falls into this karstic sinkhole found in limestone rocks, which is ≈ 210 m (≈ 670 ft) deep and 130–150 m (≈ 427–492 ft) in diameter [162]. It is worth-mentioning that the sinkholes in Oman, despite of their importance to tourism, they are not studied, and, thus, there is no single scientific article published in refereed journals about them. The largest sinkhole, that has been reported so far, is the 'Xiaozhai Tiankeng Sinkhole' in China, which is up to 662 m deep (≈ 2172 ft), with nearly vertical walls. This sinkhole is one of the most impressive natural attractions on the Earth, which had been carved out in limestone rocks by a powerful underground river [204, 234, 243]. A Chinese-British expedition's team that surveyed this giant sinkhole can be seen on this short YouTube (1.31 min' long): https://youtu.be/j4hjkZfEdUU?t=4 [74].

Remarkably, there are also under-sea (underwater) sinkholes—known as 'blue holes' [115, 168, 169]. Some of the literature given above about sinkholes in different countries of the world also talks about the 'blue holes.' These blue holes are large marine sinkholes that mostly formed during past ice ages when sea levels were much lower than that in the present time. They were subject to the same process of erosion from rain and chemical weathering as any other area that have sinkholes. After being submerged, the erosion ceased, and the deep blue caverns (sinkholes) are left. Some examples on the underwater sinkholes (blue holes) are studied by Palozzi et al. [170] in Italy, Biddanda et al. [42] in the USA (Lake Huron—one of the Great Lakes), and Medina-Moreno et al. [160] in Mexico, and also as reported by Tennenhouse [214] in China, and by Shepert [197] in Canada. There are no scientific publications available on the last two examples of blue holes existing in China and Canada.

According to La Rosa et al. [142], more than 40% of the sinkholes of Italy are found in seismically hazardous zones. However, according to these authors, it remains unclear whether seismicity in that region may trigger sinkholes' collapses or not. La Rosa et al. [142] used a multi-disciplinary data set of Interferometric Synthetic Aperture Radar (InSAR), surface mapping, and historic records of sinkholes' activity to show that the Prà di Lama Lake is a long-lived sinkhole that was formed in an active fault zone and grew through several events of unrest, characterized by episodic subsidence and lake-level changes. Moreover, InSAR measurements showed that continuous subsidence at rates of up to 7.1 mm/yr occurred during 2003–2008, between events of unrest. However, earthquakes on the major faults near the sinkhole do not trigger sinkhole's activity, but low-magnitude earthquakes at 4–12 km depth occurred during sinkholes' unrest in 1996 and 2016 [142]. These observations were interpreted as evidence of seismic creep at depth, causing fracturing, and ultimately leading to the formation and growth of the Prà di Lama sinkhole (Lake). In Japan, a massive sinkhole occurred in a Japanese road after an earthquake centered in Osaka, which caused substantial destruction to regional infrastructures, and, at least, four deaths [159]. This sinkhole resulted in hundreds of people being injured, walls being knocked over, and fires triggered in Japan's second-most populous city—Osaka. In addition, 170,000 homes were left without power, and flights in and out of the city's airport were grounded. That was a result of the 6.1-magnitude earthquake that hit Osaka city, Japan, on June 18, 2018 [159]. So, sinkholes can be directly or indirectly triggered and/or caused by seismic events, including micro- and macro-scaled earthquakes.

Researchers have currently applied advanced techniques to investigate sinkholes. For instance, Al-Kouri et al. [18] used geographic information system (GIS) and remote sensing's (RS) techniques, including a spatial multi-criteria evaluation's (SMCE) approach to produce a geo-hazard's map for the limestone sinkholes in the Kinta Valley, northeastern Malaysia. Over the last 3 decades, these sinkholes were man-made because of the uncontrolled land-use and development's activities that have led to significant changes in topography and geomorphology that have caused the occurrence of sinkholes.

Goldshleger et al. [110] developed methods for prediction of sinkholes' occurrence by using mapping and monitoring methods, based on active and passive RS' means. These methods are based on combined measurements, including field spectrometry and geophysical instruments, such as ground-penetrating radar (GPR) and frequency domain electro-magnetic (FDEM). These measurements were undertaken at different times to monitor the progress of an 'embryonic' sinkhole (a progressing one). Accordingly, it was found that higher electric conductivity and higher soil moisture characterizing the site of that progressing sinkhole. Benito-Calvo et al. [40] explored, for the first time, the application of a terrestrial laser scanner (TLS) and a comparison of point clouds in the 4D-monitoring of active sinkholes. Their approach was tested in three highly-active sinkholes in northeast Spain, related to the dissolution of salt-bearing evaporites overlain by unconsolidated alluvium. The sinkholes are located in urbanized areas, and have caused severe damage to critical infrastructures (flood-control dike, a major highway, etc.).

Regarding the sinkholes in the Dead Sea Basin (DSB), as being the focus of this study, the DSB is a hub for thousands of sinkholes, representing a remarkable phenomenon that has been developed in the last few decades. The rapid development of such a phenomenon in the DSB in the last few decades poses major geological, geotechnical, and geoenvironmental hazards to the local population, agriculture, and industry (e.g. [9, 10, 16, 17, 25, 54, 55, 67, 85, 87, 138, 176, 184–186, 192, 203, 212]. Recently, some studies were conducted on the DSB to investigate sinkholes in the region, using geophysical and other kinds of techniques. More details are given below.

2 Study purpose

This paper deals with one of the most serious and dramatic occurrences of the Earth's surface, in one of the most amazing places on the Earth—it is the sinkholes in the Dead Sea Basin. The paper's main target is to analyze this hazardous phenomenon, in terms of multi- and inter-disciplinary approaches, with respect to the region's geology, geophysics, seismology, limnology, climatology, environment, and socioeconomics. In this case, it is believed that the sinkholes in the DSB have been steadily evolving as a result of either anthropogenic (man-made) acts, naturally induced, or both, based on the facts and arguments presented and discussed herein. The paper investigates the sinkholes in the DSB, and presents the resulting evaluation to those concerned with the issue of sinkholes as a geohazard's phenomenon, at academic, research and developmental, industrial, governmental, and nongovernmental institutions. To achieve the goals of the paper, a wide range of up-to-date scientific and technical publications, dealing with several areas of expertise, have been comprehensively reviewed, analyzed, and cited in this paper. Field visits were also carried out, and available data was analytically used and analyzed.

3 Data and observations

3.1 Geological–geophysical setting (tectonics and seismology) of the Dead Sea Basin

The Dead Sea Basin is part of a seismically active region that locates between two mobile tectonic plates: (1) The African Plate (including the Sinai Peninsula Sub-Plate) to the south and southwest of the Dead Sea; and (2) The Arabian Plate to the north and northeast of the Dead Sea [57, 157] (Fig. 1). The location of the DSB between these two mobile, active plates, on the one hand, and between two major active faults, bordering the DSB from the west and the east, on the other hand (as discussed below), has made the DSB a very active region, tectonically and seismically.

As shown in Figs. 1 and 2, the Dead Sea is bordered by two major strike-slip faults on the west and the east. The fault on the west is known as the 'Jericho Fault,' located in Historic Palestine; and the fault on the east is known as the 'Wadi Araba Fault,' (also known as Araba (or Arava) Fault), located in Jordan. The common model of the DSB, which describes its structure, is of a 'Pull-Apart Basin' [102], affected by both fault systems (the Jericho Fault and the Araba Fault) on both sides of the DSB. The DSB is a long (≈ 150 km), narrow (≤ 15 km), and deep (< 8.5 km) basin, located along the Dead Sea's Transform Fault (DSTF) [213, 229].

The Dead Sea Basin is divided into two main sub-basins, which are the northern sub-basin and the southern sub-basin. The northern one is larger and deeper than the southern one, whereby both sub-basins are separated by the Lisan Peninsula. The Lisan Peninsula is underlain by a large salt diaper, with a thickness of about 8 km, a length of up to 20 km, and a width of about 7 km, extending under the Dead Sea [20, 21, 39, 52]. It is noteworthy to mention that according to recent studies, the DSB shows evidence of hydrocarbons [56]. The Dead Sea itself is located within a tectonic rift (known as the 'Jordan Rift Valley' (JRV) or 'Jordan Valley'), forming a topographic depression (known as 'Graben') with a width of 15–25 km, extending from the Gulf of Aqaba on the Red Sea in the south, to Lake Tiberias (Sea of Galilee), in the north. The JRV, formed in the Miocene Epoch (23.8–5.3 million years ago), is mainly covered by playa deposits (salt, sand, and mud) and sand dunes. The highlands of the JRV consist of much older rocks to young deposits, ranging in age from Precambrian in the south to Tertiary in the north.

Hofstetter et al. [120] obtained a velocity-structure profile of the crust across the DSB, by applying a tomography-based method to local earthquakes. They used compressional wave (P-wave) travel-times of 614 earthquakes that occurred in the DSB during a period of 26 years (1983–2009). As a result, they found that the DSB, at all depths, is characterized by lower velocities relative to its both western and eastern sides. They also found that a significant seismic activity is taking place at a depth of about 20 km, mainly in the central and northern parts of the DSB. At shallower depths (i.e. < 15 km), there is more seismic activity on the eastern side of the DSB than on its western side. They also found that the northern part of the DSB (or Northern DSB) is generally more active than its southern

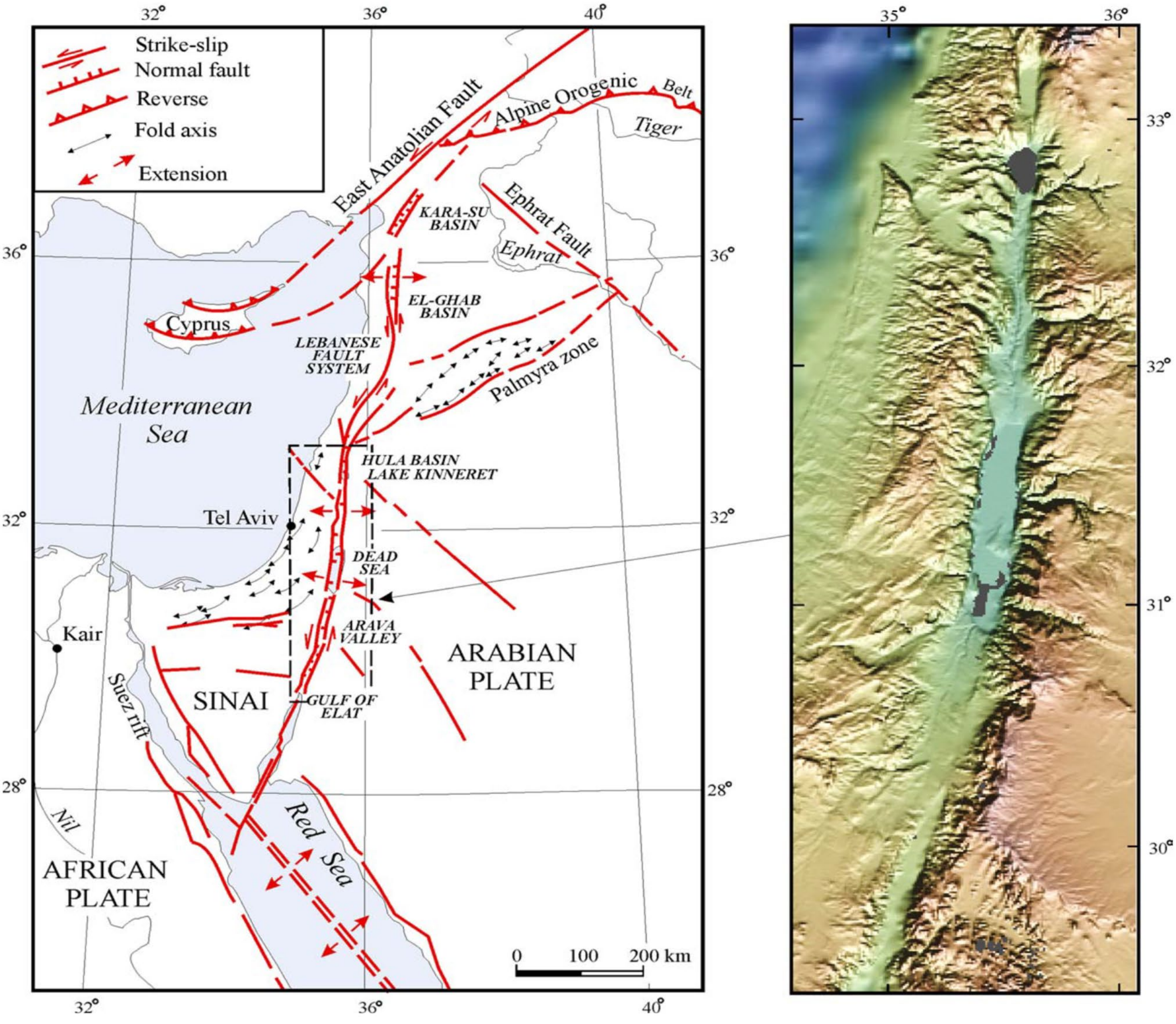

Fig. 1 Left: the tectonic framework of the Dead Sea Basin (DSB) and of the adjacent areas; right: digital shaded-relief map of the DSB (after [57, 157])

part (or Southern DSB). Asymmetry is also observed in the fault systems that border the DSB from the west (bordered by the Jericho Fault) and from the east (bordered by the Araba Fault) (Fig. 2). The Araba Fault System on the eastern side of the DSB appears to be a clear boundary at all depths down to about 20 km. Meanwhile, the depth extension of the Jericho Fault System, on the western side of the DSB, is definitely limited to less than 15 km.

The concentration of earthquakes in the central part of the DSB (Fig. 2—Middle) at depths larger than 15 km suggests that both of the western and eastern fault systems of the Dead Sea act, at those depths, as one single fault that is located in, or near, the central axis of the DSB, which is widely known as the 'Dead Sea Transform Fault' (DSTF), named also as 'Dead Sea Transform' (DST) or Dead Sea Fault System (DSFS). The DSTF is a major fracture zone and physiographic feature that extends from northern Red Sea to the Taurus Mountains in Turkey, along a distance of around 1000 km. It is a strike-slip fault system, which currently accommodates 5–7 mm/yr of left-lateral motion, over the past 5 million years, between the Arabian and African tectonic plates [38, 59, 144]. A total offset of 105–110 km has accumulated along the plate boundary since the Middle Miocene (17–18 million years) [59, 90, 179]. The Dead Sea Basin has been accumulating sediments since the formation of the plate boundary [47, 158] and continues to subside at present that is evidenced by its low surface elevation, which is currently at ≈ 435 m below mean sea level (MSL), as discussed below.

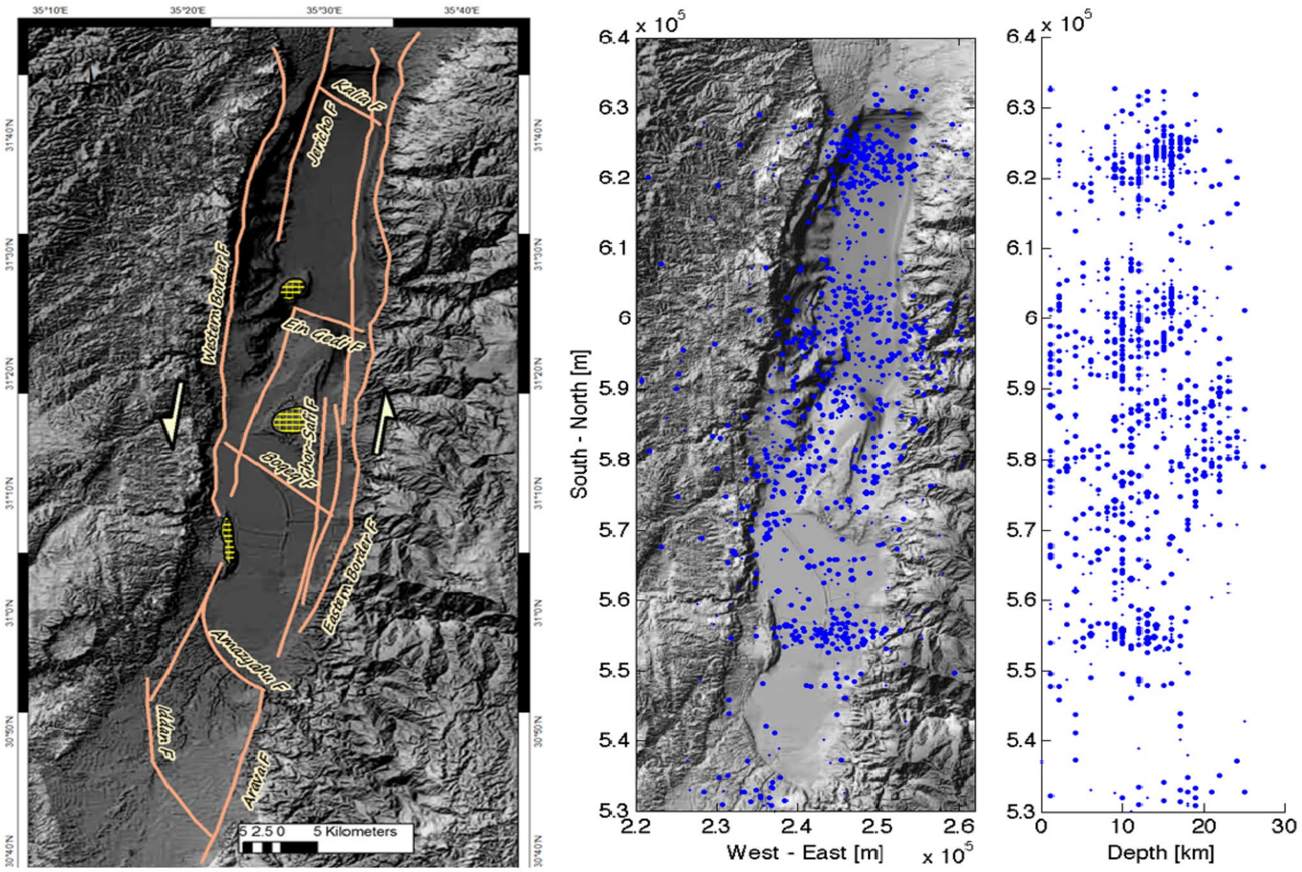

Fig. 2 Left: map of the Jericho Fault and Araba Fault on both sides of the Dead Sea Basin (DSB), as well as some other smaller faults affecting the DSB; middle: a map view of the seismic activity (earthquakes; blue dots) along the DSB; right: a depth north–south cross-section of the Dead Sea's seismicity (after [228])

Studying this fault system (DSFS) is of fundamental significance to the Earth Sciences [221]. Continental transform faults, such as the DSTF (DSFS), provide a simple setting, in which deformation as a function of rock properties, temperatures, and pressures of the continental crust, can be studied. These studies are important to understand the long-term strength of the continental lithosphere, subsidence of sedimentary basins, and the earthquakes' deformation cycle, as well as sinkholes, which are developed and still developing in the Dead Sea Basin.

3.2 Unique characteristics and biodiversity of Dead Sea Basin

The Dead Sea receives its water from several sources, mainly the Jordan River, which is more than 360 km long, and from its tributaries, namely Yarmouk, Hasbani, Dan, and Banias, as well as from wadis (valleys), such as, among others, Zerqa, Mujib, Kerak, and Hasa, on the eastern side; and Far'a, Auja, Qelt, and An-Nar, on the western side. The Dead Sea has a catchment area of 41,650 km^2, current surface area of 605 km^2, maximum depth of 378 m, average depth of 147 m, maximum length of 76 km, maximum width of 18 km, water density of 1.24 kg/l, and water salinity [total dissolved solids (TDS)] of 33.7% (337 g/l), which reaches, at lower depths, 34.8% (348 g/l) [95, 191, 192]. This makes the Dead Sea the saltiest and heaviest water body on the Earth and, therefore, it is known as the 'Hyper-Saline Lake' (HSL) [103]. The Dead Sea's brine (hyper-saline water) has a uniquely ionic composition, consisting of magnesium (Mg: 1.98 mol/l), sodium (Na: 1.54 mol/l), calcium (Ca: 0.47 mol/l), and potassium (K: 0.21 mol/l), whereas the main anions are chloride (Cl: 6.5 mol/l) and bromide (Br: 0.08 mol/l). Additionally, the Dead Sea's brine has low water activity (< 0.699) [172], and its pH is ≈ 6 [167].

Until 2009, the water level (surface elevation) of the Dead Sea was 421–422 m (≈ 1381–1384.5 ft) below MSL [11–13, 191], and in 2018 it was around 430 m (≈ 1411 ft) below MSL [174, 233]. The latest measurement of the Dead Sea' water level is 435 m (≈ 1427 ft), as provided by EO Sharing Earth Observatory Resources on July 21, 2019 [70]. This means that the Dead Sea's water level has declined no less than 13 m within 10 years (2009–2019) only—an average of 1.3 m/yr, which has increased from 0.7 m/yr in the 1970s and 1980s [70, 111]. The Dead Sea's water level has primarily dropped as water has been diverted from its only tributary—the Jordan River—to serve the surrounding communities with water in Israel and Jordan, and also due to the water pumping from the Dead Sea to the evaporation ponds on both of its shores.

In addition to the fact that the Dead Sea is the lowest point and deepest HSL on the Earth, the Dead Sea region is known by its unique climate, as it has more than 330 sunny days, and its average temperature is around 40 °C in summer and around 15 °C in winter, and the mean relative humidity ranges between 34 and 50% over the 12 months of the year [191]. The annual rainfall over the Dead Sea region is around 90 mm, meanwhile the annual evaporation rate is 1500 mm, with an actual evaporation rate of 1300–1600 mm/yr, depending on the salinity and temperature variations at the surface of the Dead Sea, which both are affected by the annual volume of freshwater inflow into the Dead Sea. These evaporation rates indicate that an average deficit of about 1400 mm of the Dead Sea water occurs every year [191]. The high rates of evaporation result in the actively precipitation of the halite and gypsum minerals, as a response to the negative water balance of the HSL, because the evaporation rates are much greater than the inflow rates [154, 199, 206], resulting in greater salinity [180]. The crystallization and precipitation of the halite and gypsum minerals and salt layers in the Dead Sea and its surrounding area have been comprehensively investigated by many researchers over the last few decades (e.g. [50, 101, 164, 207]), as well as in different salty environments in various locations around the world (e.g. [29, 88, 89]).

The Dead Sea area is still the home of rare species. In the mountains, oases, marshes, and temporary rivulets surrounding the Dead Sea, there are many animals, including leopards, ibex, antelope species steenbok, and the griffon vulture, as well as hundreds of bird species. The Jordan Rift Valley and the Dead Sea Basin are among the most important migration routes for the black and white stork and many other bird species on their migration route from the breeding areas in Eastern Europe and the Middle East to Africa [108]. The Dead Sea Basin, as an extremely stressful hyper-saline environment, is considered a unique model for tracking evolutionary dynamics of biodiversity under increasing salinity. The stress of the high salinity of the Dead Sea eliminates most life forms except one alga, several species of Archaea, bacteria, and filamentous fungi [172]. Species' diversity has steadily decreased—a phenomenon that is highly and significantly correlated with the decline of the Dead Sea's water level, and with increasing its water's density and salinity, which is currently 348 g/l, as mentioned above. Two Dead Sea's surviving species—*Aspergillus amstelodami* Thom et Church and *Aspergillus ruber* Thom et Church—increase in frequency in the Dead Sea, down to a depth of 291 m below MSL, due to their evolved adaptations to tolerate hyper-salinity [172].

The Dead Sea also houses some unique bacteria, though its water is 'hyper-saline' (or brine). During December 1941, a number of samples of sediments were collected at depths of 70–330 m below MSL of the Dead Sea, which, after analyses, indicated the presence of some kinds of bacteria in the Dead Sea [223]. Micro-organisms that inhabit hyper-saline lakes may be halo-tolerant or halo-philic. The ability to tolerate high-salt concentrations without compromising growth is characteristic of halo-tolerant micro-organisms. Micro-organisms that have adaptations, which require salt as a growth factor, are referred to as halo-philic. Both halo-philic and halo-tolerant micro-organisms perform one of two different mechanisms to ensure that they can persist in the high-salt concentrations of hyper-saline environments. Ionescu et al. [125] discovered several underwater fresh to brackish water springs in the Dead Sea, harboring dense microbial communities. This can be seen on the YouTube video (2.46 min' long) provided on this Link https://www.youtube.com/watch?v=aoXddPg4lFw [123]. This short video, showing the 'First Scientific Diving Expedition in the Dead Sea: Springs of Life in the Dead Sea', has led to the discovery of a complex community of living microbes found in freshwater springs on the bottom of the deepest HSL on the Earth. To locate and study these springs, it was quite a task for the scientific diving team, as the high-salt concentration makes the diving dangerous and difficult. The divers located the springs and took water and sediments' samples, in which they detected novel micro-organisms [161].

3.3 Dead sea as health resort

The Dead Sea is the only place on the Earth where one can sunbathe for long periods of time with little or no sunburn, because harmful ultra-violet rays are filtered through three natural layers, which are: (1) An extra atmospheric layer; (2) An evaporation layer that exists above the Dead Sea; and (3) A rather thick Ozone Layer (OL). However, some recent studies indicated that there is depletion in the OL over the Dead Sea, which is due to chemical effects. Measurements of the ozone (O_3) and bromide (or bromine oxide—BrO) concentrations over the Dead Sea indicated that Ozone Depletion Events (ODEs)—widely known to happen in polar regions—are also occurring over the Dead Sea, due to the very high bromine content of the Dead Sea's hyper-saline water [200]. Bromide could play a significant role in the interaction dynamics on the surface of crystallized sea salts [137], which may result in interactions with the OL. The bromide enrichment of the salt surfaces can play an important role in some global atmospheric processes, like depletion of the atmospheric OL [107].

3.4 Paleo-climate of the Dead Sea Basin

Nearly 305 m (≈ 1000 ft) below the bed of the Dead Sea, scientists have found recently evidence that during past warm periods, the Middle East has suffered drought on scales never recorded by humans—a possible warning for current times [135, 143]. Thick layers of crystalline salt, termed by Talbot et al. [211] as 'salt reefs,' show that rainfall plummeted to as little as a fifth of modern levels during the Later Quaternary—some 120,000 years ago (Pleistocene Epoch on the Geological Time Scale), and again about 10,000 years ago (Holocene Epoch on the Geological Time Scale). Today, the region is drying again due to global warming, resulting from climate change, which is even getting worse. The Holocene Epoch (also known as the 'Anthropocene Epoch') is the current period of geologic time, whereas its primary characteristic is the global changes caused by human activity. The Holocene Epoch began 12,000 to 11,500 years ago at the close of the Paleolithic Ice Age and continues through today [31].

Charrach [51] studied the geological history and paleoclimate of the Dead Sea's region based on drill-holes' data, and found that a composite stratigraphic column for the Holocene Epoch, of multiple lime carbonate and halite sedimentation, has been constructed for the Southern Dead Sea Basin (SDSB). During that period of time, the SDSB has subsided at a rate of 8.5–11 m/ka (meter per a thousand years), while the subsidence of the Northern Dead Sea Basin (NDSB) may have reached 25–30 m/ka. The Holocene has been divided into 13 major climatic intervals, starting with a very arid climate from ≈ 11,700 to ≈ 8800 BP (Before Present), where halite precipitated in both basins (NDSB and SDSB), while the Dead Sea's water level possibly reached ≈ 419 m below MSL. After ≈ 8800 BP, there was a very intense pluviatile period, with the formation of alluvial fans opposite wadi channels, reaching up to 45 m in thickness [51].

3.5 Decline of the Dead Sea's water level

The Dead Sea's water level has been declining since the 1950s at alarming rates of approximately one meter per year, on average [241] (Table 1; Figs. 3, 4). The main reason for this rapid decline is the decreasing inflow of fresh water through the Jordan River into the Dead Sea, which has been reduced from around 1250 million cubic meter/year (MCM/yr) in the 1950s to ≈ 260 MCM/yr in 2009 [191], representing less than 21% of the original flow. As a result, the Dead Sea's surface area has also been dramatically shrinking (Table 1).

Table 1 Observed and projected variations of the mean sea level (MSL) and surface area of the Dead Sea over a period of 90 years (1960–2050) [191]

Year	MSL (m)	Surface area (km^2)
1960	− 390	1020
2005	− 420	635
2050	− 500	520

Table 1 demonstrates that within 90 years only (1960–2050), the water level of the Dead Sea has and will be declined by no less than 110 m (this is equivalent to more than 1.2 m/yr, on average, as indicated also above). In absolute terms, the Dead Sea's water level has declined by 37 m as of 2017, and is forecasted to drop a further 25–70 m by year 2100 [26, 105, 191, 192, 226, 238]. However, simulations based on ranges of water withdrawal's scenarios suggested that the Dead Sea will not 'die;' rather a new equilibrium is likely to be reached in about 400 years after a water-level decrease of 100–150 m [238]. Also, as shown in Table 1, the surface area of the Dead Sea, for the same period (1960–2050), has and will be shrunk by about 500 km^2 (this is, on average, 5.5 km^2/yr). Abu Ghazleh et al. [11] gave an average of 4 km^2/yr, as they did not consider the projected variations in the Dead Sea's surface area until 2050.

Of the annual water inflow (≈ 1.3 billion cubic meter 'BCM/yr'), which used to naturally flow in the Jordan River, ending in the Dead Sea, more than 96% is diverted for agricultural and domestic usages by the neighboring countries (mainly Israel and Jordan, and Syria to a lesser extent), leaving only a very small amount of water to reach the Dead Sea. In addition to diversion of the Jordan River's waters by Israel and Jordan, solar evaporation carried out by the Israeli and Jordanian mineral extraction companies on western and eastern shores of the Dead Sea along its Southern Dead Sea Basin have contributed to the drastic decline of the Dead Sea's water level (as indicated above), and to the decrease in its surface area and, thus, shrinking the Dead Sea's extension (Figs. 3, 4).

A great portion of the fresh water that used to recharge the Dead Sea through the Jordan River has been replaced, for many years now, by domestic and industrial sewage that continues to flow into the Dead Sea, causing a great damage to the Dead Sea itself, and to the Jordan River, as well as to the unique ecosystem of the Dead Sea Basin and the surrounding environment. As the water level of the Dead Sea is steadily declining at an alarming rate of more than 1 m/yr, its surface area is also considerably shrinking (Table 1; Fig. 4). Based on satellite's imagery for a period of 41 years (1972–2013), El-Hallaq and Habboub

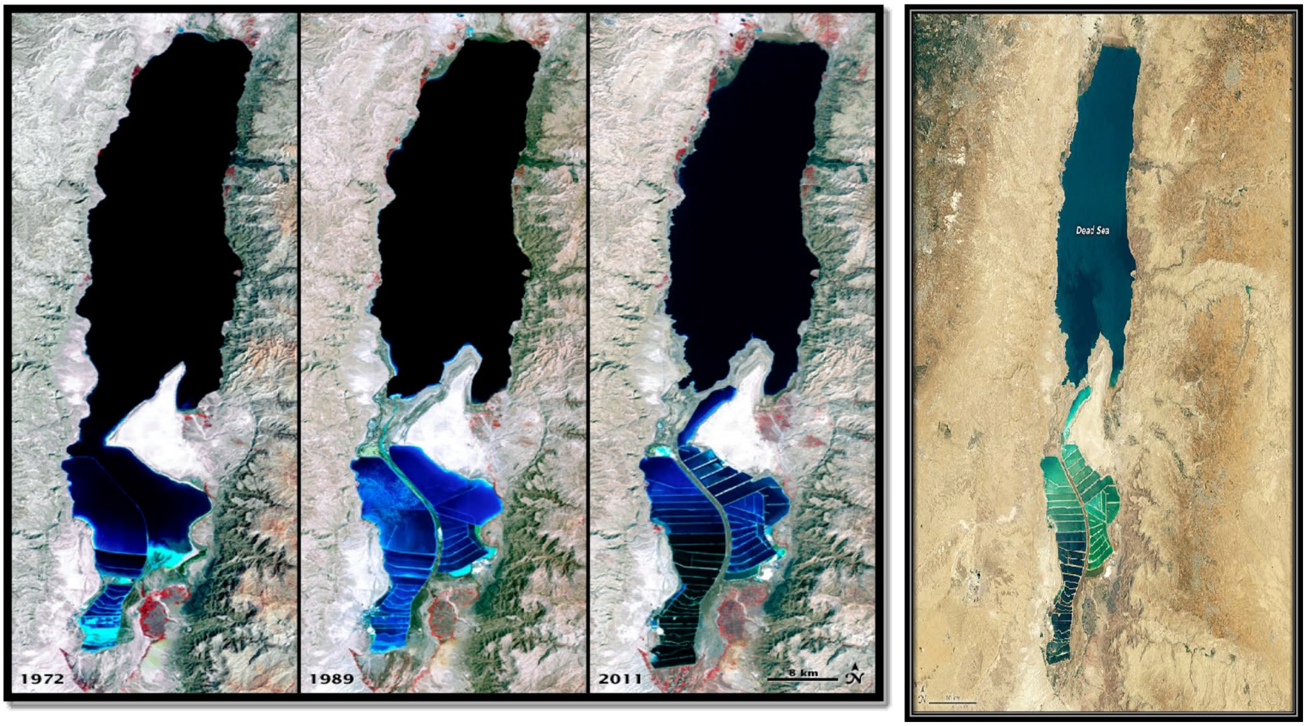

Fig. 3 Satellite images revealing the Dead Sea's shrinkage in surface area and water volume (from left—first: September 15, 1972; second: August 27, 1989; third: October 11, 2011; and fourth: July 21, 2019), as well as the growth of mineral-extraction evaporation ponds (shown in blue and green) in the Southern Dead Sea Basin (after NASA Earth [163] (first three images), and EO SEOR 2019 (forth image—originally a NASA image))

[66] estimated that the Dead Sea's water area shrank, on average, at a rate of ≈ 2.9 km^2/yr.

4 Results and discussion

The Dead Sea represents a unique ecosystem, with geological, chemical, biological, physical, environmental, ecological, limnologic, and climatic characteristics that are found nowhere else on the Earth [37, 191]. The combination of these elements of uniqueness and the special characteristics of the Dead Sea, with respect to climate, hypersalinity, mineralogy, topographic and geological settings, seismicity, hydrology, hydrogeology, hot springs, biodiversity, archeology, etc. have turned the Dead Sea into a major health resort, with particularly beneficial effects on skin diseases. They also have turned the Dead Sea Basin into a 'Mecca' for research scientists, locally, regionally, and internationally. Among the major concerns for research scientists in the DSB are tectonics, geodynamics, seismicity, hyper-salinity, climate, decline of its water surface, shrinkage of its size and surface area, and sinkholes, which all, by way or another, are directly or indirectly related to each other and are impacted by each other. The following section discusses the issue of the DSB's sinkholes, in particular, from various points of view and multi- and inter-disciplinary approaches, as being the primary target of this paper.

4.1 Sinkholes

4.1.1 Anthropic interferences and how to deal with sinkholes

The high anthropic (anthropogenic) interferences and the high susceptibility of the Dead Sea's area (for health reasons and tourism) ask for multi- and inter-disciplinary research to investigate the reasons behind the occurrence of thousands of sinkholes in the Dead Sea Basin. Additionally, the sinkholes' phenomenon in the DSB is investigated in this study, based on the fact that the DSB and its tectonic and geodynamic settings—primarily the DSFS—are considered globally an open natural laboratory for tectonics, seismology, geology, water sciences, and various disciplines of engineering. Furthermore, sinkholes are investigated in this paper because of safety reasons, based on the fact that they can open-up suddenly and without warning, causing fear, panic, and anxiety, as well as death to people, and damage to property. Therefore, those who plan roads, constructions, and infrastructures should carefully choose

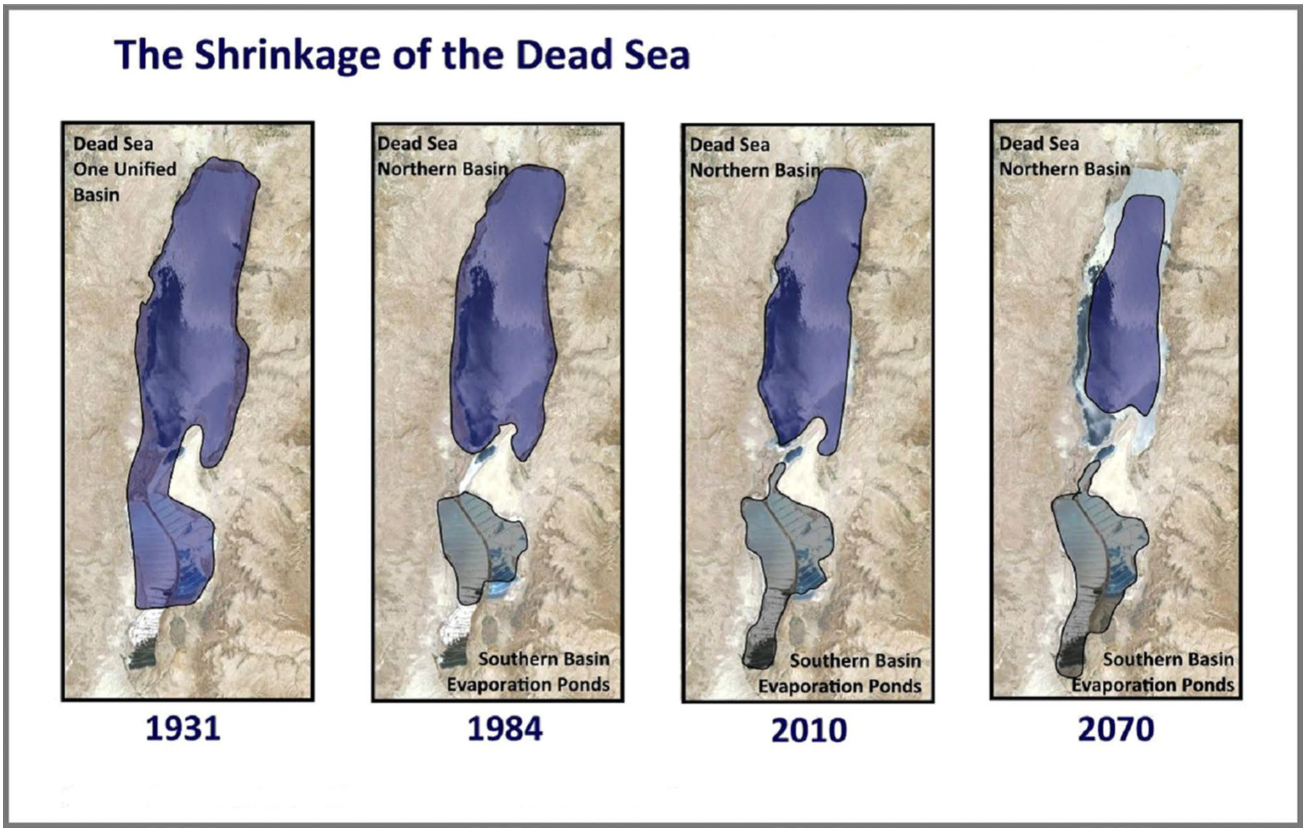

Fig. 4 Shrinkage of the surface area of the Dead Sea as a result of the decline in its water level since 1931 through the years 1984 and 2010, and as projected for the years 2070 (after [231])

where to put them, considering the sinkholes existing in the region and others that may develop and occur anytime. Because sinkholes do not only impact the local infrastructures and facilities, as well as well-being of humans, but also affect the area's hazards and risks, early monitoring of sinkholes' development is needed, in order to protect life of people, and also to reduce severe economic damages and loss that may result from sinkholes (e.g. [24, 43, 124, 145]), as discussed below. In addition, remarkably sinkholes have become home for new micro- and macro-organisms, some of which are new to the habitat of the DSB. They can be homes for communities of unusual plants and animals, and also be a special link between the Earth's surface and underground resources [14, 91, 130].

4.1.2 Occurrence of sinkholes in the Dead Sea's Basin: frequency

Sinkholes in the DSB were first noticed in the 1970s [5], and since then they have rapidly increased in number and size. Currently they count, primarily on both western and eastern shores of the Dead Sea, in thousands, varying in diameter, depth, size, and shape, whereas some of which are vertiginous openings tens of meters deep (Fig. 5). The largest sinkhole in the DSB has a circular shape with a diameter of 60 m and a depth of 35 m, as well as a volume of ≈ 100,000 m^3 [92, 183].

Though the exact number of the sinkholes in the DSB is unknown, estimates indicated that their number on both sides of the Dead Sea (east and west) has probably exceeded 6000 [33]. Until 2015, the number of sinkholes on the western shore of the Dead Sea reached more than 4000 that were formed since the 1970s within a 60-km long and 1-km wide strip, and the formation's rate of sinkholes in the DSB has accelerated in recent years to more than 400 sinkholes per year [240].

However, the majority of the Dead Sea's sinkholes are mainly located in its southern part and on both sides of the 'Lisan Peninsula' of the Dead Sea. These sinkholes are observed mainly along the edge of a salt layer deposited during the latest Pleistocene (2.6 million years ago and lasted until about 11,700 years ago on the Geological Time Scale), when Lake Lisan receded to become later the Dead Sea [75, 94]. The presence and frequent occurrence of more sinkholes in the southern part of the Dead Sea could be attributed to man-made activities, represented

Fig. 5 Pictures of some examples of the sinkholes in the Dead Sea Basin (DSB) (with various scales)

in the heavy industry as being progressively covered by solar evaporation ponds for exploitation of the Dead Sea's minerals on the Dead Sea's western and eastern shores. It could also be attributed to naturally-induced causes, represented in the tectonic deformations that are clearly visible in the region, because of the uplift in the salt-diapir. These two drives (anthropogenic and natural) together might lead to the formation and development of more sinkholes in the southern part of the Dead Sea.

4.1.3 Occurrence of sinkholes in the Dead Sea Basin: morphology

In the 1960s, the Dead Sea's area was 1200 km^2 (80-km long times 15-km wide). Since then the Dead Sea's area has reduced by almost half; being now around 605 km^2 [19, 49, 64, 191, 209, 230, 236]. This has resulted in major changes in the hydrogeological setting and in the landscape and morphology of the Dead Sea, as being direct reasons for the formation of sinkholes that have been occurring since then at alarming rate in the DSB. The ground collapse and subsidence in the DSB, characterized by underground drainage systems, have resulted in sinkholes, as well as in caves and cavities. The geomorphologic features of sinkholes in the DSB, caused by ground collapse and subsidence, represent an exceptional case, since they are directly or indirectly originated by man [92].

4.1.4 Occurrence of sinkholes in the Dead Sea Basin: hydrology and hydrogeology

As the Dead Sea's water level declines and its surface area shrinks (Figs. 3, 4), the temperature of the Dead Sea's surface water has also changed. Using observations from 10 moderate resolution imaging spectroradiometer (MODIS), positive trends were detected in both day-time (0.06 °C/yr) and night-time's (0.04 °C/yr) surface temperature of the Dead Sea over the period of 2000–2016 [136]. This implies greater rates of evaporation and, thus, greater declines in the Dead Sea's water level, and further shrinkage in its surface area, resulting in developing more sinkholes.

As the brine (hyper-saline water) of the Dead Sea recedes, fresh groundwater moves up and dissolves layers of salt, creating large underground cavities, above which sinkholes are evolved. The decrease in the Dead Sea's brine volume has pushed the fresh water to move from the neighboring groundwater aquifer systems on the eastern and western sides of the Dead Sea, replacing the brine. Some scientists, however, believe that salt layers are dissolved by the Dead Sea's brine [84]. This has resulted in dissolving the salty deposits or layers, which has led to subsidence and collapse of the rock formations and, thus, to the formation of sinkholes, with tens of meters in diameter and depth, along the Dead Sea's eastern and western shores. These sinkholes cluster mostly in specific locations up to 1000-m long and 200-m wide, which align parallel to the general direction of the Dead Sea Fault System, associated with the structural complex of the Dead Sea and the Jordan Rift Valley. As seen in Fig. 6, the dramatic decline of the Dead Sea's water level for the period of ≈ 40 years (≈ 1978–2018) is strongly associated with a dramatic increase in the number of sinkholes occurred in the DSB [165]. This represents strong linkage between the two phenomena—the decline of the Dead Sea's water level and the frequent

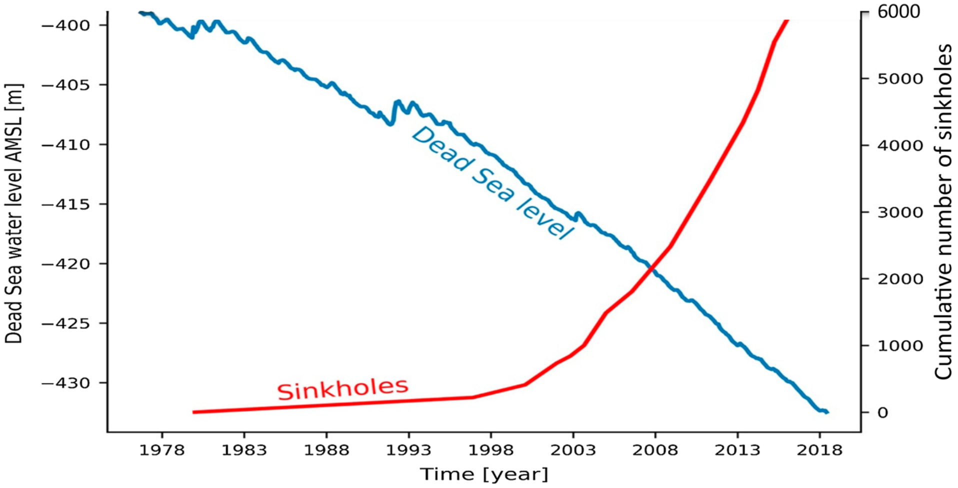

Fig. 6 Cumulative number of sinkholes (red line) and decline of the Dead Sea's water level (blue line) for a period of approximately 40 years (≈ 1978–2018) (after [165])

increase of the number and size of the sinkholes in the DSB.

Over the last decade or so, the World Bank led an initiative to carry out a mega project to bring water, through a conduit with a total length of ≈ 200 km along the Wadi Araba (Arava Valley), from the Red Sea to the Dead Sea, for the purpose of rising the Dead Sea's water level [19, 49, 64, 191, 209, 236]. Nevertheless, such a project, known as the 'Red Sea–Dead Sea Conveyance (RSDSC) project,' with the cost of billions of USD, will never be able to provide enough water to stem the continued decline of the Dead Sea's water level. Whatever provided of saline water from the Red Sea to the Dead Sea will be a very tiny amount of what the Dead Sea really needs. Furthermore, the project will create, on the short-run and long-run alike, more problems than solving the already existing ones [191]. Additionally, such a mega project (RSDSC) would exacerbate the sinkholes' formation in the DSB. The more diluted water brought from the Red Sea, in comparison to the Dead Sea's water, will help in dissolving more salt layers in the region. These salt dissolved layers might be, in turn, absorbed by the aquifers and streams in the region and, thus, accelerate the collapse of the ground, resulting in the formation of new sinkholes and in enlarging the existing ones.

4.1.5 Occurrence of sinkholes in the Dead Sea Basin: seismology (natural and induced earthquakes)

The features of heavy tectonics (including faults, mainly the Dead Sea Fault System; ruptures; fractures; flexures; anticlines; synclines; etc.) and seismicity (seismic activity resulting in micro- and macro-earthquakes with small and large magnitudes) that affect the DSB and the surrounding regions could also be triggers as a result of the formation and evolution of sinkholes in the DSB (Fig. 7). To investigate this and approve it scientifically, some advanced measurements are needed to be undertaken in the region. In some other parts of the world, as discussed above, it was shown that the occurrence of sinkholes in seismically active regions is accompanied by earthquakes. Also, infrastructures and other kinds of projects may trigger sinkholes. Salem [191] concluded that the Red Sea–Dead Sea Conveyance project, though it has some advantages, has also several disadvantages. Accordingly, large projects that may be undertaken in the region, such as the RSDSC project, could be a reason that triggers earthquakes and causes the formation of new sinkholes and, thus, worsens the situation much more than that which is already exists. Sinkholes tend to develop along lineaments [4], which can be traced up to ≈ 2 km. The orientations of the sinkholes' lineaments are strikingly similar to the orientation of the faults forming the Dead Sea and the Jordan Raft Valley. These observations imply that the formation of sinkholes is related to tectonic faults buried in the Rift's sediments [4]. The observed linkage between tectonic faults and sinkholes implies genetic relationships, where, beside the presence of salt layers, the formation of sinkholes is strongly affected by the presence of a prominent tectonic fault, which is the DSFS [209].

An early hypothesis postulated that clay softening, liquefaction, and mobilization in the subsurface, due to the dilution of former highly salty pore-water by freshwater inflows, generate the sinkholes [25]. As discussed by Ezersky and Frumkin [79], two other factors may control the location of the sinkholes at the Dead Sea, namely: (1) The presence of a thick, massive salt layer that is exposed to a dissolution front at its edge; and (2) The presence of subsurface faults that control freshwater inflow into, and, thus, enable dissolution of, the salt layer. According to Ezersky and Frumkin [79], there are two conflicting models of sinkhole development along the Dead Sea. The first

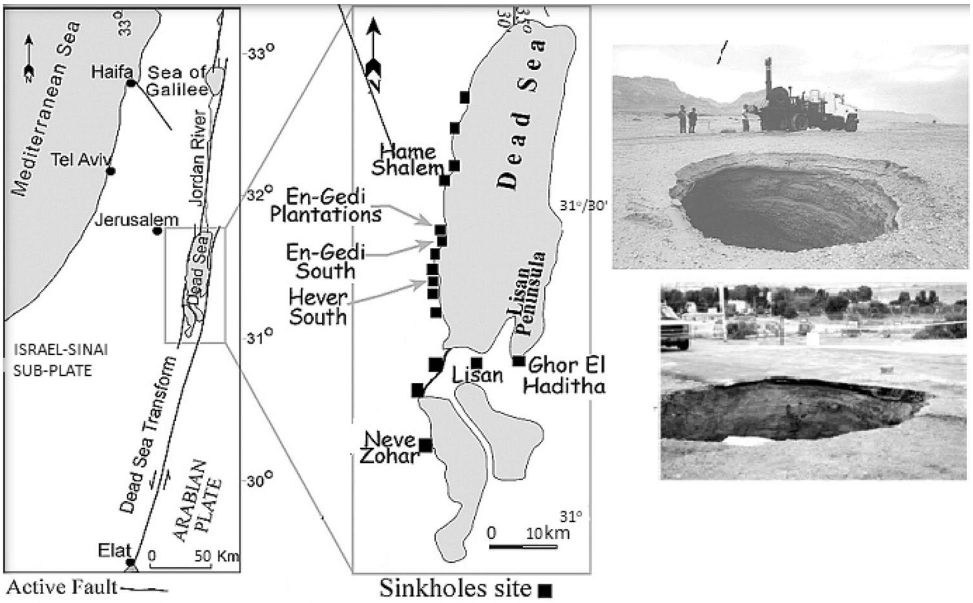

Fig. 7 Left: location map of the Dead Sea Basin (DSB) and the Dead Sea Transform Fault (DSTF) system; Middle: distribution of sinkholes' locations along the Dead Sea's western shore; Right: pictures of some sinkholes in the DSB, which may exceed 15 m in depth and 25 m in diameter (after [4, 191, 198])

one considers structural control on sinkholes, constraining them to tectonic lineaments. This hypothesis is based on seismic reflection studies suggesting that sinkholes are the surface manifestations of active neotectonic faults that may serve as conduits for under-saturated groundwater, enabling its access across aquiclude layers. The second hypothesis, based on results of multi-disciplinary geophysical studies, considers the salt edge dissolution front as the major site of sinkholes' formation. This hypothesis associates sinkholes with karstification of the salt edge by deep and shallow groundwater aquifers.

4.1.6 Occurrence of sinkholes in the Dead Sea Basin: seismic velocities and velocity ratio variations with respect to salt layers and hydrodynamic parameters

In addition to the Dead Sea water level's decline that most likely related to the sinkholes' occurrence in the Dead Sea Basin, as well as to the earthquakes that take place in the region and that are potentially behind the formation and evolution of sinkholes in the region, seismic observations, in terms of seismic velocity variations, also indicated acceleration of the development of sinkholes in the region. Geophysical studies (e.g. [75, 80, 81]) showed that sinkholes in the DSB are associated with a particular layer of halite (salt mineral), deposited 10,000 years ago [239]. Based on in situ seismic measurements, the halite layer exhibits a broad range of compressional wave (P-wave) velocity (V_p), between 2800 and 3600 m/s, reflecting the texture of the salt layer, which varies between solid and crumbly texture [239]. On the other hand, in situ measurements showed that the shear wave (S-wave) velocity (V_s) in the Dead Sea's halite layer ranges between 750 and 1600 m/s [82, 85]. These ranges of the P-wave and S-wave velocities result in velocity ratio (V_p/V_s) values in the range of 2.25–3.73.

Meanwhile, other salt layers in other regions of the world (e.g. [45, 242]), and salt minerals (halite and sylvite) that were tested in laboratory under high pressures [208], exhibit V_p values in the range of 4500–5500 m/s and V_s values in the range of 2500–3100 m/s. These V_p and V_s values result in relatively low values of V_p/V_s, ranging from 1.77 to 1.80. A comparison between these results indicates that the geological subsurface layers of the Dead Sea Basin are characterized by lower degrees of compaction and solidification, as well as by relatively greater values of porosity (φ) and permeability (hydraulic conductivity) (k), as well as by lower values of tortuosity (τ) (e.g. [3, 34, 82, 96, 106, 146, 173, 189, 190]). The variations in these hydrodynamic (fluid-flow) parameters (φ, k, and τ) are greatly affected by dissolution of the salt layers in the Dead Sea Basin, which result in relatively lower values of the seismic velocities (V_p and V_s) and higher values of the seismic velocity ratio (V_p/V_s). According to Ezersky and Goretsky [82], geophysical data testify that the in situ porosity indicates zones of heightened voidness (where $\varphi > 25\%$), and that k for the same zones are high and, thus, they expected that in larger salt volumes these two parameters (φ and k) can yet increase.

In seismic imaging, the salt body is often assumed to be isotropic and homogeneous with constant velocities [97]. The large variations in the P-wave velocity (2800–3600 m/s) and the S-wave velocity (750–1600 m/s), as indicated above, resulting in large values of the velocity ratio (2.25–3.73) indicate anisotropy and heterogeneity, characterizing the salt layers in the DSB. These indications of anisotropy and heterogeneity of the Dead Sea's salt layers agree well with the results obtained by Hatzor and Heyman [117] from laboratory tests on salt (halite) samples taken from the salt deposits in the DSB. Anisotropy, associated with heterogeneity, as in the case of the Dead Sea's halite (salt) layer, means variations in the physical properties in the three directions (X, Y, Z) of the salt layer, such as variations in hydraulic, electric, and heat flow, as well as in propagation of seismic wave (acoustic signal) velocity [187].

4.1.7 Occurrence of sinkholes in the Dead Sea Basin: geochemistry-fluid dynamics

Shalev et al. [196] showed, through finite-element modeling, that dissolution of the salt layer(s) in the Dead Sea Basin is a plausible mechanism to explain the rapid creation of subsurface holes that collapse, forming sinkholes. The positive interaction among the rate of flow, the rate of chemical reaction, and the variation in permeability (hydraulic conductivity) accelerates the dissolution process, which might result in 'reactive infiltration instability.' This is manifested in interconnected cavities, into which fluid is channeled, as a result of salt dissolution. The frequent occurrence of sinkholes, the spacing between them, and the high rate of their development and formation in the DSB are controlled by several factors. These factors include the following: (1) Properties of structural and textural elements (lineaments), such as faults, ruptures, fissures, flexures, channels, large voids and pores, etc.; (2) Flux and freshness of incoming groundwater; (3) Rate of dissolution; (4) Effective specific surface area of particles (e.g. [188]); (5) Porosity and permeability of the salt and clay layers; (6) The φ–k–τ relations or their dependence on each other; (7) Dispersivity; and (8) Thickness and depth of salt layers. The salt dissolution in the underlying layers results in higher values of porosity and permeability, and lower values of tortuosity (as indicated above), which all lead to easy flow of fresh water into the salt layers. Thereby, this will lead to increasing the rates of both solute transport and the chemical reactions, resulting in fluid channeling and, thus, cavitation, which will lead to easy collapse, resulting in sinkholes. A large number of sinkholes occurred where both the edge of the halite (salt) layer and underground discontinuities (faults or fractures, acting as preferential channel-ways) are simultaneously present [79]. However, these three fluid-flow (hydrodynamic) parameters (φ–k–τ) need to be measured, in order to further understand the fluid-dynamics' impacts of the fresh water and saline water interactions on the sinkholes' formation in the Dead Sea Basin.

4.1.8 Occurrence of sinkholes in the Dead Sea Basin: socioeconomic impacts

Sinkholes in the DSB are constantly damaging the existing infrastructure and, thus, affecting the development and growth potential in the Dead Sea region. Unfortunately, the Dead Sea is rapidly disappearing and its beaches are almost unrecognizable. In addition, the sinkholes on both eastern and western shores of the Dead Sea continue to cause more damage to the shorelines. On both eastern and western coasts of the Dead Sea, there are farms; tourist's destinations, including resorts, hotels, and parks; and industrial facilities, including, for instance, the Jordanian Arab Potash Company (APC). Sinkholes in this region of the world represent a substantial geo-hazard, as they have already destroyed or damaged several tourism facilities, factories, evaporation pond dykes, highways, link roads, houses and farmland [126, 226]. Additionally, the threat that more sinkholes will form in the near future has caused several existing facilities to close or stop production [23, 27, 116, 178, 232]. Hasson [116] reported, "Fields of sinkholes instead of beaches, roads swept away by floods, large industrial ponds instead of a sea and one overarching question: What can be done so that things don't get even worse in the next 20 years?"

Furthermore, the economic growth in the region is limited because the threat of sinkholes is considerably high, so the formation of sinkholes keeps people away from investing in new development or businesses in the area. These factors combined make sinkholes a very costly problem. The sinkholes on the western side of the DSB have cost Kibbutz Ein Gedi more than USD 25 million in earnings since 1995, because they have had to close down a resort village, abandon a date palm orchard, and cancel future development plans in these areas [118]. In addition, the Israel Roads Company has had to invest millions of dollars over the past years to improve highway No. 90 that runs parallel to the Dead Sea, whereas the latest works took place near Ein Gedi in 2015 [232]. On the eastern shores of the DSB, the APC is expected to suffer around USD 70–90 million in damages due to the decreasing water level of the Dead Sea. The APC was constructing salt evaporation ponds when a sinkhole damaged about 100 m of roadway. A short time later, part of a salt evaporation pond collapsed causing millions of USD of losses on infrastructure and product [53]. According to the APC, the company has insurance to cover such hazards caused by the sinkholes formation [23]. Situations such as these are likely to continue and even become more frequent so long as the water level of the Dead Sea continues to decline.

5 Various techniques used to investigate sinkholes in the Dead Sea Basin

As a matter of fact, various techniques have been used over the last four decades or so to investigate the sinkholes' phenomenon in the Dead Sea Basin. These may include seismic (multichannel analysis of surface waves (MCASW), seismic refraction, and seismic reflection, using compressional wave velocity (V_p) and shear wave velocity (V_s); electric resistivity tomography (ERT) using electric resistivity (ρ); transient electromagnetic (TEM); time-domain electromagnetic (TDEM); magnetic resonance sounding (MRS); surface nuclear magnetic resonance (SNMR); ground-penetrating radar (GPR); microgravity; gravimetry, as well as interferometric synthetic aperture radar (InSAR); differential interferometric synthetic aperture radar (DInSAR); geographic information system (GIS); remote sensing (RS); satellite image time series (SITS); moderate resolution imaging spectro-radiometer (MODIS); terrestrial laser scanner (TLS); spatial multi-criteria evaluation (SMCE); and light detection and ranging (LiDAR); along with detailed geomorphological, geological, seismological, and limnologic studies and surveys. Table 2 summarizes some of the achievements, regarding investigations of the sinkholes' phenomenon in the DSB, over the last few decades.

6 Conclusions and recommendations

Sinkholes—large, open holes that result from the collapse of the Earth's surface—represent serious environmental, geological, and geotechnical problems in the Dead Sea Basin. Sinkholes began to form and develop in the DSB about 20 years after the Dead Sea's water level started to decline. The 20-year delay in the occurrence of sinkholes after the beginning of the Dead Sea's recession means it takes 20 years for the freshwater to flush all the way to salt layers and then to dissolve them, creating cavities within the salt layers, up to the shallower clay and gravel layers underneath the Earth's surface. This indicates that there is a strong correlation between both phenomena: the decline of the Dead Sea's water level, on the one hand, and the remarkable and frequent occurrences of sinkholes in the Dead Sea Basin, on the other. This means that the greater the decline of the Dead Sea's water level, the greater the number and the larger the size of the sinkholes that have been already developed and others that may develop anytime in the DSB.

In addition, the tectonics and seismic activities that affect the DSB, besides the Dead Sea's water level decline and the shrinkage of its surface area, might trigger the occurrence of plenty of sinkholes in the region. The tectonic features existing in the region (faults, fissures, ruptures, fractures, flexures, etc.) serve as conduits, channeling freshwater from the deeper aquifer systems to the shallower ones, dissolving the salt layers and, thus, promoting the evolution and formation of sinkholes in the DSB. This implies that more voids are created and, thus, higher porosities and hydraulic conductivities are resulted, which lead to the movement of greater amounts of freshwater. Once porosity and permeability (hydraulic conductivity) are increased by dissolution, fluids are channeled into the dissolved sections and accelerate the process, as the salt layers become more porous and more permeable and, thus, less tortuous, leading to easy flow of fresh water into the salt layers. In other words, the anisotropy and heterogeneity, resulted from salt dissolution, magnify this instability and lead to more and larger sinkholes in the DSB.

The factors discussed in this paper, including decline of water level, shrinkage of surface area, decrease of water volume, tectonic features, and seismicity, affecting and will affect the Dead Sea Basin, have led to and will further lead to the occurrence of sinkholes and formation of new ones in the DSB. The impacts of these phenomena are reflected, physically, chemically, and hydro-geologically, on the variations in the seismic wave propagation and hydrodynamic (fluid-flow) parameters. These include seismic wave velocity, velocity ratio, porosity, permeability (hydraulic conductivity), tortuosity, and others. Analyses of available data of the compressional and shear wave velocities and fluid-flow parameters indicate that the relatively low values of in situ velocities of both kinds of seismic waves (compressional and shear) result in greater values of their velocity ratio. These observations indicate heterogeneity and anisotropy, as well as less compaction and solidification of the layers of the DSB, which are considered encouraging factors for sinkholes to be formed and further developed in the Dead Sea Basin.

Some of the factors mentioned above are anthropogenic (including the Dead Sea's water level decline and its surface area's shrinkage and, thus, decrease in its water volume), and some others are naturally induced (including tectonics and seismicity). Based on the investigation and data analyses provided in this paper, it is believed, however, that these factors combined have resulted in the formation of the already existing sinkholes and of the new ones that may develop in the future. Nevertheless, the anthropogenic factors could be avoided, if man really pays attention to nature and the environment, especially when it comes to a uniquely beautiful natural feature like the Dead Sea Basin, including the Dead Sea itself, the Jordan Rift Valley, and their surrounding regions.

Table 2 Various techniques used to investigate the sinkholes' phenomenon in the Dead Sea Basin (DSB) (adopted, modified, improved, and updated after [85])

Technique(s) used	Properties investigated and/or measured	Capability's detection	References
InSAR	Sinkhole distribution, combined with gradual land subsidence	Studying subsidence that appeared to be structurally controlled by faults, seaward landslides, and salt domes. Resolving temporal and spatial relationships between gradual subsidence and sinkhole collapse. Tracking young fault systems suspected as active, concealed within the fill of the Dead Sea Rift. Translating areal growth rate to a salt dissolution rate of the salt layer. Revealing two peaks in the history of the salt dissolution rate	[4, 7, 28, 30]
DInSAR	Integration of three different wavelengths	Studying the complex dynamics of the Lisan Peninsula's salt dome	[87]
Seismic Refraction	V_p in salt layers	Detecting elastic properties and delineating salt layers	[75, 77]
MCASW	V_s in salt layers	Measuring salt shear velocities and modulus to estimate salt porosity and karstification	[44, 80, 81]
P-wave seismic reflection	Subsurface structure (down to 200 m), detection of sub-horizontal interfaces and faults	Detecting faults, and salt layers within sediments	[79, 132–134]
S-wave seismic reflection	Subsurface structure (down to 100 m), detection of sub-horizontal interfaces and faults	Detecting faults, and salt layers within sediments	[139, 175, 176]
Combination of seismic velocities and electric resistivity	V_p, V_s, and ρ	Estimating representative properties affected by porosity and permeability (hydraulic conductivity) changes during sinkhole development	[82]
TEM and TDEM	Low resistivity of aquifer formations (0.5–1 Ω m) in contrast to the surrounding sediments (more than 10 Ω m)	Identifying accurate location of the top of the aquifer, and mapping water salinity variations	[78, 84, 109, 128]
ERT	DC resistivity in subsurface	Searching anomalously high resistivity	[22, 76]
MRS, SNMR, and 3D-SNMR	Water in the karst voids and in the surrounding sediments produce nuclear magnetic resonance signal with different relaxation time (less than 150 ms in sediments and more than 600 ms in karst	Detecting water filled voids and estimating water volume in karstic caves	[147, 148, 152, 153]
MRS and TEM	Bulk resistivity, water content, permeability (hydraulic conductivity) and relaxation time that allows resolve equivalency	Identifying subsurface lithology	[149–151]
MRS and MCASW	k and V_s	Estimating salt permeability (hydraulic conductivity)	[83]
GPR	Structure of most shallow sediments (down to 10–15 m) located over karstified unconsolidated salt	Detecting density deficit caused by cavities moving upward (stoping)	[93, 94]
Bouguer gravity	3-D gravity modelling. Large negative gravity anomalies ($< -100 \times 10^{-5}$ m/s^2) observed in the DSB correspond with the spatial distribution of salt diapirism with an average density of 2.1 kg/m^3	Identifying three salt structures, which are found beneath the Sedom area, the Lisan Peninsula and the Dead Sea. Identifying the thickness of the sedimentary infill overlying the basement in the DSB that decreases from 14 km in the vicinity of the Lisan Peninsula to 8 km in the northern and the southern sub-basins	[52]
Microgravity	Gravity anomalies against strong noise background	Detecting caverns and estimating their depths and volumes	[67, 71–73, 81, 183]
Gravimetry and DInSAR	Ground subsidence caused by deficit of mass	Identifying potentially hazardous areas because of underground cavities	[53, 165]

Table 2 (continued)

Technique(s) used	Properties investigated and/or measured	Capability's detection	References
GIS and RS	Spatial behavior of the Dead Sea through time, for which satellite imageries were used	Detecting changes in the Dead Sea's area, shape, water level, and volume. Developing methods for prediction of sinkholes appearance by using mapping and monitoring methods based on active and passive remote-sensing means. Showed that the 35 m base-level fall has caused shoreline retreat of up to 2.5 km, and formation of > 1100 sinkholes by combining remote sensing data with close-range photogrammetric surveys	[66, 110, 226]
SITS	Ground reflectance, diachronic analysis, and spatial co-occurrence	Identifying the decrease in the Dead-Sea's water level, and also areas prone to sinkholes	[16, 203]
Aerial photogrammetric survey	Helikite Balloon at low altitude (< 150 m above the ground)	Showing a km-scale sinuous depression bound partly by flexures and faults. Estimating the minimum volume's loss of the sub-sided zone, which is 1.83 MCM with an average subsidence rate of 0.21 m/yr over the last 25 years	[16]
InSAR and LiDAR	Systematic high temporal and spatial resolution	Resolving temporal and spatial relationships between gradual subsidence and sinkholes' collapse. Detecting minute precursory subsidence. Mapping zones susceptible to future sinkholes' formation	[28, 30, 165]
Nano-seismicity and micro-seismic activity monitoring	Monitoring of subsurface material failures before sinkhole collapse. Vibrations produced by falling stones in the underground cavities	Detecting the extremely low-energy signals produced by cavitation in unconsolidated layered media. Identifying re-collapse of sinkhole's activity inunconsolidated media. Conducting a numerical simulation model of the interaction of cavity growth, host material deformation, and overburden collapse, in order to have a better understanding of the sinkholes' hazards	[6, 237]

The Dead Sea's shorelines are undergoing continuous damages and eco-hazards, mainly due to the Dead Sea's water level's decline, because of anthropogenic impacts, and also because of the intensive activities related to infrastructures, building of constructions (such as hotels, etc.), and potential mega projects, such as the Red Sea-Dead Sea Conveyance (RSDSC) project. These activities, in turn, deform drainage systems; cause landslides, land collapse, and subsidence; pollute the Dead Sea's environment; and cause the formation of sinkholes and development of new ones. Several alarming cases happened in the last few years in the DSB, as a result of the collapse and subsidence of the Earth's surface, resulting in many, huge sinkholes. Subsequently, destination for recreation and tourism has been considerably decreased, because of warnings related to further development of sinkholes and, thus, tourists are scared from further disasters and eco-geo-hazards that may take place in the region, anytime. Therefore, additional investigations are requested to study the salt layers of the DSB on all shores of the Dead Sea, including the southern shores, where the RSDSC project is planned to take place, if presumably will be undertaken. Field and laboratory measurements, related to the sinkholes and other features of the Earth's surface collapse and subsidence in the DSB, should be conducted, using various geophysical and other techniques indicated in this paper.

Based on the fact that the sinkholes' phenomenon has created a state of fear and panic in the region, which has already affected the recreation and tourism businesses, measurements and monitoring actions need to be steadily and permanently undertaken in the region. An early warning system needs to be installed, so that it can provide dual services, in relation to the tectonic and seismic activities that result in micro- and macro-earthquakes that frequently hit the region, and also in relation to the sinkholes that frequently occur in the region. InSAR–LiDAR-derived subsidence maps are fundamentally used for sinkholes' early warning and mitigation along the western shore of the Dead Sea, which are incorporated in all sinkholes' potential maps that are mandatory for the planning and licensing of new infrastructures in the region.

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Compliance with ethical standards

Conflict of interest There is no potential of conflict of interest of any kind (financial or otherwise).

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