AC1 to RC1

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. We would like to thank you for your most valuable suggestions.

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

1. *My first, and main, concern is about correspondence between the title and the content of the manuscript. Given the title, I would have expected more space in the manuscript to be given to the issue of vulnerability, which seems to me to be just touched in a few points (for instance, by quoting the Cooper's classification of damage to buildings, and through brief description of the main man-made infrastructures in the area).*

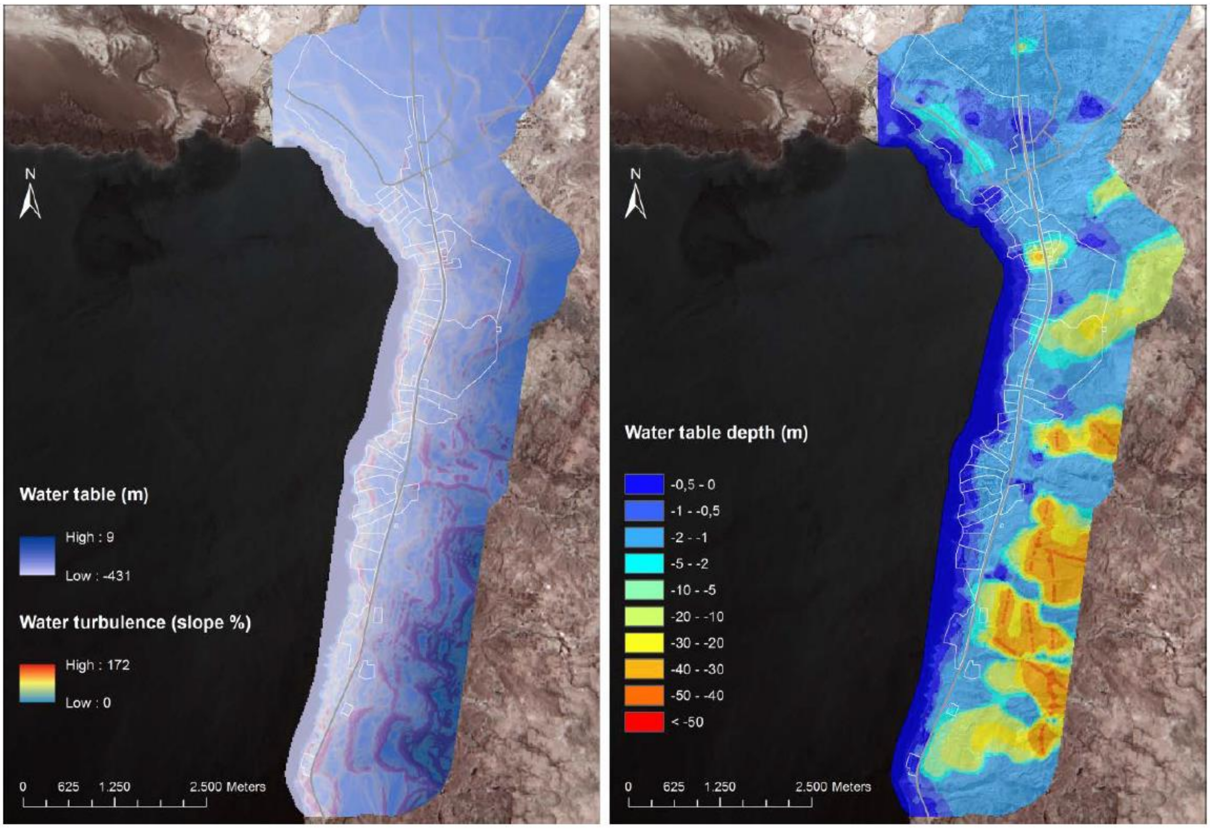
We agree with the statement and propose a new title more in phase with the content:

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

⇨ **Exposition of tourism development to salt karst hazards along the Jordanian Dead Sea shore.**

2. *Authors also mention some classification, specific to karst, about the disturbance induced by man to the natural environment, but they fail to apply any of this.*

This is correct. We have started to model the underground water circulation but the results are not enough satisfactory for the moment to be discussed in a paper. More investigations are needed.



Expanded water table model of the entire AOI showing (left) absolute height and turbulence, and (right) relative height.

3. *I believe some efforts should be done in this direction, in the attempt to evaluate how the vulnerable elements in the area might be affected, and how this might contribute in the aforementioned indices to the overall disturbance of the area.*

We fully agree. Geo-hazards along the coast are the consequence of the underground water circulation caused by the drop of the Dead Sea water level.

Three parameters have to be taken into account prior to the mapping of vulnerable areas:

1. The modeling of the top of the water table with a special emphasis over the zones where there are strong gradients. In those areas the maximum of energy is dissipated leading to landslides and sinkholes.
2. The spatial delineation of the assets with their safety coefficient.
3. The strategy to mitigate the ground deformations.

4. Further, some other indices may also be mentioned, such as that by Angulo et al. (2013); Authors are invited to check the brief review by Mazzei and Parise (2018) about indices on karst.

It is done as illustrated below (Angulo et al. (2013), and we will take it into account in our future researches.

Table 1
Indicators for evaluating the zonal Karst Disturbance Index (adapted from van Beynen and Townsend, 2005).

Category	Attribute	Indicator	3	2	1	0
Geomorphology	Surface landforms	Quarrying/mining	Large active open cast mines	Other mining works and/or infrastructures	Removal of pavement or inactive mines	None
		Dumping	Large and continuous dumping	Large but sporadic dumping	Inactive dumping and/or dispersed	None
	Soils	Erosion	High erosion rates (>100 tons/ha/yr)	Moderate erosion rates (50–100 tons/ha/yr)	Low erosion rates (10–50 tons/ha/yr)	Natural rate
		Compaction due to livestock or machinery/crowding	High rates due to intensive activities	Moderate associated with extensive activities	Low due to occasional activities	None
	Subsurface karst	Human-induced alteration (mineral/speleothems removal, desiccation, condensation corrosion, constructions, compaction, flooding)	Speleological network with widespread and high disturbance	Speleological network with widespread but low disturbance	Few modifications. Isolated spots disturbed	Pristine
Hydrology	Water quantity	Hydraulic infrastructures/activities affecting surface water (reservoirs, flow diversion, dredging.)	Watershed in which the drop or diversion of mean flow is>50%	Watershed in which the drop or diversion of mean flow is between 25 and 50%	Watershed in which the drop or diversion of mean flow is<25%	No disturbance
		Hydraulic infrastructures/activities affecting groundwater	Sectors of the aquifer in which water level decline>10 m	Sectors of the aquifer in which water level decline between 5 and 10 m	Sectors of the aquifer in which water level decline < 5 m	Only natural variability
	Water quality	Activities or practices affecting the water body quality	Industrial activities. Brownfields	Intensive agriculture/forestry/ farming (pesticides, herbicides, slurry…)	Activities from extensive agriculture and farming	No activities, pristine waters
Biota	Vegetation	Deforestation	Areas without vegetation	Plantation forestry and/or grazing land	Scrubland, ferns and/or grassland	Natural forest
	Subsurface biota	Species richness and population density (% decline)	>50%	20–49%	1–19%	0%
Cultural	Infrastructures and human activities	Roads – tracks	Main roads	Secondary roads	Minor trails	None
		Building over karst features	Large cities	Towns	Rural/tourist settlements	No development

Table 2
Indicators for evaluating the zonal Karst Significance Index.

Category	Attribute	Indicator	3	2	1	0
Geomorphology	Exokarst	Karst landforms including karren/doline fields/karst valleys	Well-developed, preserved and outstanding features with natural dynamic processes	Features well-developed with processes notable at regional scale	Common features and processes	Not developed
	Endokarst	Dissolution features (caves, shafts…) and associated deposits	Well-developed, preserved and outstanding network which can be visited	Well-developed and preserved network but not possible to visit	Common speleological network	Not developed
	Other morphologies and dynamics	Gravitational/glacial/periglacial processes and features. Cliffs, canyons, fluvial/lacustrine features	Features and processes outstanding, well developed, and preserved	Features well-developed and associated processes notable at regional scale	Common features and processes	Not developed
Geology	Geological framework	Geologic structures: folds, faults, diapirs, volcanic structures	Well-developed, preserved and unique structures	Structures well-developed, notable at regional scale	Minor geological structures	None
	Mineral and sediments	Mineral and fossil formations. Sediment sequences	Well-preserved and representative deposits (e.g. golden spyke)	Formations well-preserved representatives at regional scale	Formations with specific interest	None
Biota	Vegetation	Singularity and naturalness of habitats and species	Endemisms, rare or threatened species	Native habitats	Plantation to recover native habitats	No singularity
	Subsurface biota	Species abundance and diversity	Endemisms, rare or endangered species	Diversity and abundance of species	Common species	No species
Hydrology	Water recharge	Infiltration rate	Preferential recharge areas directly connected to the underground flow system (i.e.checked with tracer tests)	Less direct recharge areas (doline fields)	Diffuse recharge areas (karren)	No recharge
	Water circulation and discharge	Drainage network and spring discharge	Karst conduits well-developed and/or main discharge areas ($Q > 500$ l/s)	Preferential flowpath and/or minor discharge areas ($Q < 500$ l/s)	Drainage network less developed/temporal discharge areas	None
Cultural	Infrastructures and human activities	Historical/architectural sites. Archaeological-Ethnographic heritage (surface and subsurface karst)	Sites unique and well-preserved. Areas associated with ancestral and vanishing legends, customs or traditions	Sites well-preserved and notable at regional scale	Sites notable at local scale	None
		Education, sports and recreational provisions	Areas of didactic and educational interest. Interpretative centres	Recreation areas (trekking, sports areas: climbing, fishing, etc.)	Other provisions: picnic sites, shelters, campsite	No provisions

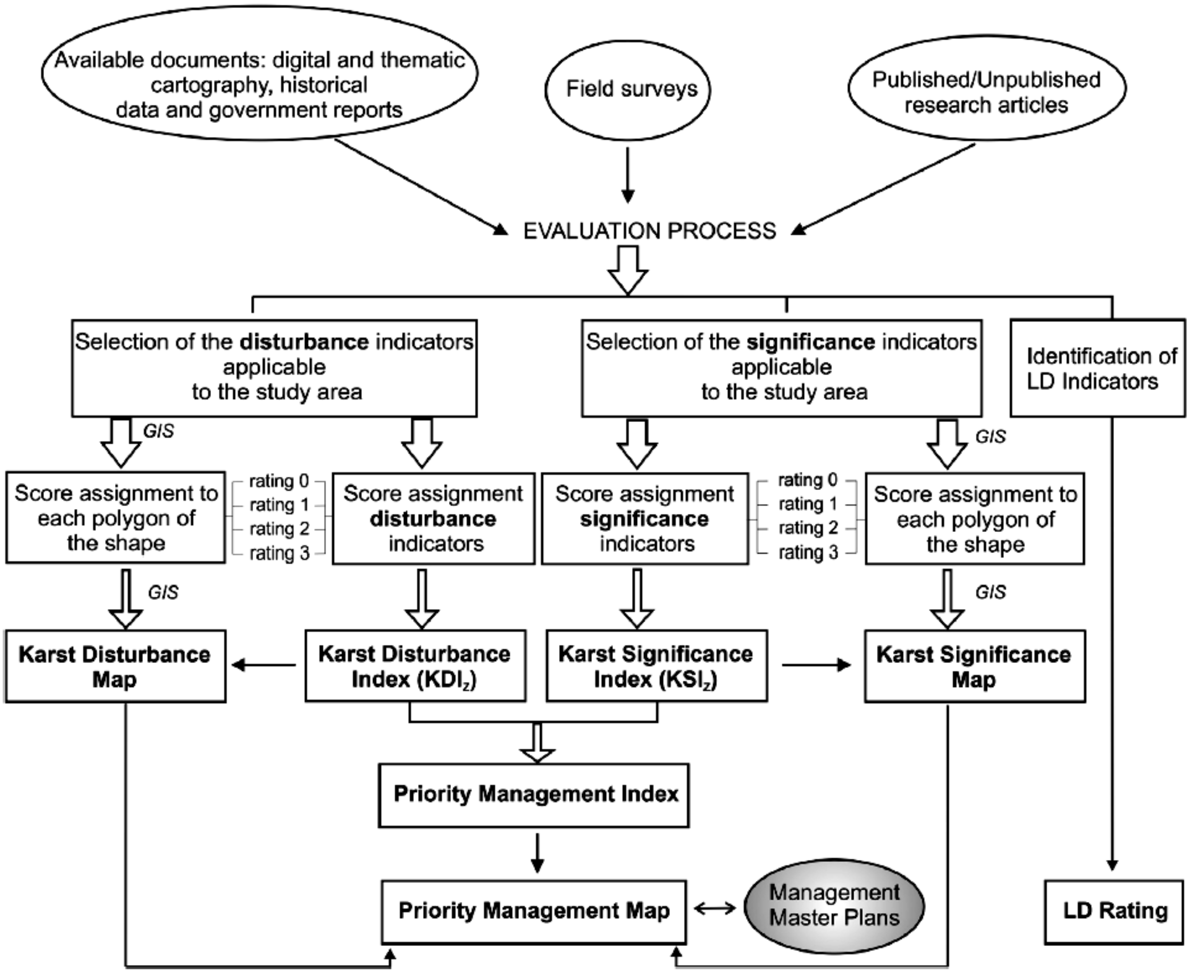


Fig. 1. Flow chart summarizing study methodology.

5. About the vulnerability mapping, this is a very important section, which should be in some way widened and improved. The same Authors admit that "The quality and reliability of the produced maps is strongly dependent on the completeness of the available photographic documentation". This is actually a very strong limit, which would deserve more discussion and comments. For instance, it is unclear to me how the damage detected by the pictures are integrated with satellite data.

The knowledge of the vulnerability inside a particular cadastral parcel is an iterative and continuous work. Our approach is based on the experience and numerous observations. There is a clear correlation between the subsiding areas observed with radar interferometry techniques and the damages inside cadastral parcels.

The very first step consists in the interferometric process of radar images. Depending on the data sources (e.g. from medium resolution Sentinel-1 (C band) to high resolution Cosmo-SkyMed (X band)), the deformations field is either poorly or relatively well detailed. Among others, the result depends on the acquisition mode, the sensors' frequency, the temporal sampling, and the algorithm used (with its parameters) to extract the information. Ideally, medium and high resolution data should be processed but the high resolution has to be paid. Each source brings an independent contribution with partial redundancies.

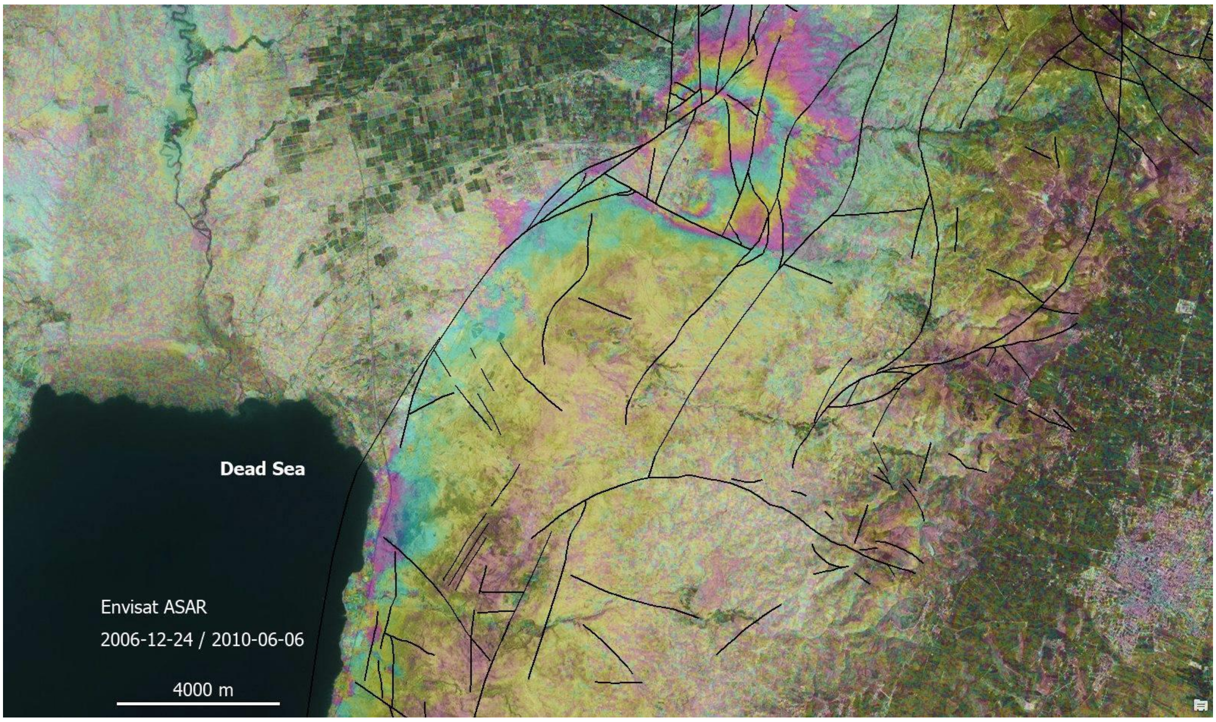
What is important at this stage is to retrieve “the big picture”. How is the deformation field? Where are the hot spots? Where are the discontinuities and why (e.g. signal decorrelation), etc. In our work, we have processed with advanced algorithms (PS + SBAS) a stack of Sentinel-1 images (>2014) and have retrieved the deformation field along the Sweimeh stretch of coast. Based on previous studies, we have also used other medium resolution sensors such as Envisat and ERS to get knowledge of the past deformations. The results were quite poor due to the temporal sampling of 35 days leading to decorrelation in the most interesting places.

When zooming in the Sentinel-1 database, analysts can see that the spatial sampling is very regular because of spatial averaging parameters. The measurements are accurate but not precise. Hence, by itself, this information informs us about the spatial continuity of the deformations along the coast at affordable cost but it is almost impossible to deduce anything at cadastral parcel level.

A set of 3 m resolution Cosmo-SkyMed data (2012-2013) was available from previous investigations and it highlighted much more local deformations over a short period of time. We have used here the simple interferometric processing.

The redundancy between information was good enough to clarify some ideas about the “hot spots” where field investigations should be done.

In the second step, the deformations field is analyzed in a GIS, with respect to ancillary data such as wells, structural elements (see figure below), and vegetation patches (indicating the presence of accessible fresh water), and geomorphologic evidences of subsidence, landslides and sinkholes in order to make understandable the fringe patterns in the differential interferograms, their shape and numbers. It helped us to understand what the overall situation for a particular time laps.



Comparison between structural data and ground deformations in a GIS. Background is a Landsat image. The crops explain the decorrelation in the interferometric signal.

Also in this step was the interpretation of the deformation field with optical data at high and very high resolution. Here, the main problem is related to the fact that there is practically all the time a temporal mismatch between the sources. Most researchers are visualizing their differential interferograms in Google Earth. This is a practical way to enlarge the context of the interpretation but there are also uncertainties when comparing “landscapes” not acquired at the same moment.

We have analyzed our data with Google Earth and other sources as well (Worldview images). We have been able to point out many places to inspect in the field.

The <u>third step</u> corresponds to the repeated field surveys with – as background knowledge – all the deformations (from radar images) and the exposed assets (from optical data). As an illustration, the interferograms are accessible throughout social media and the geo-tagged pictures are located in the conversation. The survey is shared in real time and it allows a direct link between the lab and the team in the field.

A subsidence area was detected over a pair of Cosmo-SkyMed images. Field survey indicated that strong deformations had been recorded by the walls.

At this stage, the support of hotel owners and security engineers is mandatory to have access to the field, to understand the repair works, and the “strategy” (if any) to monitor and deal with geo-hazards.

Here we have clearly seen that the concept of vulnerability does not only rely on the geological hazards dynamics but also depends on the perception of the security engineers of the hazardous situation and on the support they can get from their hierarchy…

Several times, it happened that the places suspected to be prone to collapse were known for years as dangerous by security engineers. At a first glance, this could appear strange but indeed it is just the logical consequence of the way the development of tourism infrastructures is occurring (in reference to the “Dead Sea Master plan”). In the whole decision making process there is no place for an independent evaluation of natural/environmental hazards. Hence, when the hotels are built over areas that have been affected by landslides it is too late… and that’s the reason a EWS has to be designed.

During the field surveys, based on the knowledge derived from satellite imagery and GIS analysis we can ask the right questions at the right persons and at the right places. Then, it is now just a formality to take a maximum of geo-tagged pictures of the places suspected to be at risk. Interesting to note is the fact that we can get pictures from inside the buildings and thus by-pass the limitation of remote sensing methods.

In <u>step four</u>: we iterate and go back to the lab to reprocess/re-interpret the remote sensed data. The pictures are interpreted in a GIS environment and compared to independent datasets of remote sensed data. The major challenge here is to combine observations taken at different moments.

The result is an appreciation of the situation that is materialized in vulnerability maps at the cadastral parcel scale. The interpretation of the pictures is based on the work of Cooper. The spatial splitting of the cadastral parcel is arbitrary since there is no clear demarcation line that can be observe in the field.

This approach is very pragmatic but it suffers from the lack of data collected systematically everywhere inside a cadastral parcel. Indeed, working in 5-star hotels is very difficult. The time for observation is limited and shared with interviews. The focus is on the most exposed places while other observations elsewhere could improve the approach and the understanding.

Of course the final version of our manuscript and conclusions will be greatly be improved from your suggestions. Thank you.