AC3 to RC3

(1) comments from Referees

The manuscript describes damaged infrastructures along the northeastern shores of the Dead Sea and presents results from three different methodologies that demonstrate the damage and are aimed to be used as inputs for a vulnerability map of the region.

Comments:

1. The title of the paper and the expected product of this study is a vulnerability map (section 4.4). The definition of vulnerability is the degree of (potential) exposure to damage, and in this respect a vulnerability map should show levels of potential (future) damage, in areas that were damaged and in those that were not damaged yet. What is shown here are damage classification maps of specific areas that cannot serve as vulnerability maps for future planning in any nearby or other areas in NE Dead Sea. The workflow for preparation of such maps is described in page 8 and Fig. 3 and includes InSAR, vegetation, wells data, salinity variations and more methods, but the maps shown in Fig. 10 were not prepared by any of these methods and a resulting vulnerability map is not shown in the paper. The proposed approach is said to have been proved several times before (page 8, lines 28-30) but no references are given for the reader to understand what has been actually done before.

2. The title and many places in the text use the term "salt karst". In many places along the Dead Sea (the entire west coast and possibly also the southern east coast), a layer of salt is dissolved and salt karst sensu-stricto develops. What is described here as the cause for landslides, subsidence and sinkholes is chemical and mechanical erosion of interstitial salt that remained between the grains when the DS level dropped and was washed by fresh groundwater. This is not salt karst. Furthermore, the proposed mechanism is speculative in its basis and has not been proved by any of the methodologies used here. What can be the size of a cavity that is formed from such salt remains? If fresh water dissolves that salt, it should show chemical evidence for dissolution in the springs, such as Na/Cl ratios, density, etc. Without such evidence the entire theory cannot hold.

3. On page 9 the authors write that the velocity map supports the hypothesis that the subsidence is the result of chemical erosion and that the landslides and sinkholes are consequences of mechanical erosion by underground water flows. No other mechanism (e.g., consolidation-driven subsidence; gravity-driven landslides) is even considered (or rejected) and no independent evidence is shown to prove this hypothesis (see also section 2 above). The fact that highest subsidence is found in the exposed muddy plains may support the consolidation mechanism. Furthermore, how do the authors prove the existence of mechanical and chemical erosion and how do they distinguish between them and relate each mechanism to a different phenomenum (landslide, sinkhole, subsidence).

4. The proposed mechanism for landslides is also by "increased lateral water injection into soft sediments on a slope balance profile created under the DS level. . ..favored by a sudden drop of the DS level that usually occurs during the dry period" (page 12, lines 3-5). There are continuous monthly measurements of the DS level since 1976, and if the authors looked at these results they would have found that there is no sudden drop in the DS level in any of the 3 periods, and on the contrary, from February to May 2009, the level even rose by about 3 cm. This speculation adds to the previous ones and gives the impression that although the damage observations are clear, the mechanism is far from being explained.

5. Subsidence is also interpreted as a consequence of permeability increase due to fractures, but no evidence is given that certain areas are more fractured than others.

6. Geological setting: The reference provided for the Lisan Formation is Landmann et al., 2002. This formation has been defined much earlier (Begin et al., 1974 and 1980). In a similar manner the fact that the DST is an active structure has been shown long before Al-Awabde et al., 2016 (e.g, by Garfunkel, Freund, De Sitter, and many others in the second half of the 20th century). Citations should refer to the earliest or to the key papers that mention the feature.

7. InSAR: In page 3 the authors write that they analyse both D-InSAR and A-DinSAR. In page 5 the authors write that the derived products are intensity and coherence maps, interferograms, differential interferograms (what is the difference between the two?), velocity/displacement maps and ground displacement time series. In the paper we can see only one map of vertical velocity (Fig. 4.). My questions are: (a) What is A-DInSAR and where are all the other radar products mentioned in the paper (including time series that were mentioned again on page 8 line 1-2)? (b) InSAR measures satellite to ground line of sight (LOS) displacements, while Fig. 4 shows vertical velocities. How were the LOS measurements converted to vertical velocities, and how did the authors take into account possible horizontal movements (particularly important in cases of landslides) that could also be components of the measured displacements? (c) As InSAR is one of the major techniques, some elaboration should be added regarding to the noise level, the elevation model (DEM) used in the processing, incidence angles, etc. This is particularly important because velocities lower than 10 mm/year are also interpreted as real (Fig. 4 and page 11, lines21-23). (d) West of the 2000 shoreline there is no SRTM DEM (page 7, line 17), so how was topography corrected for these important areas (where most of the subsidence occurs). The coastline of February 2000 should be shown on Fig. 4 so that the reader could get an impression of where topo corrections were made and where not (or made by another way).

8. Discussion: A discussion should deal with the results of the paper. The majority of the discussion (from line 9 in page 12 to the end of the discussion) is made of declarations about the importance of the area and of carrying out the research in this area, meetings, strategy, etc. This is not an appropriate discussion in a scientific paper.

9. Conclusions: The conclusions should also deal with the results of the paper and instead they mention (for the first time in the paper) a future EWS, and repeat some general declarations about the world changing and the need for expert overviews of the environmental situation.

10. To summarize this review, in this manuscript there are many examples of damage, in pictures and maps, but no demonstration of their use for vulnerability assessment and no proved mechanism. The paper is on a level of a technical report and not of a scientific paper in a high-impact journal. My comments above deal with every aspect of the paper and thus only complete rewriting may bring it to the required standard. Thus, I recommend rejection of the paper.

(2) author's response

This paper will be adapted according to balanced, objective and appropriate suggestions of all reviewers. We are confident that this will offer more valuable data to the international community and further enhance the awareness of the DS subsidence and sinkholes related hazards.

Here are specific answers to your comments which are presented first In ***Italics***

1. The title of the paper and the expected product of this study is a vulnerability map (section 4.4). The definition of vulnerability is the degree of (potential) exposure to damage, and in this respect a vulnerability map should show levels of potential (future) damage, in areas that were damaged and in those that were not damaged yet.

What is shown here are damage classification maps of specific areas that cannot serve as vulnerability maps for future planning in any nearby or other areas in NE Dead Sea. The workflow for preparation of such maps is described in page 8 and Fig. 3 and includes InSAR, vegetation, wells data, salinity variations and more methods, but the maps shown in Fig. 10 were not prepared by any of these methods and a resulting vulnerability map is not shown in the paper. The proposed approach is said to have been proved several times before (page 8, lines 28-30) but no references are given for the reader to understand what has been actually done before.

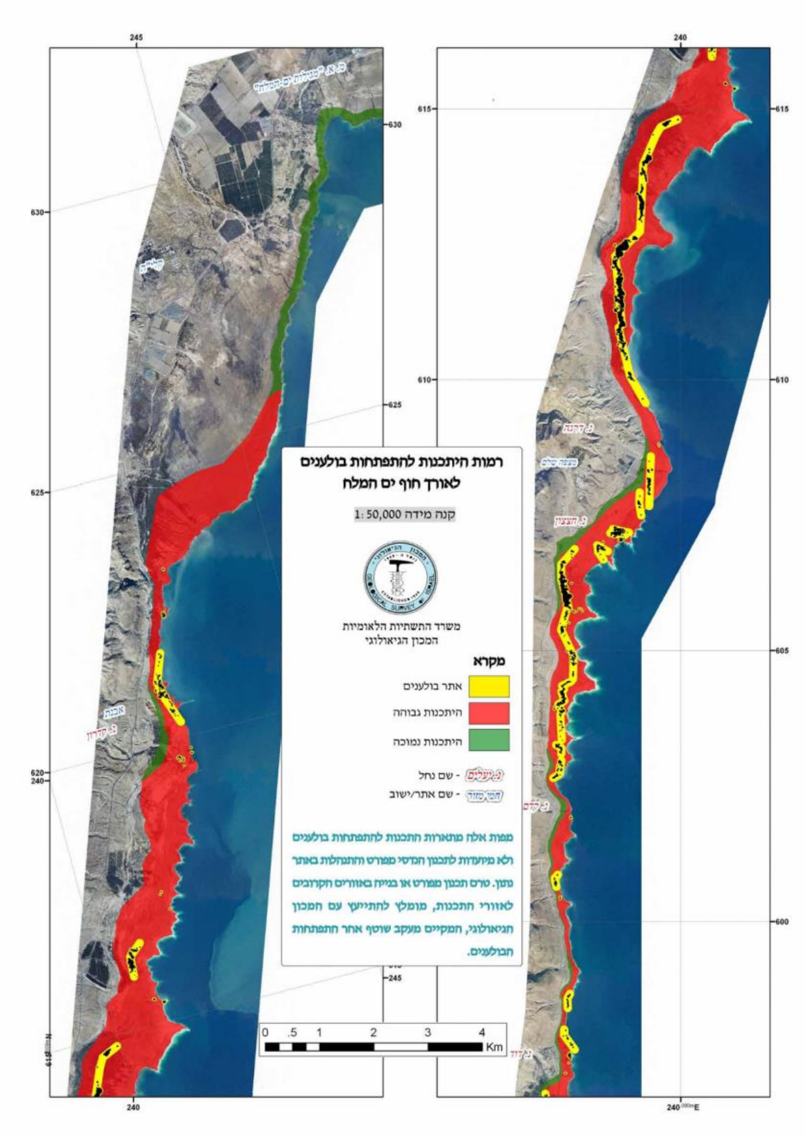
In response to what was justly signaled by your review and the two previous ones RC1 and RC2 we modified the scope of the work, our new revised version puts very much less emphasis on the vulnerability, the title of the paper was modified the word vulnerability is replaced by “exposition” a more realistic one, liberating our paper from the vulnerability issue as a very narrow technical term, exposition being more appropriate for meeting the main objective of our work at this stage (i.e. provoking more awareness of planers and decision makers involved in the development of the Jordanian DS shore).

2. ***The title and many places in the text use the term "salt karst". In many places along the Dead Sea (the entire west coast and possibly also the southern east coast), a layer of salt is dissolved and salt karst sensu-stricto develops*.**

Two comments:

1). The salt layer has not been found along the entire west coast, especially in the NW part. The map below (left) indicates low probability to find out a salt layer because of the absence of boreholes data available and also because of the important quantity of water existing in the underground. The mudflat at the opposite of Sweimeh is felt as not affected. Additional information can be found here: Abelson, M., Y. Yechieli, G. Baer, G. Lapid, N. Behar, R. Calvo, and M. Rosensaft (2017), Natural versus human control on subsurface salt dissolution and development of thousands of sinkholes along the Dead Sea coast, J. Geophys. Res. Earth Surf., 122, doi:10.1002/ 2017JF004219.

In his recent papers, Michael Ezersky extrapolated the presence of the salt layer to the Northern DS and the whole Eastern DS coast but this is not attested by evidences from boreholes since they do not exist.



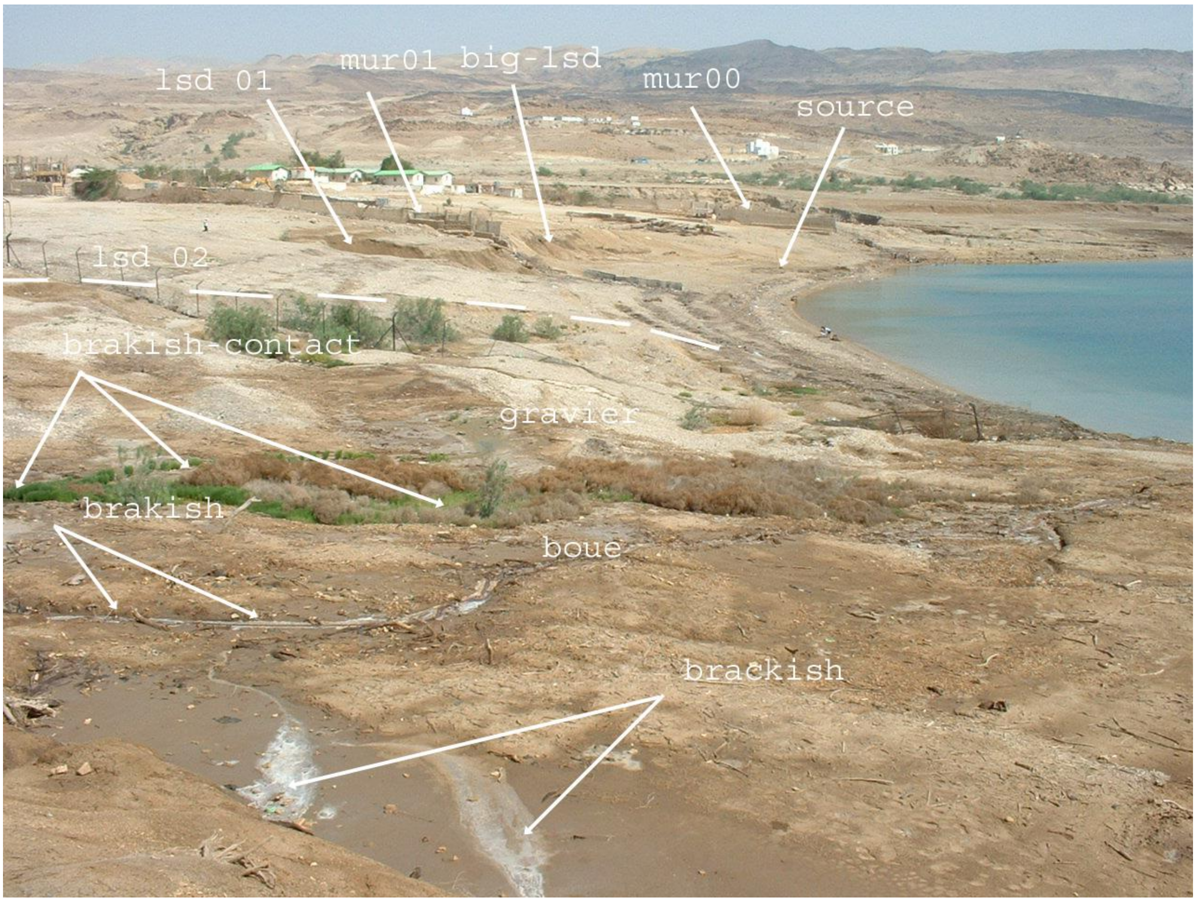
מפות אלה מתארות התכנות להתפתחות בולענים ולא מיועדות לתכנון הנדסי מפורט והתנהלות באתר נתון. טרם תכנון מפורט או בנייה באזורים הקרובים לאזורי התכנות, מומלץ להתייעץ עם המכון הגיאולוגי, המקיים מעקב שוטף אחר התפתחות הבולענים.

2). In <u>the **whole** Dead Sea area, sinkholes do not need **necessarily** a salt layer to exist</u>. The dissolution of salt remains in the soil matrix or the dissolution of salt lens can trigger the mechanism of cavity formation. This statement is based on numerous observations done in the Sweimeh area from 2004 onwards (example pictures 1-7).

Consequently, there is no “karst sensu-stricto" nor “karst sensu-lato". There is a salt karst system where sinkholes can be created in at least two ways: salt layer dissolution and salt remains dissolution.

Below are pictures taken from 2004 to 2009 in Sweimeh. They attest that various types of water are found around the Holiday Inn based on salt dissolution all along underground flow paths. Some springs are sweet, others rather brackish, and still others are highly salty.

A water sampling campaign took place about ten years ago in the southern DS and results published in “Landslides along the Jordanian Dead Sea coast triggered by the lake level lowering”. February 2010. Environmental Earth Sciences 59(7):1417-1430.



Picture 1: April 2004 © Damien Closson & Najib Abou Karaki

Lateral injection of water creates different types of sliding.

Picture 2: April 2004 © Damien Closson & Najib Abou Karaki

From a year to another the amount of water and its salinity fluctuated a lot.

Picture 3: May 2005 © Damien Closson & Najib Abou Karaki

Metric sinkholes are found in many places. They do not result from the dissolution of a salt layer.

Picture 4: May 2005 © Damien Closson & Najib Abou Karaki

Picture 5: May 2005 © Damien Closson & Najib Abou Karaki

In 2005, metric sinkholes existed and then decametric sinkholes have been observed in the Holiday Inn.

Picture 6: 29 April 2009 © Damien Closson & Najib Abou Karaki

Sinkholes were wide enough to swallow an excavator. Picture taken in the Holiday Inn construction site.

Picture 7: May 2009 © Damien Closson & Najib Abou Karaki

All these features are salt karst feature sensu-stricto and they have been created without the dissolution of a salt layer. The soil conditions are similar to the ones found in the NE corner of the DS.

What is described here as the cause for landslides, subsidence and sinkholes is chemical and mechanical erosion of interstitial salt that remained between the grains when the DS level dropped and was washed by fresh groundwater. This is not salt karst.

The latest statement is wrong. This is salt karst (pictures 5-7). Besides, the pictures above are just a few samples of what we have observed since 1991 along the Eastern DS coast.

***Furthermore, the proposed mechanism is speculative in its basis and has not been proved by any of the methodologies used here*.**

The observations in the field are unambiguous (picture 1 foreground). They attest that our hypothesis is correct. Besides, predictions based on such hypothesis have been verified several times.

What can be the size of a cavity that is formed from such salt remains?

Based on our field observations they range from 1 m to 12 m (see pictures 5-7).

If fresh water dissolves that salt, it should show chemical evidence for dissolution in the springs, such as Na/Cl ratios, density, etc. Without such evidence the entire theory cannot hold.

Just have a look at picture 1 and you will understand that salt dissolution is obvious. As soon as the water pours out of the ground, the salt is deposited (picture 1, foreground)

3. On page 9 the authors write that the velocity map supports the hypothesis that the subsidence is the result of chemical erosion and that the landslides and sinkholes are consequences of mechanical erosion by underground water flows. No other mechanism (e.g., consolidation-driven subsidence; gravity-driven landslides) is even considered (or rejected) and no independent evidence is shown to prove this hypothesis (see also section 2 above).

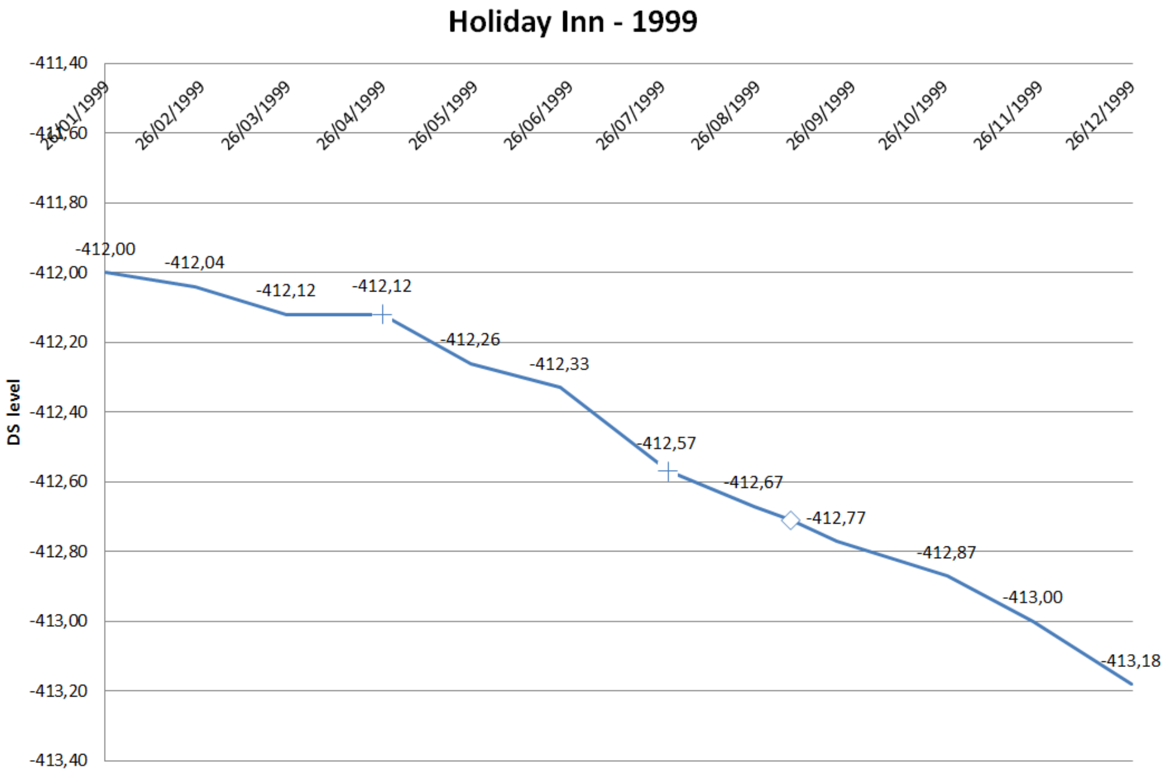
This problem had been tackled around 10 years ago. Results have been published here: Landslides along the Jordanian Dead Sea coast triggered by the lake level lowering. February 2010. Environmental Earth Sciences 59(7):1417-1430.

The fact that highest subsidence is found in the exposed muddy plains may support the consolidation mechanism. Furthermore, how do the authors prove the existence of mechanical and chemical erosion and how do they distinguish between them and relate each mechanism to a different phenomenon (landslide, sinkhole, subsidence).

This issue was analyzed in depth and the results published here: Sustainable development and Anthropogenic induced geomorphic hazards in subsiding areas. Anthropogenic sustainable development in subsiding areas. September 2016, Earth Surface Processes and Landforms, DOI: 10.1002/esp.4047.

4. The proposed mechanism for landslides is also by "increased lateral water injection into soft sediments on a slope balance profile created under the DS level. . .. favored by a sudden drop of the DS level that usually occurs during the dry period" (page 12, lines 3-5). There are continuous monthly measurements of the DS level since 1976, and if the authors looked at these results they would have found that there is no sudden drop in the DS level in any of the 3 periods, and on the contrary, from February to May 2009, the level even rose by about 3 cm. This speculation adds to the previous ones and gives the impression that although the damage observations are clear, the mechanism is far from being explained.

We do not interpret the actual data in the same way. The graph “Holiday Inn 1999” clearly show a drop from –412.12 to –412.57 in only 3 months... 45 cm of base level drop for an already unstable system is an important parameter to keep in mind. It was even 65 cm at the moment of the landslide.



6th September 1999.

Besides, **Sirota et al., 2016** (See Figure 3 (b) reproduced below) have clearly shown that the rate level change in m/month is varying seasonally (e.g. in 2013-2014-2015). The landslide period corresponds to moment of the year when this curve present minima. This temporal co-occurrence suggests a possible causal link.

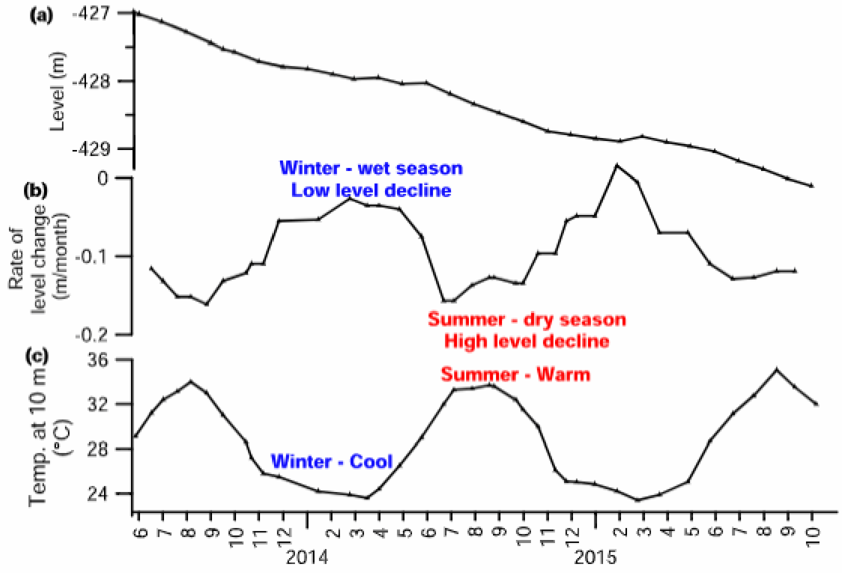


Figure 3. The seasonal external forcing. (a) Dead Sea level decline, (b) rate of level change, and (c) temperature of the epilimnion (10 m depth).

Source: Sirota, I., A. Arnon, and N. G. Lensky (2016), Seasonal variations of halite saturation in the Dead Sea, Water Resour. Res. , 52 , doi:10.1002/ 2016WR018974.

5. ***Subsidence is also interpreted as a consequence of permeability increase due to fractures, but no evidence is given that certain areas are more fractured than others.***

This issue had been tackled and very much documented by Mohammad Al-Awabdeh in his thesis and related publications:

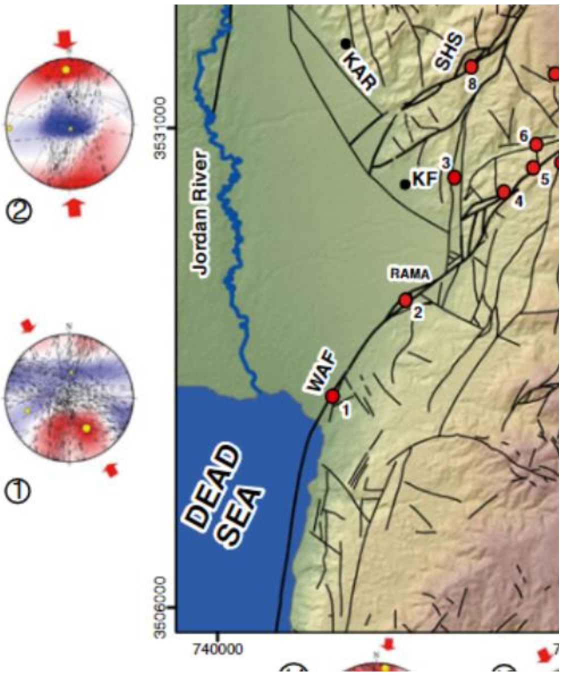
See page 65 and others here: https://hera.ugr.es/tesisugr/25624581.pdf

There are dozens of pictures and information available

Also here:

e.g. Mohammad Al-Awabdeh, J. V. Pérez-Peña, J. M. Azañón, Jorge Pedro Galve et al. Stress analysis of NW Jordan: New episode of tectonic rejuvenation related to the Dead Sea transform fault. April 2016, Arabian Journal of Geosciences 9(4):264. DOI: 10.1007/s12517-015-2239-z

Mohammad Al-Awabdeh, J. V. Pérez-Peña, J. M. Azañón, Jorge Pedro Galve et al. Quaternary tectonic activity in NW Jordan: Insights for a new model of transpression–transtension along the southern Dead Sea Transform Fault. April 2016, Tectonophysics. DOI: 10.1016/j.tecto.2016.04.018



Detailed datasets have been used to link InSAR deformations with mapped structural features.

Source: Al-Awabdeh, M.: Active tectonics of the Amman-Hallabat and Shueib structures (NW of Jordan) and their implication in the Quaternary evolution of the DS Transform Fault system, PhD Thesis, pp. 207, University of Grenada, Spain, 2015. Available at: https://hera.ugr.es/tesisugr/25624581.pdf

6. Geological setting: The reference provided for the Lisan Formation is Landmann et al., 2002. This formation has been defined much earlier (Begin et al., 1974 and 1980).

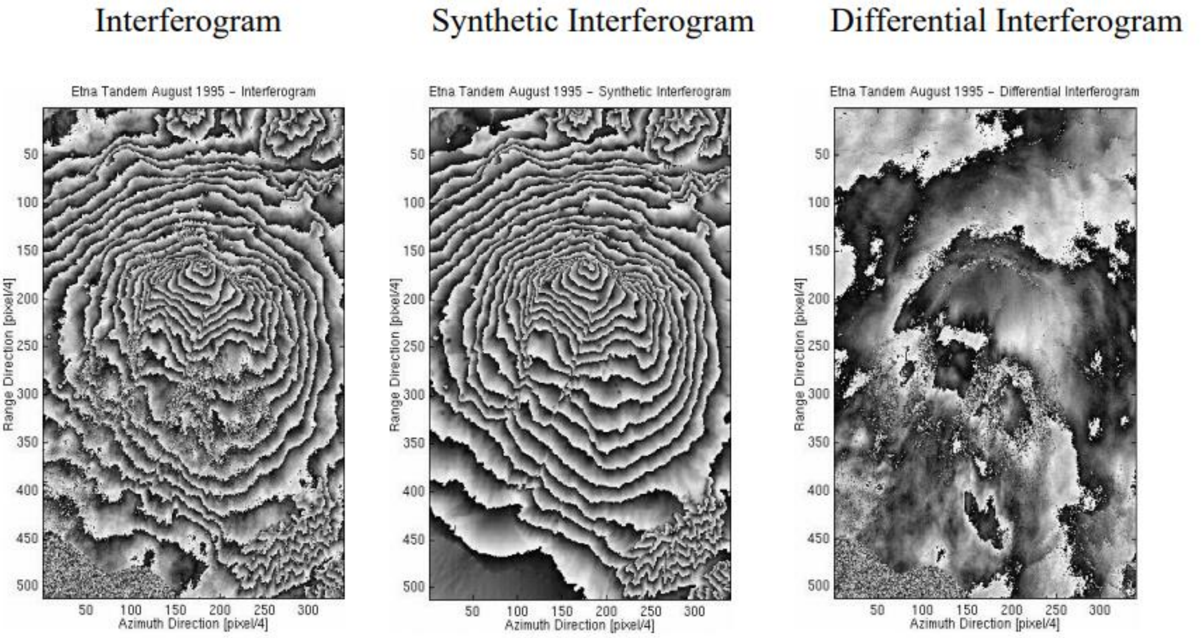
The history of Lake Lisan is recorded in its deposits, known as the Lisan Formation. This term was first used by Louis Lartet (1869) Essai sur la Géologie de la Palestine, Masson Paris. (https://www.worldcat.org/title/essai-sur-la-geologie-de-la-palestine/oclc/493602635) However, many others have mentioned these deposits (e.g., Picard, 1943; Quennell, 1956; Bentor and Vorman, 1960; Bender, 1968).

***In a similar manner the fact that the Dead Sea Transform is an active structure has been shown long before Al-Awabde et al., 2016 (e.g, by Garfunkel, Freund, De Sitter, and many others in the second half of the 20th century). Citations should refer to the earliest or to the key papers that mention the feature*.**

Then, we propose the most important benchmarks; Quennell 1958 , Garfunkel et al. 1981. Although saying that the DST is an active structure is an evidence given the huge number of publications dealing with the whole spectrum of seismic activity, instrumental, historical, archaeo and paleoseismicity. Abou Karaki (1987 and references therein including Willis, Seiberg, ,Abel, Arieh, Ben-Menahem, Shapira, Mamoun, El-Isa, Taher, Poirrier and Taher, Hoffstetter.. etc)

7. InSAR: In page 3 the authors write that they analyse both D-InSAR and A-DinSAR. In page 5 the authors write that the derived products are intensity and coherence maps, interferograms, differential interferograms (what is the difference between the two?), …

As illustrated below, an interferogram (left and middle) gathers information about the topography, the phase delay caused by the atmosphere, and the ground movements between two acquisitions. Once the topographic phase is removed, only the displacements and the atmospheric phase delay remain (differential interferogram). When the atmospheric conditions are favorable, the ground displacements appear. One can add that when the perpendicular baseline is very short (a few meters) between the two acquisitions, then the interferogram and the differential interferogram are equivalent.



What is A-DInSAR and where are all the other radar products mentioned in the paper (including time series that were mentioned again on page 8 line 12)?

The term A-DInSAR stands for Advanced DInSAR, which is a category of techniques used to process multi-temporal stacks of SAR images. Another term often used in literature is Multi-Temporal InSAR (MT-InSAR). The two main A-DInSAR approaches are the Permanent Scatterers (PS) and Small Baseline Subset (SBAS), the latter was used in this study.

During the SBAS processing chain, a series of intermediate products are derived for each interferometric pairs. These products are generally used to check the quality of specific interferograms or in specific dates to better explain surface changes. The difference between an interferogram and a differential interferograms is that in the second the phase related to the topography is removed with an external DEM.

These products are generally not showed in scientific journals as a whole, because: 1) the huge amount of intermediate data produced (even thousands, depending of the number of

SAR images used and the number of connections); 2) they are often meaningful if taken one by one; 3) they can be of difficult interpretation.

The final product of the A-DInSAR analysis is the time-series for each of the detected point. These can be showed as a map of mean velocity values (in mm/yr) or cumulative displacements (in mm). Figure 4 presented in the manuscript, shows the final product of the SBAS processing of the available Sentinel-1/2 images as mean velocity map projected along the vertical direction. For each of those points, it is possible to extract the displacement time-series. Examples of time-series extracted for some selected points in significant areas will be added to the text.

InSAR measures satellite to ground line of sight (LOS) displacements, while Fig. 4 shows vertical velocities. How were the LOS measurements converted to vertical velocities, and how did the authors take into account possible horizontal movements (particularly important in cases of landslides) that could also be components of the measured displacements? (c) As InSAR is one of the major techniques, some elaboration should be added regarding to the noise level, the elevation model (DEM) used in the processing, incidence angles, etc. This is particularly important because velocities lower than 10 mm/year are also interpreted as real (Fig. 4 and page 11, lines 21-23).

The measured velocities are projected from LOS to the vertical direction according to the incidence angle calculated at the location of each point. The formula used is simply “Vdef = LOSdef/cos θ”, where Vdef is the deformation calculated along LOS and θ is the incidence angle of each point.

As written in the text, the DEM used for all the InSAR processings is the SRTM DEM with a resolution of around 30 x 30 m. Unfortunately, this is the only DEM available for the area. Unfortunately, the Dead Sea level drop and the consequent change in topography elevation occurred between 2000 and 2018 is not compensated by the DEM. Anyway, the SBAS stacking technique is able to make height corrections of the difference between the observed and the DEM elevations based on the perpendicular baselines of the generated interferograms. This helps in minimizing the errors related to the absence of a more recent DEM.
A table with the main features of the SAR datasets used in the work will be added to the text.

West of the 2000 shoreline there is no SRTM DEM (page 7, line 17), so how was topography corrected for these important areas (where most of the subsidence occurs). The coastline of February 2000 should be shown on Fig. 4 so that the reader could get an impression of where topo corrections were made and where not (or made by another way).
As said in the previous comment, the SBAS algorithm is able to compensate for “inaccuracies” in the used DEM in order to minimize the topographic errors in the recently exposed areas of the DS.

The coastline of February 2000 will be added to Figure 4. We will of course adequately care for the discussion and conclusions of this paper.

8. Discussion: A discussion should deal with the results of the paper. The majority of the discussion (from line 9 in page 12 to the end of the discussion) is made of declarations about the importance of the area and of carrying out the research in this area, meetings, strategy, etc. This is not an appropriate discussion in a scientific paper.

See (3) author's changes in manuscript

9. Conclusions: The conclusions should also deal with the results of the paper and instead they mention (for the first time in the paper) a future EWS, and repeat some general declarations about the world changing and the need for expert overviews of the environmental situation.

See (3) author's changes in manuscript

10. To summarize this review, in this manuscript there are many examples of damage, in pictures and maps, but no demonstration of their use for vulnerability assessment and no proved mechanism. The paper is on a level of a technical report and not of a scientific paper in a high-impact journal. My comments above deal with every aspect of the paper and thus only complete rewriting may bring it to the required standard. Thus, I recommend rejection of the paper.

See (3) author's changes in manuscript

(3) author's changes in manuscript

Exposure of tourism development to salt karst hazards along the Jordanian Dead Sea shore

Najib Abou Karaki[1*], Simone Fiaschi[2], Killian Paenen[3], Mohammad Al-Awabdeh[4], Damien Closson[5]

[1] Department of Environmental and Applied Geology, University of Jordan, Amman, 11942, Jordan
*On sabbatical leave at the Environmental Engineering Department, Al-Hussein bin Talal University, Ma’an-Jordan
[2] UCD School of Earth Sciences, University College Dublin, Belfield, Dublin 4, Ireland
[3] Vrije Universiteit Brussel & Katholieke Universiteit Leuven, Belgium
[4] Tafila Technical University, Aţ Ţafīlah, Jordan
[5] GIM n.v., Leuven, Belgium

Correspondence to: Najib Abou Karaki (naja@ju.edu.jo & naja@ahu.edu.jo)

Abstract. The Dead Sea shore is a unique young and dynamic evaporite karst system. It started developing in the 1960s, when the main water resources that used to feed the terminal lake were diverted towards deserts, cities and industries. During the last decade, the water level has been lowering at more than 1 meter per year, causing a hydrostatic disequilibrium between the underground fresh waters and the base level. Thousands of underground cavities have developed as well as hectometer-size landslides, and entrenched rivers. The geological discontinuities are the weakest points where the system can re-balance and where most of the energy is dissipated through erosional processes. Groundwater is moving rapidly along these discontinuities to reach the dropping base level. The salt that soars the sediments matrix is dissolved along the paths favoring the development of enlarged conduits, cavities, and then the proliferation of sinkholes. Despite these unfavorable environmental conditions, large touristic projects have flourished along the northern coast of the Jordanian Dead Sea. In this work, which is based on a multi-methodical approach (times series of satellite radar images, interpretation of optical satellite data, in-situ observations, and public science), we show that a 10 kilometers-long strip of coast that encompass several resorts is exposed to subsidence, sinkholes, landslides, and flash floods. Hotels' front beaches, roads and bridges are the most affected infrastructures. In this paper, we show how we have proceeded to delineate hazardous areas inside cadastral parcels of five major resorts. We also analyze the setting of a bridge that collapsed in October 2018.

1. Introduction

The Dead Sea (DS) is a terminal lake located in a pull-apart basin laying in a complex transform fault plate boundary. This tectonically active zone has been historically exposed to destructive earthquakes (Garfunkel et al., 1981; Abou Karaki 1987; Bonnin et al., 1988; Abou Karaki et al., 1993; Galli, 1999; Klinger et al., 2015). In the last two decades, most of the coastal segments of the lake turned into a young and dynamic salt karst system. Subsidence and sinkholes developed very quickly and disrupted the economic development (El-Isa et al., 1995; Salameh and El-Naser, 2000; Arkin and Gilat, 2000; Parise et al., 2015; Abou Karaki et al., 2017; Al-Halbouni et al., 2017; Ezersky et al., 2017; Fiaschi et al., 2017; Polom et al., 2018, and references therein). Since the sixties, the DS level has dropped at an accelerating pace. From 1960 (397 m below mean sea level) to 2018 (432 m bmsl), the level dropped by 35 m due to the transfer of the water from the Tiberias Lake, the damming of the main tributaries, and the exploitation of the DS brine itself for industrial purposes. More recently, a persistent drought has further aggravated the situation.

This drastic change and its aftermaths leaded the DS region to become a natural laboratory for the Anthropocene studies (Abou Karaki et al., 2016 and references therein). The expectation of an economic growth based on the natural DS resources is facing the reality of the human-induced geological hazards.

The environmental impact of water scarcity is so high that, during the last decade, the Jordanian, Israeli, and Palestinian authorities agreed to work on a mega-engineering project, the Red Sea–Dead Sea Water Conveyance. It plans to promote the development of the area, to stop the degradation of the environment, and to solve the problems related to the fresh-water needs. One of the expected outcomes would be the raise and stabilisation of the water level at 410 m bmsl (“Base Case Model B/2000/410” in Coyne et Bellier et al., 2014). However, with a target year of 2050, the proliferation of subsidence and sinkholes will continue. Hence, it will be more and more necessary to systematically delineate, monitor and model the hazardous areas.

Studies concerning the DS sinkholes started in mid-1990s, concomitantly to an always increasing occurrence of decametre-size collapses. The southern part of the lake was first affected (Figure 1: Lisan Peninsula (LP), Ghor Al-Haditha (GAH)). In the 2000s, the western coast was progressively covered by dozens of sinkhole clusters (Abelson et al., 2006; 2017; Ezersky et al., 2017). At the opposite, the eastern side was not affected because it is essentially made of rock cliffs plunging directly into the DS. Noticeably, the northern part of the terminal lake (Figure 1: Sweimeh) was less exposed during most of that period (Abou Karaki and Closson, 2012). It is only during the last 10 years that the number of hazardous events increased. The pace remains low, but the type of incidents is different. The landslides – with or without the occurrence of sinkholes – are predominant.
[FIGURE 1]

Geological and geophysical surveys carried out in the southern DS have highlighted the main conditions associated with the formation of sinkholes:

1. the seawards migration of the underground interface between fresh and salt water is causing the lake-ward shifting of a dissolution front (El-Isa et al., 1995; Salameh and El-Naser, 2000; Ezersky and Frumkin, 2013);

2. along the western coast, one salt layer (~11000 yr in age) had been identified as the main source of the underground cavities leading to ground collapses (Yiechieli et al., 1993; Abelson et al., 2003; Ezersky et al., 2017). Below the Lisan wave-cut platform, (Lisan Peninsula, Figure 1), a thick salt layer had been identified by the Arab Potash Company (APC) security engineers dealing with grouting operations for earthen dikes' stability (Mansour, oral communication 2017). In the eastern part, the existence of this salt layer is still in debate, essentially due to the lack of boreholes with unquestionable dated rock samples. An alternative model developed by Al-Halbouni et al. (2017) suggests a mechanism based on numerous salt lens/layers dispersed into the alluvial fan sediments;
3. sinkholes are developing in elongated clusters following geological discontinuities and underground flow paths (Abelson et al., 2003; Closson and Abou Karaki, 2009). Faults and fractures act as conduits that facilitate the displacement of the underground water towards the base level (Ezersky and Frumkin, 2013; Abou Karaki et al., 2016);
4. the difference in elevation between the riparian fresh groundwater and the base level leads to the circulation of underground water with high erosional capabilities (both chemical and mechanical) and increasing velocity along interconnected subsurface channels. One of the consequences is that dissolution can take place below the DS water level (Abou Karaki et al., 2016);
5. recent studies (e.g. Abelson et al., 2017) have highlighted a connection between the rainfall regime in the recharge zones surrounding the DS basin and the development of sinkholes along the western shore.

The co-existence and interaction between these five conditions resulted in the development of a hydro-mechanical model explaining the majority of the thousands of sinkholes that are punctuating the coastal zones (e.g. Ezersky et al., 2017). Anyway, this model encountered some difficulties to convincingly explain a certain number of observations (Al-Halbouni et al., 2017; Ezersky et al., 2017), especially in Sweimeh, located along the DS north-eastern coast, which is the area of interest of this work (Figure 1). The fundamental reason is the presence of different aquifer systems along the DS coast that do not react in the same way to the base level drop. Repeated field surveys in the northern DS have shown that sinkholes are not only associated with subsidence but also with hectometre-wide landslides and/or strong subsidence (Closson et al., 2010).

The Sweimeh area is a singularity in the context of the DS geo-hazards because of the number of exposed people/assets. In the mid-1990s, the Jordanian authorities invested in infrastructures (e.g. roads, bridges, water pipelines) to create a favourable nest for private investments in the tourism sector. In the frame of the "Dead Sea Master Plan", dozens of five-star hotels have been built along a ~10 km long stretch of the coast. Although the urbanization occurred concomitantly with a sporadic development of destructive landslides and sinkholes, no adaptations/remediation measures were taken. In the mid-2000s, it became obvious that the sustainability of private and public investments in tourist resorts and infrastructures along the DS shoreline was questionable.

In this paper, we present the results of a selection of observations collected in the Sweimeh area in the last two decades. We discuss the main findings with respect to a prototype of hydro-mechanical model by combining field observations, Synthetic Aperture Radar Interferometry (InSAR) techniques, both Differential (D-InSAR) and Advanced Differential (A-DInSAR) and the analysis of thematic maps and ancillary data in a Geographical Information System (GIS). Following this approach, we deduce that the development and application of an Early Warning System (EWS) in the DS area based on the detection of characteristic precursory deformations of collapses (Closson et al., 2003) is necessary to monitor the development of hazards and to provide warning signals prior to the occurrence of major threatening ground failures.

2. Geological setting of the study area

The Sweimeh area corresponds to a stretch of coast, about 2 by 10 km, situated along the north-eastern part of the DS (Figure 1 and 2). The landscape is shaped by Pleistocene to Holocene sediments overlying a thick Mesozoic sequence of Triassic and Cretaceous rocks. The Triassic is represented by the Zarqa Ma'in Group (dolomitic limestone and marls, massive limestones, sandstones and shales). The Cretaceous sequence composed of sandstones, limestones and dolomitic limestones, overlays the Triassic Zarqa Ma'in group.

The Middle-Late Pleistocene is represented by the Lisan Formation that is made of lacustrine sediments (sandstone, marl and claystone) of the Lisan lake yielding ages from 70 to 12 kyr (Landmann et al., 2002). On top of the sequence, Holocene sediments are made of gravels and soils that cover broad areas in the Jordan valley. The Sweimeh Formation (Shawabkeh 1993, 2001) comprises massive and bedded Anisian Dolomitic Limestone interlayered with colourful Scythian Sandstone (Bandel and Abuhamad, 2013). The Kurnub Sandstone and the Naur Dolomitic Limestone (Lower to Middle Cretaceous) overlaying these strata crop out in the central and north-eastern parts of the study area, while the Lisan Formation and the Holocene colluvial sediments overlay the Triassic and the Lower Cretaceous in the northern part.

Regarding the structural setting, the eastern branch of the Dead Sea Transform (DST) fault emerges and reactivates the Amman-Hallabat Structure (AHS) in its southernmost tip (Figure 2); (Al-Awabdeh et al., 2016a). The AHS is an 80 km fold-bend fault striking NE-SW running from the easternmost corner of the DS up to central Jordan (Diabat, 2009; Al-Awabdeh et al., 2012; Al-Awabdeh, 2015).

The DST is an active structure (e.g. Al-Awabdeh et al., 2016b). Conjugated normal and normal dextral fault systems are being developed in NW-SE direction. Fracture systems in Sweimeh point to compressional stresses in N-S and NNE-SSW directions and, in return, tensional stresses in NW-SE directions. These fractures and active faults are concordant with the current stress configuration.

In terms of hydro-geological setting, the Sweimeh area is highly fractured and the damaged fault zones contribute to the dispersion of the rainfall (346 mm per year) percolating from the Moab plateau (East – not visible in Figure 2) to the base level. Most of the precipitation drains and only a small portion infiltrates through fractures into the groundwater aquifers (Salameh, 1996; Odeh et al., 2013).

About surface water, flash floods initiated by heavy rainstorms are common. They induce damage infrastructures and are potentially lethal. The 25th October 2018, a bridge collapsed and 21 people lost their live. Most of the energy released during such event is dissipated through incision into weak mud deposits.

Regarding ground waters data and volumes, for the whole East coast of the Dead Sea, the Natural outflow was 300 MCM per year before the lowering. Nowadays, it is evaluated at 500 MCM. For Sweimeh, it is evaluated at 15 MCM per year (Elias Salameh, Personal Communication 2018). This includes the underwater springs.

[FIGURE 2]

3. Material and methods

The strategy to understand the dynamics of the geological hazards in the DS, and to derive maps of the most exposed areas, is based on a combination of inputs coming from three independent data collection approaches:

1) Images acquired by satellite radar sensors have targeted the mapping of the ground displacements. Differential interferograms and velocity maps computed from multi-temporal DInSAR analysis have been used to delineate ground deformations. These observations have also served to prepare field validation campaigns;
2) Satellite optical images were used for the detection of the shoreline's positions through time, infrastructures (building footprints, roads, bridges), soil moisture gradient, and vegetation appearance/disappearance, especially in the recently emerged areas;
3) Field surveys were carried out to confirm the observations obtained with the satellite imagery and to record additional information such as wall repairs and cracks in the facades that are otherwise impossible to capture with space-borne sensors.
All the available information was geocoded and imported in a geographical information system to perform spatial and statistical analysis.

3.1. SAR datasets and derived products

Sentinel-1A/B (S1-A/B) SAR images have been processed with the Small Baseline Subset (SBAS) (Berardino et al., 2002) technique implemented in Sarscape™ software to map and to quantify the deformations in Sweimeh from 09/2015 to 09/2017. A detailed description of the SBAS processing workflow adopted in this study is available in Fiaschi et al., (2017). This approach was successfully applied over the Lisan Peninsula and surroundings, in southern DS. The results are shown in Figure 4. The derived products consisted of geocoded intensity and coherence maps, interferograms, differential interferograms, velocity/displacement maps, and ground displacements time-series.

The obtained results were supported and were validated by field observations and visual interpretation of optical images. Ancillary data, such as the location of the pumping stations and the faults/fractures datasets, were integrated in the analysis of the results to obtain a more comprehensive overview of the ground deformation dynamics.

3.2. Optical images and derived products

Three datasets derived from space-born optical sensors have been used to get knowledge of the landscape evolution:

1) Very High Resolution (VHR) WorldView-2 (WV-2) images (Digital Globe™) have been processed to extract information of the shoreline position, the building footprints, the vegetation, the soil moisture, and of geomorphological features such as depressions located below the water level, generally associated with the presence of underwater springs.

The WV-2 images consist of one VHR panchromatic band at 0.46 m resolution and eight spectral bands at 1.86 m resolution, "coastal, blue, yellow, green, red, red edge, Near-InfraRed (NIR), and NIR2". Image fusion algorithms implemented in ENVI™ and Erdas Imagine™ were applied to create pan-sharpened images, i.e. an image with colour information but at 0.46 m resolution. Such processed images are very efficient for the extraction, interpretation and validation of infrastructures, vegetation, etc. Further specifications are found in Table 1.

[TABLE 1]

2) LANDSAT and Sentinel-2 imagery were used to monitor the position of the DS shoreline and the vegetation development along the coast from the early 1970s until 2017. The most recent LANDSAT data are at 15 m spatial resolution in panchromatic and 30 m in optical-NIR spectral bands. Pan-sharpening techniques were applied to work at high resolution with colours.
Sentinel-2 images are at 10 m resolution for the optical-NIR bands. In this case, there was no need to apply pan-sharpening methods.

3) Declassified CORONA scanned pictures dating back to the late 1960s were interpreted to map the shoreline prior to the base level drop. At that time, a relative equilibrium existed in the coastal environment as attested, for example, by the river profiles. Besides, the vegetation had colonized almost the totality of the shore. According to the CORONA mission designator, the Best Ground Resolution (BGR) achievable was 2.74 m. After a careful geocoding of the scanned pictures, and without resampling the original data from the USGS, a resolution of around 10 m was found.

The extraction of data about the landscape's changes was performed by computing two basic indices over Worldview-2, Sentinel-2 and Landsat-8 images: the Normalized Difference Vegetation Index (NDVI = (R-IR)/(R+IR)) and the Normalized Difference Water Index (NDWI = (G-IR)/(G+IR)). They were applied to map the vegetation cover and the emerged areas between two acquisition dates. Changes have been computed based on a simple difference between pairs of images acquired by the same sensor. The classification of the results was based on standard deviation. Emphasis was given to the extreme classes corresponding to the appearance of vegetation.

The interpretation of the data sets targeted the detection of springs and to infer shallow flow paths in the emerged lands. This material was also used to select the locations for field observations. With less than 100 mm of rainfall per year, the growth and decline of vegetation in the DS depends on small variations in the groundwater elevation, which in turn, depends on the elevation of the base level. Hence, the study of the vegetation and of the soil moisture targets the modifications of the underground water circulation close to the shoreline.

The footprints of the buildings have been digitized manually since they are not covering wide areas. Hotel parcels' boundaries were derived from the interpretation of the VHR satellite images and compared to available land planning maps.

3.3. Field surveys and ancillary data

Since the beginning of the 1990s, our research team has been photographically documenting the induced geological hazards in the whole Jordanian DS area. The location of each observation is recorded with a GPS system or over standard topographic maps, and then imported in a geo-database.

Field surveys were carried out at multiple times in order to follow up the development of fissures, landslides and sinkholes. During the last 15 years, the emergence of pictures repositories (e.g. Flickr) on the Internet has given access to new original data sources. Sometimes the pictures were geo-tagged which helped to speed up the work of archiving those images.

The geo-tagged images have been collected and archived in such a way allowing multi-temporal analysis in a GIS system. The mapping of vulnerable zones through time relies on this source of data too, and has supported the delineation of work inside the cadastral parcels. Web Map Service (WMS) servers have provided a large number of ancillary data such as VHR images from Bing and Open Street Map. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a spatial resolution of 30 m x 30 m was used to position all observations into a 3D environment and to remove the topographic phase in the interferometric processing.

The SRTM DEM corresponds to the landscape of February 2000 (DS elevation -413 m), therefore there is no topographic data for the coastal zones that have emerged after that date (DS elevation -433 m in 2018). Considering the delineation of the thalwegs with hydrological tools in ArcGIS™, the missing information for the landscape that has emerged after 2000 was derived from the visual interpretation of the more recent VHR images.
Geological data have been collected from the existing published sources at 1:50,000 scale (1980s) and complemented by more recent studies at 1:10,000 scale (early 2000s) (e.g. Al-Awabdeh, 2015).

The "master-plan development strategy of the Jordan Valley" prepared by Tegler (2007) was used to extract and digitize the cadastral maps matching the area of interest, in order to obtain a more precise mapping and classification of the damage to the infrastructure in study area.

Well data have been collected to support the interpretation of the differential interferograms. The underground water resources in the Jordan Valley are extremely solicitated for irrigating crops. There is a considerable number of pumping stations. Their impact on soil deformations has been investigated by radar remote sensing. These deformations are therefore unrelated to those resulting from the lowering of the Dead Sea level. On the one hand, subsidence results from soil compaction following the extraction of water; on the other hand, subsidence is the consequence of the dissolution of salt residues in the soil matrix. The subsidence surface that results from the extraction of water surrounds the pumping station while subsidence related to dissolution is located generally along the coastline. Therefore, the inventory of pumping stations is important for the interpretation of subsidence zones. Some of the wells managed by the Jordan Ministry of Water and Irrigation (MWI) were monitored in conjunction with the U.S. Geological Survey (USGS) to extract groundwater-levels and salinity trends (Goode et al., 2013). Groundwater level data from 30 of these wells were available for the northern DS, among which only 3 are located in the Sweimeh area.

3.4. Method for mapping exposure of tourism infrastructures

In the present study, the term "exposure" concerns the situation of tourism infrastructures (buildings, roads, front beaches, bridges, walls, buildable cadastral parcels) located in hazard-prone areas (landslides, sinkholes, subsidence, rivers' incision triggered by the DS lowering). The measures of exposure include the spatial extent of the damages observed in the field and with satellite imagery, the period of time a particular asset is regularly affected, its location (especially its distance from the receding shoreline), and the frequency at which it is affected.

The workflow that was used to create an exposure map is presented in Figure 3. Radar images (SAR data) are used to create InSAR time-series from which ground deformations are derived. InSAR is one of the main techniques used to quantify the changes in the coastal areas. The results are validated during regular field observations. Ground deformations related to wells are excluded from the process. The ones related to the DS level lowering represent the main input of the study and they are related to cadastral parcels in a Geographical Information System (GIS). The owners have been contacted for collaboration and to plan field surveys with security engineers.

Optical imagery also plays an important role in providing information about the landscape modifications that range from the appearance/disappearance of springs to the construction of new urban areas. NDVI and other indices are used to capture some specific elements related to the vegetation distribution and its stress, as well as major changes in the soil moisture corresponding to the emergence of a new spring (prior to the development of vegetation).

The NDVI has been correlated to long-term water stress (e.g. Martin et al., 2005). NDVI has to be considered as a measurement of amalgamated plant growth that reflects various plant growth factors. The physical characteristics detected by the index are likely related to some measure of canopy density or total biomass. The underlying factor for variability in a typical vegetation index cannot be blindly linked to a specific input without some knowledge of the primary factor that limits growth. For example, in the DS coastal zone the limiting factor can be the drop of the groundwater level caused by the base level lowering.

Well data and field observations are useful to obtain information about the status of the water table level, the groundwater flow dynamic and position, as well as about the variations in the salinity of the springs that may correspond to variation in the salt dissolution processes in the upstream. Field surveys served also to validate the satellite-based observations and delineate more accurately the areas exposed to geological hazards.

The exposure map of touristic cadastral parcel represents a combination of evidences that an ongoing threat is emerging. The main causes of the occurrence of sinkholes, subsidence and landslides are related to the underground water circulation: flow rates, saturation with respect to salt, and the lateral variation of facies in the DS alluvial-colluvial environment. In terms of measurements, the lack of boreholes in the area can only be compensated by regular and systematic observations of the changes at the ground surface.

In this study, we postulated that the water table depth can be extrapolated by combining different sources of information including streams and springs locations, vegetation covers/types, structural features, and ground displacements. Direct observations are only provided by well data. Assumptions are needed for the other elements: thalwegs are mostly dried up, but water is still present beneath the surface at a depth of ~1 m; springs elevation indicates the intersection of the water table with the surface; elevation of water residing in sinkholes is another source of direct observations; roots characteristics of different vegetation are used to map the water table level at 1 m – 2 m of depth, depending upon the type of plants concerned; unstable areas detected from radar images are considered as the places where the water table presents higher gradient with respect to the surrounding areas.

This cost-effective approach already proved to be efficient several times in the southern DS with the predictions of the destruction of the Numeira Salt factory at Ghor Al Haditha and the deterioration of the southern part of dike 18 of the Arab Potash Company network (Parise et al., 2015). The same approach also explained the destruction of dike 19 by sinkholes and strong subsidence.

[FIGURE 3]

4. Results

1.1. Ground deformations derived from A-DInSAR

Before the 1960s, the DS water level was relatively stable through decades (-395 m b.s.l.). It fluctuated by around 2 m per year due to rainfalls variations in the watershed. On average, the lake body and the surrounding aquifers were in equilibrium. When the lake level dropped, the groundwater level adapted to the failing DS level that lead to an increased groundwater discharge. With the movement of the DS/groundwater interface, sediments rich in halite started to dissolve, leaving voids that iteratively increased until becoming unstable. Because the Northern DS is essentially a muddy area, it gradually sinks causing structural deformation. Ground deformations observed all along the coast (Figure 4) are interpreted as the consequences of the lateral shift of the interface between the DS brine/fresh water.

[FIGURE 4]

Previous investigations in the Southern DS related to the collapse of Arab Potash Company "dike 18" have suggested that subsidence could be the result of chemical erosion, while landslides and sinkholes would be the consequences of mechanical erosion by the underground water flows. In this case, the high topographic gradient of the water table is influenced by the proximity between dike 18 and Wadi Araba acting as the dropping base level (Abou Karaki et al., 2016). In Sweimeh, the high topographic gradient of the water table would be related to the general topographic conditions in the north-eastern side of the DS, and the important fresh water supply coming from the Moab plateau as well as from major structural features.

The velocity map obtained from the processing of S-1A/B data (Figure 4) indicates that all areas west of the 1959 shoreline (Figure 4, red line) are affected by subsidence (red and purple areas). Highest subsidence velocities up to -130 mm/yr are found in seepage areas along the coastline (seepage areas, e.g. Figure 5) and in the exposed muddy plains. The front beaches of the parcels A, B and D are the most affected, with velocities reaching -25 mm/yr, -36 mm/yr and -68 mm/yr. Field observations have confirmed that sinkholes and landslides affect the front beaches over a distance between 100 to 200 m landwards. Subsidence affects also some areas east of the former 1959 shoreline, in particular between parcels A and B. This zone corresponds to the damage fault zone associated to the Amman-Hallabat Structure. A possible explanation for this subsidence could be the permeability increase (fractures) that allows a more important underwater flow than in the surrounding areas. The same phenomenon occurs also between parcels C and E.

1.2. Vegetation dynamics from optical imagery

Figures 5 and 6 illustrate the contribution of the vegetation to the identification of areas prone to landslides and sinkholes. Figure 5 displays side by side a major landslide observed with the optical channels and its equivalent using the NDVI index. Vegetation appears in green while salty-mud is in yellow. The DS is in the lower left corner (dark colour). Tamarix bushes underline the seepage zones corresponding to the landslide crown and the steams as well. Reeds are found in the downstream parts of the landslide.

[FIGURE 5]

Springs represent the intersection between the top of the water table and the ground surface. They are several meters above the base level. This difference in elevation is proportional to the disequilibrium in the hydrogeological system. In the 1950s-1960s, the springs appeared more or less at the same level than the lake. Figure 6 shows the reclassified vegetation change values obtained from the difference between the 2010 and 2017 NDVI maps.

[FIGURE 6]

The largest part of the vegetation loss comes from the development of tourism projects north of the Holiday Inn. White circles point out four major vegetation development corresponding to actual mudslides. The emergence of springs in the front beach of hotels is particularly hazardous (see also Figure 8C). Since early 2016, we observed in the Holiday Inn front beach two distinct places where reeds have developed (see also Figure 8D). The areas have been fenced by the security engineers. Sinkholes are found some meters above the springs.

1.3. Field observations

Figures 7-8-9 illustrate different damages that are the consequence of the DS level lowering. Figure 7 shows the practical effect of the subsidence mapped with A-DInSAR techniques. Figure 8 indicates that some hotels are affected on two fronts: river incision and lateral slopes displacement, and springs in the front beach areas. Heavy engineering work is needed to "freeze” the river profile and to avoid slopes undermining during flash flood events. Figure 9 reveals that strong river incision is also endangering all bridges hundreds of meters away from the DS shore.

[FIGURE 7]

During the last decade, frequent, regular, almost biannually field inspections were carried out to follow and monitor the deteriorations of the DS shore in the hotels area in Sweimeh. All areas show surface deformations reflecting the ongoing subsurface dissolution processes. Cracks are everywhere on land, walls, swimming pools and other man-made structures.

As illustrated in Figure 7, no effort was made by investors to investigate the causes or define a reasonable strategy to deal with the quite visible deteriorations. Instead, these were being “repaired” hastily and mostly on daily basis for inefficient makeup purposes. Land cracks are being systematically filled with sand. Cracks affecting structures with concrete. Figure 7 shows typical recent repairs of structural cracks in one of the 5 stars hotels in the area (Movenpick).

[FIGURE 8]

Figure 8 shows the situation and the repair works done to protect the King Hussein bin Talal convention centre, located between the parcels B and C. The complex, the largest in Jordan, is a 3-story centre featuring 27 conference halls often used for winter World Economic and Scientific Forums, major exhibitions, conferences and meetings, and capable of hosting up to several thousand participants each time. The protection efforts seem to focus on large scale engineering measures designed to attenuate the erosion effects of flash floods on the slopes (Figure 8A, situation in April 2009; Figure 8B, March 2013). However, field evidence on the shore front demonstrates the presence of water seepage that seems to come from beneath the centre. On the long and medium terms, years to decades, this may increase the geological hazard of the area, which could be exposed to subsidence, sinkholes and landslides, as already occurred in the near coastal zones. Figure 8D illustrates the development of vegetation around such springs in the front beach of the Holiday Inn hotel. This resort area had been hit at least 3 times (September 1999, May 2009, and August 2012) by hectometre-size landslides, as already happened along the near coastline.

[FIGURE 9]

There are several major bridges on the DS highway, all suffering the effects of the DS water level lowering, especially the vertical erosion processes. In October 2017, one of these bridges located three kilometres south of parcel E, was heavily damaged and lost one of the supporting pillars. Another bridge that suffered significant damage as consequence of vertical soil erosion is the Zara-Ma'in Bridge, situated just a few kilometres south of the study area. Figure 9 shows the extent of the evolution of the damage affecting the western side of the Zara-Ma'in Bridge on the highway between the 2012 (renovated bridge), and nowadays (2018). Most of the other bridges on the eastern shore of the DS highway show advanced signs of deteriorations.

1.4. Exposure map

Figure 10 illustrates the segmentation of the cadastral parcels based on the combination of multi-temporal field observations, security engineers/employees' testimonies, and remote sensing diachronic results.

[FIGURE 10]

The maps concern five main touristic infrastructures. The polygons were drawn manually after a careful analysis of all pieces of evidences. The contribution of field pictures is essential since it provides information not accessible with remote sensing techniques. The building damages are categorized in eight classes from 0 (minimum) to 7 (maximum). Visible signs on buildings gradually increase from hairline cracking (rank 1) to total collapse (rank 7) - see Cooper (2008). A similar approach was successfully applied in two previous cases: the forecast of the Numeira Salt Factory destruction more than one year before being swallowed by sinkholes, and the prediction of the collapse of a 3 km-long section of dike 18 (Abou Karaki et al., 2016) one year before the amputation of the affected segment from saltpan SP-0A.

2. Discussions

The A-DInSAR results show the intensity and the spatial distribution of the mean ground deformations along the north-eastern DS coastline from 2015 to 2017. The detected ground subsidence extends well beyond the old 1960s' coastline. We interpreted this outgrowth (Figure 5, subsidence between parcels A and B, east of the red line) as a repercussion of the continuous lowering of the DS level over the groundwater discharge several kilometres inland.

The magnitude of the ground deformations decreases with the distance from the shoreline. The zone around the shoreline is the most affected, and the highest intensity corresponds to the location of the intersection between the water table and the ground surface. This intersection zone is materialized by the presence of vegetation, major ground failures, sinkholes and landslides.

This assertion is based on both repeated field surveys carried out during two decades over the cadastral parcel currently occupied by the hotel Holiday Inn, and optical satellite interpretations. As an example, a first landslide occurred in this area in September 1999. Then, two others occurred in May 2009 and in August 2012. The interesting aspect to consider in this series of landslides is the period of the year in which they occurred. If we consider the rainfall as the main triggering mechanism, the landslides are expected to be more frequent during the wet season and scarce during the dry season. However, here, the origin of such instabilities could be the lateral injection of fresh water into soft sediments on a slope balance profile created under the DS level. One hypothesis could be that the injection is favoured by the drop of the DS level that usually occurs during the dry period. This phenomenon has been quantified in Sirota et al., 2016 (see Figure 3 (b) in their publication showing the rate level change in m/month).

The landwards extension of the subsidence related to the DS level drop could be result of a greater permeability of certain zones characterized by an increased density of fractures. The zone co-occurs with the Amman-Hallabat Structure. The latter was analyzed by Al-Awabdeh (2015) and hundreds of observation points have attested the great fracturation in the whole area.

The DS area is one of three poles of major tourism development projects in Jordan; these also include the capital Amman and the southern port of Aqaba at the northern tip of the Red Sea. The amount of new investments in the DS and Aqaba areas was evaluated to be about 22.6 Billion US $. By the year 2022, tourism industry is expected to generate 8.6 Billion to the national economy (Ennab, 2017; 2018).

Investigations regarding the technical decision-making process for land-use and land-planning in Jordan have highlighted the weaknesses and the general framework in which industrial projects originate, are designed and realized (Abou Karaki et al., 2016).

Four categories of stakeholders can be distinguished: i) funding providers and industrial projects developers want a rapid return on their investments, especially in areas of potential multivariable conflicts. Environmental constraints are often considered as secondary issues and very seldom properly taken into account; ii) engineers, architects, and planners are generally working on a range of global projects and are in charge of project design. Anyway, their knowledge of the environmental setting of any particular remote local project is generally poor, or at best based on a limited dataset centred over the parcels they have to valorise. They tend to minimize geomorphologic constraints. The real geomorphological conditions of an area are thus often neglected or reshaped without taking into account the dynamic nature of the ongoing transformations and deformations; iii) companies qualified to construct infrastructures are a mixture of local and international enterprises. In general, local workers are more informed about the environmental issues in their work areas. However, their main objective is to realize the project, not planning or questioning it, if they ever have any opinion to express; iv) security engineers in charge of preserving projects after completion are locals who are fully aware of the environmental degradation processes, although they lack a synoptic view and a sound understanding of the underlying mechanism.

Security engineers of five parcels have been consulted for the inspection of their area of interest. They provided a large amount of relevant data regarding the intensity and frequency of the repairs. Their knowledge, complemented with our own data collection process (field observations guided by InSAR deformation maps), have been summarized in the exposure maps. To turn those maps into operational documents, in late 2017, several meetings and workshops were held in Amman, Jordan, with the participation of the main governmental and private stakeholders. The records of the geological hazards in the Sweimeh area collected by our research team in the last twenty years were presented and discussed.

In November 2017, an extended special session of the World Science Forum 2017 devoted to the DS environmental issue was held at the King Hussein Convention Centre, in Sweimeh. It was the first scientific forum to be held in the area affected by these phenomena and deformations. The exchanges and discussions have highlighted the absence of appropriate awareness about the ongoing karst development (Abou Karaki et al., 2017).

Currently there is practically no strategy in the “Dead Sea Master Plan” to manage the geological hazards resulting from the DS lowering in relation to the tourism development. The lessons learned from these meetings and discussions are: all business related to major touristic infrastructures in karst environment (i.e. hotels, roads, dams, etc.) depends on decisions made by the national touristic authorities, land planners, architects, civil engineers, and private investors; the very nature of these decisions is affected by the quality, the completeness and the immediacy of the information available to the decision makers. The access to the information needed for the decision-making process, is strongly influenced by how business knowledge is managed.

The ability to leverage expert knowledge, especially in matter of environment, is a critical yet significantly underutilized asset. Explicit knowledge, codified into repositories, is more easily accessed but still requires a level of interpretation.

From the field surveys carried out in the study area and from the interviews of the safety engineers of each inspected hotel, we observed that most of the damage to the structures were repaired as soon as they appeared. However, the repair/remediation works were carried out without any consideration or knowledge of the underlying causes of the damage, and without thinking to what might happen either in the near future (re-occurrence of the damage) or to the adjacent parcels (extension of the damage).

In the framework of large infrastructure planning and construction, it is necessary to consider the geological and geomorphological factors that shape and modify the territory in order to avoid or reduce damage and economic losses. Most of the accidents involving the heavy damage or destruction of man-made structures are often related to the inadequate knowledge of the geotechnical conditions at which the constructions took place, and to the absence of a monitoring system capable of apprehending ground deformations such as collapses, subsidence, and landslides. For a given project, the principle "observe-plan-do-check-adjust" should be applied each time a new stakeholder is involved. Based on the habits of the new generation of stakeholders, each project should ideally have traceability for the common good and enable stakeholders to learn from failures.

In the karst terrains more than elsewhere, every project should have a platform where different stakeholders can communicate and share relevant information in complete transparency. The implementation of indices like Karst Disturbance Index and Karst Sustainability Index (van Beynen and Townsend 2005; North et al., 2009; van Beynen et al., 2012; Mazzei and Parise, 2018) specifically developed for karst, will represent an important step in accurately defining the problems related to this fragile environment and developing proper land use planning and management techniques.

3. Conclusions

In early 2018, a Jordanian teenager died after falling into a sinkhole at Ghor Al Haditha, South-eastern DS, Jordan. This tragic event underlines the necessity to include geological hazards related to the DS level lowering in the development plans and that appropriate measures should to be taken to avoid new lethal incidents. This is especially true with regards to the hotels' area where the exposed population is much higher than in any other place along the DS. The mapping of exposure areas at the cadastral parcel level is the very first step towards the computation of vulnerability and risk, and also towards an early warning system.

At this stage, the exposure maps at the cadastral parcel level (Figure 10) are a combination of information coming from four major sources: optical and radar remote sensing, direct field observations (structural geology), and interviews of security engineers – hotel managers. The approach presented in this paper is very pragmatic but efficient.

The most relevant pieces of evidence are collected, geocoded, and used to analyse and interpret open source satellite images (mostly). Our team is observing the DS environmental degradation since more than 20 years. Progressively, we have gain experience, knowledge and expertise regarding the stability of infrastructures. The lack of financial support and of interest from the authorities forced us to retrieve the maximum of information from open source data and to complement them with visual inspections. The robustness of this approach relies on the multi-sources, and multi-temporal analysis.
At this stage, the data fusion process is still carried out through discussions and debates between members of our team.

Human activities have left signatures on the Earth for millennia, and the magnitude of this fingerprint is currently growing with clear impacts upon morphology, ecosystems, and climate. It is now widely accepted that the world is changing fast and at a pace that could become a real issue for business development. The agricultural sector is well aware of this, due to it being already strongly impacted by changing climatic conditions. The tourism sector could be negatively impacted in the near future as well. Geological hazards in karst areas are feared by engineers since the 19th century (Milanovic, 2000, 2002; Parise et al., 2015, 2018 and references therein; Stevanovic, 2015). In the next few decades a sharp increase in karst geo-hazards is expected due to global water resources becoming scarcer, leading to a drop of water tables, and consequently leading to proliferation of subsidence areas, sinkholes and related phenomena. To avoid exposure of people and assets to these hazards, land planners and investors need an overview of the environmental situation. Presently, recognition and analysis of environmental changes forms a considerable challenge for sustainable development and profitability of major tourism projects.

Acknowledgments: Part of the work of Najib Abou Karaki was done during a sabbatical year supported by the Deanship of scientific research – The University of Jordan.

References

Abelson, M., Baer, G., Shtivelman, V., Wachs, D., Raz, E., Crouvi, O., Kurzon, I. and Yechieli, Y.: Collapse-sinkholes and radar interferometry reveal neotectonics concealed within the Dead Sea basin, Geophysical Research Letters, 30, 10, 1545, 52-1 – 52-4, doi:10.1029/2003GL017103, 2003.

Abelson, M., Yechieli, Y., Baer, G., Lapid, G., Behar, N., Calvo, R., and Rosensaft M.: Natural versus human control on subsurface salt dissolution and development of thousands of sinkholes along the Dead Sea coast. Journal of Geophysical Research: Earth Surface, 122, doi: 10.1002/2017JF004219, 2017.

Abelson, M., Yechieli, Y., Crouvi, O., Baer, G., Wachs, D., Bein, A. and Shtivelman, V.: Evolution of the DS sinkholes. In: Enzel, Y., Agnon, A. and Stein, M., (eds), New frontiers in Dead Sea paleo environmental research. Geological Society America Special paper, 241 - 253, doi: 10.1130/2006.2401(16), 2006.

Abou Karaki N.: Synthèse et carte sismotectonique des pays de la bordure orientale de la Méditerranée : Sismicité du system de failles du Jourdain - Mer Morte. PhD Thesis, Université Louis Pasteur de Strasbourg, Institut de Physique du Globe, IPGS, 417 p. (In French), 1987.

Abou Karaki N., Closson D.: European Association of Geoscientists & Engineers- EAGE Workshop on Dead Sea Sinkholes, causes, effects & solutions, Field Guidebook, 45 pages, 2012. Available at http://www.eage.org/images/cms/files/Conferences/Field%20Guide%20-%20color%20-%20min%20size.pdf

Abou Karaki N., Closson D., Fiaschi S., Calve P. J, Al-Awabdeh M., Paenen K.: Can Science save the Dead Sea? World Science Forum Conference 7-11 Nov. 2017, King Hussein Bin Talal Convention Centre, Dead Sea, Jordan, 2017. Available at https://www.youtube.com/watch?v=x15KeokjPfo

Abou Karaki N., Dorbath L., Haessler H.: La Crise sismique du golfe d'Aqaba de 1983 : Implications tectoniques. C.R. Acad. Sci. Paris, t.317, Série II, 1411-1416. (In French + Abreged English version), 1993.

Abou Karaki, N., Fiaschi, S. and Closson, D.: Sustainable development and Anthropogenic induced geomorphic hazards in subsiding areas, Earth Surface Processes and Landforms, 41, 2282-2295, doi: 10.1002/esp.4047, 2016.

Akkawi, E., Kakish, M. and Haddadin, N.: The geological model and the groundwater aspects of the area surrounding the eastern shores of the Dead Sea, Jordan. WSEAS

TRANSACTIONS on INFORMATION SCIENCE and APPLICATIONS. Issue 4, Vol.6. ISSN: 1790-0832, 2009.

Al-Awabdeh, M.: Active tectonics of the Amman-Hallabat and Shueib structures (NW of Jordan) and their implication in the Quaternary evolution of the DS Transform Fault system, PhD Thesis, pp. 207, University of Grenada, Spain, 2015. Available at: https://hera.ugr.es/tesisugr/25624581.pdf

Al-Awabdeh, M., Azañón, J. and Pérez-Peña, J.: Recent tectonic activity in the intersection between the Amman-Hallabat structure and the DS Transform Fault (Jordan). Geotemas. 469-472, 2012.

Al-Awabdeh, M., Perez-Pena, J.V., Azanon, J.M., Booth-Rea, G., Abed, A., Atallah, M and Galve, J.P.: Quaternary tectonic activity in NW Jordan: Insights for a new model of transpression–transtension along the southern Dead Sea Transform Fault. Tectonophysics 693 (2016) 465–473, 2016a.

Al-Awabdeh, M., Perez-Pena, J.V., Azanon, J.M., Booth-Rea, G., Abed, A., Atallah, M and Galve, J.P.: Stress analysis of NW Jordan. New episode of tectonic rejuvenation related to the Dead Sea Transform Fault. Arab. J. Geosci. 9:24, 2016b.

Al-Halbouni, D., Holohan, E.P., Saberia, L., Alrshdan, H., Sawarieh, A., Closson, D., Waltera, T.R., Dahm, T.: Sinkholes, subsidence and subrosion on the eastern shore of the Dead Sea as revealed by a close-range photogrammetric survey. Geomorphology, 285, p. 305-324, doi: 765 10.1016/j.geomorph.2017.02.006, 2017.

Arkin, Y. and Gilat, A.: Dead Sea sinkholes – an ever-developing hazard, Environmental Geology, 39, 7, 711 – 722, doi: 10.1007/s002540050485, 2000.

Bandel, Klaus and Abuhamad, Abdalla M.B.: Permian and Triassic Strata of Jordan. Chapter in: Anner, L.H., Spielmann, J.A. and Lucas, S.G., eds., 2013, The Triassic System. New Mexico Museum of Natural History and Science, Bulletin 61, 2013.

Berardino, P., Fornaro, G., Lanari, R. and Sansosti, E.: A new algorithm for surface deformation monitoring based on small baseline differential interferograms. IEEE Transactions on Geoscience and Remote Sensing, 40, 11, pp. 2375–2383, 2002.

Bonnin J.,Cara M., Cisternas A., Fantechi, A.: Seismic Hazard in Mediterranean Regions. Springer Science & Business Media, 1988.

Closson D., Abou Karaki N.: Salt karst and tectonics: sinkholes development along tension cracks between parallel strike-slip faults, DS, Jordan, Earth Surf. Process. Landforms (www.interscience.wiley.com), doi: 10.1002/esp.1829, 2009.

Closson, D., Abou Karaki, N. and Hallot F.: "Landslides along the Jordanian Dead Sea coast triggered by the lake level lowering". Environ. Earth Sci. 59 (7): 1417-1430, 2010.

Closson D., Abou Karaki N., Hansen H, Derauw D., Barbier C., Ozer A.: Space born radar interferometric mapping of precursory deformations of a dike collapse - Dead Sea area - Jordan. Int. J. Remote Sensing 24(4) 843-849, 2003.

Cooper A. H.: The classification, recording, data basing and use of information about building damage caused by subsidence and landslides, Quarterly Journal of Engineering Geology and Hydrogeology, 41, pp. 409-424, 2008.

Diabat A.: Structural and stress analysis based on fault-slip data in the Amman area, Jordan. Journal of African Earth Sciences, 54, 155-162, 2009.

El-Isa Z. H., Rimawi O., Jarrar Gh., Abou Karaki N., Atallah M., Seif ed-din N., Taqieddin S., and Al-Saad A.: Assessment of the hazard of subsidence and sinkholes in Ghor Al-Haditha area. Center for Consultation, Technical Services and Studies. University of Jordan, final report. 141 p, 1995,

Ennab, L. (Jordanian Ministry of Tourism): www.ammonnews.net/article/3311458, 25-04-2017.

Ennab, L. (Jordanian Ministry of Tourism): www.ammonnews.net/article/384012, 11-07-2018.

Ezersky, M. and Frumkin, A.: Fault-Dissolution front relations and the Dead Sea sinkhole problem. Geomorphology 201, 35 - 44, doi: 10.1016/j.geomorph.2013.06.002, 2013.

Ezersky, M.G., Legchenko, A., Eppelbaum, L. and Al-Zoubi A.: Overview of the geophysical studies in the Dead Sea coastal area related to evaporite karst and recent sinkhole development, International Journal of Speleology, 46, 2, 277 – 302, doi: 10.5038/1827-806X.46.2.2087, 2017.

Ferretti, A., C. Prati and F. Rocca.: "Permanent scatterers in SAR interferometry," in IEEE Transactions on Geoscience and Remote Sensing, vol. 39, no. 1, pp. 8-20, doi: 10.1109/36.898661, 2001.

Fiaschi S., Closson D., Abou Karaki N., Pasquali P., Riccardi P. and Floris M.: The complex karst dynamics of the Lisan Peninsula revealed by 25 years of DInSAR observations. Dead Sea, Jordan. ISPRS Journal of Photogrammetry and Remote Sensing 130:358-369, 2017.

Galli P.: Active tectonics along the Wadi Araba – Jordan valley transform fault, JGR, Vol.104, NO. B2, 2777-2796, 1999.

Landmann, G., Abu Qudaira, G.M., Shawabkeh, K., Wrede, V. and Kempe, S.: Geochemistry of the Lisan and Damya Formations in Jordan, and implications for paleoclimate. Quaternary International, 89, 1, 45 – 57, doi: 10.1016/S1040-6182(01)00080-5, 2002.

Garfunkel Z., Zak I, and Freund R.: Active faulting in the Dead Sea rift, Tectonophysics, 80: 1-26, 1981.

Goode J. R., Buffington J. B., Tonina D., Isaak D. I., Thurow R. F., Wenger S., Nagel D., Luce C., Tetzlaff D., and Soulsby C..: Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. Hydrol. Process. 27, 750–765 (wileyonlinelibrary.com), doi: 10.1002/hyp.9728, 2013.

Klinger, Y., Le Beon, M., Al-Qaryouti, M.: 5000 yr of paleoseismicity along the southern Dead Sea fault. Geophysical Journal International. 202. 313-327. 10.1093/gji/ggv134., 2015.

Landmann, Günter & M. Abu Qudaira, G & Shawabkeh, K & Wrede, Volker & Kempe, Stephan.: Geochemistry of the Lisan and Damya Formations in Jordan and implications for palaeoclimate. Quaternary International. 89. 45-57, doi: 10.1016/S1040-6182(01)00080-5, 2002.

Martin, K.L., P.J. Hodgen, K.W. Freeman, R. Melchiori, D.B. Arnall, R.K. Teal, R.W. Mullen, K. Desta, S.B. Phillips, J.B. Solie, M.L. Stone, O. Caviglia, F. Solari, A. Bianchini, D.I. Francis, J.S. Schepers, J. Hatfield, W.R. Raun. Plant-to-plant variability in corn production. Agronomy Journal 97: 1603-1611, 2005.

Mazzei M., Parise M.: On the implementation of environmental indices in karst. In: W.B. White, J.S. Herman, E.K. Herman & M. Rutigliano (Eds): Karst Groundwater Contamination and Public Health. Springer, Advances in Karst Science, ISBN 978-3-319-51069-9: 245-247, 2018.

Mazzei M., Parise M.: On the implementation of environmental indices in karst. In: W.B. White, J.S. Herman, E.K. Herman & M. Rutigliano (Eds): Karst Groundwater Contamination and Public Health. Springer, Advances in Karst Science, ISBN 978-3-319-51069-9: 245-247, 2018.

Milanovic P.T.: Geological engineering in karst. Zebra, Belgrade, 2000.

Milanovic P.T.: The environmental impacts of human activities and engineering constructions in karst regions. Episodes, 25: 13–21, 2002.

North LA, van Beynen PE, Parise M.: Interregional comparison of karst disturbance: West-central Florida and southeast Italy. Journal of Environmental Management 9(5): 1770–1781, doi:10.1016/j. jenvman.2008.11.018, 2009.

Odeh, T., Geyer, S., Rodiger, T., Siebert, C and Schimer, M.: Groundwater chemistry of strike slip faulted aquifers: The case study of Wadi Zerka Ma'in aquifers, north east of the Dead Sea. Environmental Earth Sciences, 70(1), pp. 393-406, 2013.

Parise M., Closson D., Gutierrez F., Stevanovic Z.: Anticipating and managing engineering problems in the complex karst environment. Environmental Earth Sciences, 74: 7823-7835, 2015.

Parise M., Gabrovsek F., Kaufmann G. & Ravbar N. (Eds.): Advances in Karst Research: Theory, Fieldwork and Applications. Geological Society, London, Special Publication 466: 486 pp., ISBN 978-1-78620-359-5, 2018.

Polom, U., Alrshdan, H., Al-Halbouni, D., Holohan, E.P., Dahm, T., Sawarieh, A., Atallah, Y. and Krawczyk, C.M.: Shear wave reflection seismics yields subsurface dissolution and subrosion patterns: application to the Ghor Al-Haditha sinkhole site, Dead Sea, Jordan, Solid Earth Discussions, doi: 10.5194/se-2018-22, 2018.

Quba'a, R., Alameddine, I, Abou Najm, M. and El-Fadel, M.: Comparative assessment of joint water development initiatives in the Jordan River Basin, International Journal of River Basin Management, 15, 1, 115-131, doi: 10.1080/15715124.2016.1213272, 2016.

Salameh, E.: The economics of water; An application to the Middle East. Harvard University JFK-School of Government, 1996.

Salameh, E. and El-Naser, H.: The interface configuration of the fresh/DS water – theory and measurement, Acta hydrochim. Hydrobiol., 28, 323-328, doi: 10.1002/1521-401X(200012)28:6<323::AID-AHEH323>3.0.CO;2-1, 2000.

Sawarieh, A., Hotzl, H. and Salameh, E.: Aquifers in the eastern Jordan Valley Hydrogeology and hydrochemistry of Wadi Waleh and Wadi Zarqa Ma'in catchment, central Jordan (Book Chapter). The Water of the Jordan Valley: Scarcity and Deterioration of Groundwater and its Impact on the Regional Development. Springe pp. 361-370, 2009.

Shawabkeh, K.F.: The map of Main Area. Map Sheet No. 3153-IIII, Scale 1:50,000. National Resources Authority, Amman, Jordan, 1993.

Shawabkeh, K.F.: Geological map of Al Karama - 3153-IV, 1:50.000, Internal Report of Natural Resources Authority, Amman, Jordan, 2001.

Stevanovic Z. (ed.): Karst Aquifers – Characterization and Engineering. Professional Practice in Earth Science Series. Springer International, Basle, 2015.

Taqieddin, S.A., Abderahman, N.S. and Atallah M.: Sinkholes hazards along the eastern Dead Sea shoreline area, Jordan: a geological and geotechnical consideration, Environmental Geology, 39, 11, 1237 – 1253, doi: 10.1007/s002549900095., 2000.

Tegler, B.: Terms of reference for the master plan development strategy in the Jordan Valley. United States Agency for International Development (USAID), 45 p., 2007.

van Beynen PE, Townsend KM.: A disturbance index for karst environments. Environmental Management 36(1): 101–116, doi: 10.1007/s00267-004-0265-9., 2005.

van Beynen PE, Brinkmann R, van Beynen K. A; Sustainability index for karst environments. Journal of Cave and Karst Studies 74 (2): 221–234, doi:10.4311/2011SS0217., 2012.

Yechieli, Y., Magaritz M., Levy Y., Weber U., Kafri U., Woelfli W., and Bonani G.: Late Quaternary geological history of the Dead Sea area, Israel, Quaternary Res., 39, 59–67, doi: 10.1006/qres.1993.1007, 1993.