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

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Abstract. The Dead Sea shore is a unique young and dynamic salt karst system. It started developing in the 1960s, when the main water resources that used to feed the Dead Sea 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 hectometre-size landslides. Despite these unfavourable 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 (analyses of radar and optical satellite data, in-situ observations, and public science), we show that a 10 kilometres-long strip of coast that encompass several resorts is exposed to subsidence, sinkholes, landslides, and flash floods. 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 water paths favouring the development of enlarged conduits, cavities, and then the proliferation of sinkholes. The front beaches of the hotels, the roads and bridges are the most affected infrastructures. We point out the importance for the land planners to include in the Dead Sea development schemes the historical records and present knowledge of geological hazards in the area.

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 of the area (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 (bmsl)) to 2018 (432 m bmsl), the level dropped by 35 m due to the transfer of the Tiberias Lake water (located around 100 km north of the DS), the damming of the main tributaries (e.g. the Jordan river), and the exploitation of the DS brine itself for industrial purposes. More recently, a persistent drought has further aggravated the situation.

This drastic change in the hydrogeological setting of the area 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 in the region 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 DS water level at 410 m bmsl. However, with the target year set to 2050, the subsidence phenomena and sinkholes proliferation will continue. Hence, it is getting 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 (Fig. 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 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 (e.g. Yiechieli et al., 1993; Abelson et al., 2003; Ezersky et al., 2017). Below the LP wave-cut platform, (Fig. 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 2015, 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 that explain the majority of the sinkholes occurring in the coastal zones (e.g. Ezersky et al., 2017). This model encountered some difficulties to convincingly explain a 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 (Fig. 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 (Closson et al., 2010).

The Sweimeh area represents a singularity in the context of the DS geo-hazards because of the higher number of exposed people/assets in respect to the rest of the Jordanian DS area. 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 and discuss a selection of observations collected in the Sweimeh area in the last two decades. We describe the main features obtained 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 in the DS area of an Early Warning System (EWS), based on the detection of precursory deformations (Closson et al., 2003), is necessary to monitor the proliferation of geological hazards and to provide warning signals prior to the occurrence of ground failures.

2 Geological setting of the study area

The Sweimeh area corresponds to a stretch of coast, about 2 km wide and 10 km long, situated along the north-eastern part of the DS (Figs. 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 (Al-Awabdeh et al., 2016a) (Fig. 2). 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 (around 346 mm per year) percolating from the Moab plateau (East, not visible in Fig. 2) to the base level. Most of the precipitation drains and only a small portion infiltrates through fractures into the aquifers (Odeh et al., 2013).

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

Regarding ground waters data and volumes, for the whole East coast, the natural outflow was 300 Million Cubic Meters (MCM) per year before the lake lowering. Nowadays, it is evaluated at 500 MCM. For Sweimeh, Elias Salameh computed 15 MCM per year (Personal Communication 2018). This estimation includes also 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 sets:

1) images acquired by satellite SAR sensors are used for the mapping of ground displacements. Differential interferograms and velocity maps computed from the A-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, the infrastructures (building footprints, roads, bridges), the soil moisture gradient, and the vegetation appearance/disappearance, especially in the recently emerged areas;

3) Since the early 1990s, field surveys are carried out to complement/confirm satellite observations and to map 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 GIS to perform further analyses.

3.1 SAR data sets and derived products

The available SAR images used in this study consists of 68 Sentinel-1A/B (S1-A/B) acquired in vertical co-polarization and descending orbit from 20/09/2015 to 09/09/2017. Further specifications of the S1-A/B images are presented in Table 1. The scenes have been processed with the Small Baseline Subset (SBAS) (Berardino et al., 2002) technique implemented in the Sarscape™ software in order to retrieve information of the spatial distribution and rates of the displacements along the DS eastern coastline. In total, 463 inteferometric pairs have been connected by using 1% (in respect to the critical baseline) as threshold for the geometric baseline, and 120 days as threshold for the temporal baseline. A coherence threshold of 0.40 was used to unwrap the interferograms. A detailed description of the adopted SBAS processing workflow is available in Fiaschi et al., (2017). The products derived from the standard DInSAR analysis consisting of geocoded intensity and coherence maps, and differential interferograms are used to check, in particular dates, the displacements and changes in the geophysical properties of the ground surface. They were also used to better assess the possible cause of specific ground failure events.

[TABLE 1]

The processing results were supported by field observations and visual interpretation of optical images. Ancillary data, such as the location of the pumping stations and the faults/fractures data sets, were integrated in the analysis to get an overview of the ground deformation dynamics.

3.2 Optical data sets and derived products

Three data sets derived from space-borne 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 2.

[TABLE 2]

2) LANDSAT and Sentinel-2 imagery were used to monitor the position of the DS shoreline and the vegetation development along the coast from 1973 to 2019. 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 higher 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 the standard deviation. Emphasis was given to the extreme classes corresponding to the appearance of vegetation.

The interpretation of these data sets served for the detection of springs and shallow water flow paths in the emerged lands. 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 provides information about modifications of the underground water circulation close to the shoreline. All these observations were also used to prepare field campaigns.

The building footprints have been digitized manually. The boundaries of the hotels' parcels were derived from the interpretation of the VHR satellite images and compared to the 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. Field surveys served to validate the observations derived from satellites' imagery and to delineate more accurately the areas exposed to geological hazards. The location of each observation was recorded over topographic maps and later on with a GPS system. A geodatabase gathers the whole tracks and waypoints.

Dozens of field surveys were carried out to monitor the development of fissures, landslides and sinkholes. During the last 15 years, the emergence of pictures repositories on the Internet has given access to new original data sources. More and more, the pictures are correctly geo-tagged, which helps to speed up the work of archiving those images.

The geo-tagged images have been collected and archived to allow a multi-temporal analysis in a GIS system. The delineation of affected zones through time relies also on this source of data, and has supported the delineation of hazardous areas inside the cadastral plots. 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 InSAR processing. The SRTM DEM corresponds to the landscape of February 2000 (DS elevation of -413 m), therefore there is no topographic data for the coastal zones that have emerged after that date (DS elevation of -432 m in 2018). Considering the thalwegs delineation with hydrological tools in ArcGIS™, the missing information for the landscape that has emerged after 2000 was created 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 (e.g. Al-Awabdeh, 2015).

The "master-plan development strategy of the Jordan Valley" (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 groundwater resources in the Jordan Valley are extracted for agricultural purposes. The ground deformations related to these extractions are generally localized around the pumping stations and are not related to those resulting from the lowering of the DS level, which affects larger areas along the coastline. The inventory of pumping stations is, therefore, 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 this study, we focused on the exposure to geological hazards (i.e. landslides, sinkholes, subsidence, and rivers' incision) of the DS's tourism infrastructures (e.g. buildings, roads, front beaches, bridges, walls, buildable cadastral plots) created during the last 20 years. Exposure is the first variable that ranks areas in order of priority. Depending on the criteria used to determine this priority, high, medium or low exposure has been considered. The exposure maps are produced by classifying the damage at cadastral plot level based on the combination of field observations, security engineers/employees' testimonies, and remote sensing diachronic results. The assessment of the parcels' exposure includes the spatial extent of the observed damage, the period and frequency at which a particular asset is regularly affected, and its position in respect to critical factors such as the distance from the shoreline. The polygons were drawn manually after a careful analysis of all pieces of evidence. The contribution of the photographic documentation was essential because it provided information not accessible with remote sensing techniques. The damage to the buildings is 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) (Cooper, 2008). A similar approach was successfully applied previously in two 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 APC 'dike 18' (Abou Karaki et al., 2016) one year before the amputation of the affected segment from saltpan SP-0A. The workflow that was used to create the exposure maps is presented in Fig. 3. SAR images are used to generate time-series of ground deformation. A-DInSAR is one of the main techniques used to quantify the changes in the coastal areas. The obtained results are checked during regular field observations. The ground deformations (i.e. subsidence) related to water pumping are excluded from the process, while the ones related to the DS level lowering is used as the main input of the study. All the information is combined and is associated to five cadastral plots in a GIS environment.

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 new springs (prior to the development of vegetation).

The NDVI has been correlated to long-term water stress (e.g. Martin et al., 2005) and should be considered as a measurement of amalgamated plant growth that reflects various plant growth factors (Verhulst and Govaerts, 2010). 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, which may correspond to variations in the salt dissolution processes.

The exposure map of touristic cadastral plots includes a combination of evidences that an ongoing threat is emerging. The main causes of the occurrence of sinkholes, subsidence and landslides are mainly 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. This information can be obtained only by direct borehole measurements, which lack in the study area. For this reason, 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. For other elements some assumptions should be made: 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 observation; roots characteristics of different vegetation can be used to map the water table level at 1 m – 2 m of depth, depending on the type of plants; the subsidence detected with InSAR could occur in areas where the water table presents higher gradient in respect to the surroundings.

This cost-effective approach for the mapping of areas exposed to geohazards, 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 APC network (Parise et al., 2015). The same approach also helped in explaining the phenomena (i.e. sinkholes and strong subsidence) responsible of the destruction of ‘dike 19’.

[FIGURE 3]

4 Results

4.1 Ground deformations derived from A-DInSAR

The processing of the available S-1A/B images with the SBAS approach resulted in a detailed (~15 x 15 m pixels size) vertical velocity map of the entire study area (Fig. 4). In total, it was possible to retrieve the displacement time-series of 52,340 points. The obtained results indicate that all the areas west of the 1959 shoreline (Fig. 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 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. Examples of the displacement time-series extracted at the hotels’ location are presented in Fig. 5. Field observations have confirmed that sinkholes and landslides affect these areas over a distance between 100 to 200 m landwards. Subsidence affects also some areas East of the former 1959 shoreline (yellow and orange areas), 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.

[FIGURE 4]

[FIGURE 5]

4.2 Vegetation dynamics derived from optical imagery

Figures 6 and 7 illustrate the contribution of the vegetation mapping to the identification of areas prone to landslides and sinkholes. Figure 6 displays side by side a major landslide observed with optical imagery and its equivalent using the NDVI index. The vegetation appears in green while the salty-mud is in yellow. The DS is in the lower left corner (dark colour). The growth of Tamarix bushes at the landslide crown underline the presence of seepage zones. Areas covered by reeds are also found in the downstream parts of the landslide.

[FIGURE 6]

The springs are located at the intersection between the top of the water table and the ground surface. They are generally found 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 of the lake. Figure 7 shows the reclassified vegetation change values obtained from the difference between the 2010 and 2017 NDVI maps. The areas characterized by growth of vegetation are in green, while in red are the areas that show vegetation loss. The 18th November 2018, a 120 m wide landslide occurred at the same elevation of four former landslides.

[FIGURE 7]

The largest part of the vegetation loss can be attributed to the development of tourism infrastructure while the vegetation gains to the presence of fresh/brackish water at or close to the surface. Four main areas with major vegetation development where mudslides occurred have been observed in the study area (Fig. 7, white circles). The emergence of springs in the front beach of the hotels could represent a substantial hazard for the stability of the ground and the infrastructure (Fig. 8c). Since early 2016, we observed in the Holiday Inn front beach two distinct places where reeds have developed (Fig. 8d). These areas have been fenced by the security engineers as sinkholes developed some meters upstream.

4.3 Field observations

During the last decade, regular, almost biannually field inspections were carried out to follow and monitor the deteriorations of the DS shore in Sweimeh. All areas show surface deformations reflecting the ongoing subsurface dissolution processes. Cracks are very frequent on land, walls, swimming pools and other man-made structures (Fig. 8). In general, no efforts were made by investors to investigate the causes of the damage 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, while cracks affecting structures with concrete. Most of these cracks could be associated to the subsidence occurring in the area, as measured by SBAS. Some of the monitored infrastructures are affected on two fronts (e.g. Fig. 9): river incision that causes displacement of lateral slopes, and the emergence of springs in the beach areas connected to the development of ground collapses. Heavy engineering work is, in this case, needed to stabilize the river profile and to avoid the undermining of slopes during flash flood events. The strong effects of river incision on the stability of infrastructure are obvious especially on the bridges located hundreds of meters away from the DS shore (Fig. 10).

[FIGURE 8]

[FIGURE 9]

The King Hussein bin Talal convention centre, located between plots B and C (Fig. 4) is a 3-story building 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 recent situation and the repair works done in order to protect the convention centre are showed in Figs. 9a and b. The efforts seem to focus on large scale engineering measures designed to attenuate the erosion effects of flash floods on the slopes. However, field evidence on the front shore highlight the presence of water seepage possibly coming from beneath the centre. On the medium (years) and long (decades) terms, this water flow 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. As above mentioned, the presence of springs is one of the factors that may indicate the possible occurrence of ground instability. Figure 9d illustrates the growth of vegetation around such springs in the front beach of the Holiday Inn. This area has been hit at least three times (September 1999, May 2009, and August 2012) by hectometre-size landslides.

[FIGURE 10]

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 10 shows the extent of the evolution of the damage affecting the western side of the Zara-Ma'in Bridge on the highway between 2012 (renovated bridge), and 2018. Most of the other bridges on the eastern DS highway show advanced signs of deteriorations.

4.4 Exposure maps

Exposure maps were produced for the five main touristic infrastructures located along the DS coastline in Sweimeh (Fig. 11). The colour chart ranges from green to red. It refers to increasing structural damages observed in each plot. During the 1960s, the shoreline in the Holiday Inn plot (Fig. 4a) was in the area now occupied by the main swimming pools. Therefore, it is evident that most of the infrastructures were built on recently exposed areas and are susceptible to be exposed to geohazards. The beach area is affected by landslides and sinkholes since 1999. The beach is constantly worked and repaired to offer the tourists a pristine sandy beach. As a result, the cracks are not clearly visible. The red polygon corresponds to a landslide, while the orange one has fewer observable features. NW of the orange zone, the beach is not affected by the cosmetic work and fissures are apparent. Close to the shoreline, are found several springs of brackish water and areas covered by reeds. In the upstream part of the orange zone, the presence of sinkholes suggests groundwater circulation towards the springs. The part of the hotel next to the beach is marked by a large number of cracks in the pavements (yellow and orange polygons). They are smaller in size and less frequent in respect to the cracks in the beach area. The main part of the hotel has no visible cracks, but the main entrance of the building is subsiding with damage to the walls (in green). The Hilton plot (Fig. 11b) is affected by geohazards on two sides. The beach area (in red) is directly exposed to a landslide having its crown in the upstream part (in orange). Similarly to the Holiday Inn, the beach area is totally covered with sand and regularly worked. During the field surveys, cracks related to strong subsidence were obvious. North of the plot, the cracks were much more visible and extended hundreds of meters northwards, parallel to the shore. In this area, the whole coastal zone is apparently sliding. The obtained InSAR results confirmed these observations. The access road to the beach is located next to the landscaped Wadi Mukheris. This road shows important fissures that indirectly delineate the lack of stability of Wadi Mukheris' northern slope. South of Wadi Mukheris, the Marriott plot (Fig. 11c) is strongly affected by recurrent landslides. The whole beach area is in red-orange, depending on the damage density and size. The red colour corresponds to active landslides, while orange colour to areas where engineers managed to stabilize the hazardous situation. The whole exposed zone corresponds to the steepest emerged part of Wadi Mukheris delta. The Dead Sea Spa (Fig. 11d) presents high number of fissures in its entire area. The beach area shows many cracks and is affected by sinkholes. The entire plot is sliding towards the DS at different paces. The presence of underwater circulation is attested by ground displacements (subsidence and lateral movements), vegetation (reeds), and sinkholes. The beach of the Crowne Plaza (Fig. 11e) presents many cracks and springs of brackish water. The walls separating hanging gardens are either fissured or partially collapsed. The SE part of the plot is also affected by underground water circulation related to Wadi ad Dardur delta. Repeated field investigations suggested that although the river bed has been diverted southwards, groundwater circulation follows the previous direction, prior to the diversion.

[FIGURE 11]

5 Discussions

Before the 1960s, the DS water level was relatively stable through decades (at ~395 m bmsl). 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 DS level started to drop, the groundwater level adapted consequently leading to an increased groundwater discharge. With the movement of the 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. The ground deformations (subsidence) occurring all along the coastline could be explained because of the lateral shift of the interface between the DS brine/fresh water. Investigations carried out in the southern DS in relation to the collapse of APC “dike 18”, have suggested that subsidence could be the result of chemical erosion, while landslides and sinkholes of the mechanical erosion produced by groundwater flows (Abou Karaki et al., 2016).

The results obtained from the SBAS analysis of the S1-A/B SAR images (Fig. 4) show the rates and the spatial distribution of the mean ground deformations along the northeastern DS coastline from 2015 to 2017. The detected ground subsidence extends well beyond the old 1960s’ coastline. We interpreted this outgrowth as a repercussion of the continuous lowering of the DS level over the groundwater discharge several kilometres inland. This landwards extension of the subsidence could be result of a greater permeability of certain zones characterized by an increased density of fractures. This zone co-occurs with the Amman-Hallabat Structure, in which have been observed the presence of frequent fractures (Al-Awabdeh, 2015). The magnitude of the ground deformations decreases with the distance from the shoreline. The zone along the shoreline is the most affected, and the highest intensity generally is found where the water table intersect 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 hotels’ area, and on optical satellite interpretations. As an example, a first landslide occurred in the Holiday Inn 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 (see Fig. 3b of Sirona et al., 2016).

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 data set 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 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 repair works done. Their knowledge, complemented by our own data collection (field observations guided by InSAR deformation maps), has been summarized in the produced 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.

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, 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.

6 Conclusions

In this work, we presented the results obtained from the integration of several different data sets over the Sweimeh area (eastern Dead Sea shore). Thanks to the adopted approach, we were able to map the subsidence occurring along the Dead Sea shoreline and quantify the hazard exposure of five main touristic infrastructure. The results obtained from the analysis of Sentinel-1A/B SAR images with the SBAS approach revealed subsidence rates up to -130 mm/yr. In particular, the infrastructure built on lands that have emerged in the last 40 to 50 years are not only the most affected by subsidence but also exposed to sinkholes and landslides phenomena. The monitoring of natural vegetation growth permits to locate the water sources and partially to deduce the underground flow channels which sinuate close or beneath the hotels. This information is important to predict the occurrence of potential ground failures or underline the areas more vulnerable.

The importance of this work can be estimated with respect to some catastrophic events occurred in 2018: a Jordanian teenager died after falling into a sinkhole in Ghor Al Haditha, south-eastern DS, Jordan. Some months later, South of Sweimeh, one flash flood event killed a group of 21 children and their teachers. A bridge collapsed during the same event. The 18th November, a landslide 120 m wide destroyed a recreation area close to the Holiday In. Bridges and roads are heavily affected during flash-flood periods.

This sequence of events underlines the necessity to consider the study of geological hazards related to the DS level lowering as a priority for the sustainable development of the area. Appropriate measures for risk mitigation should also be taken to avoid further lethal incidents. This is especially true in Sweimeh area, where the exposed population is higher than other places along the DS shore. The mapping of exposure areas at the cadastral parcel level presented in this study is the very first step towards the computation of vulnerability and risk, and the development of an Early Warning System. The exposure maps are a combination of information coming from different sources such as optical and radar data, direct field observations (structural geology), and interviews of security engineers – hotel managers. The approach presented in this paper is very pragmatic but efficient, and its robustness mainly relies on the multi-sources and multi-temporal analysis.

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 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 is a considerable challenge for sustainable development and profitability of major tourism projects.

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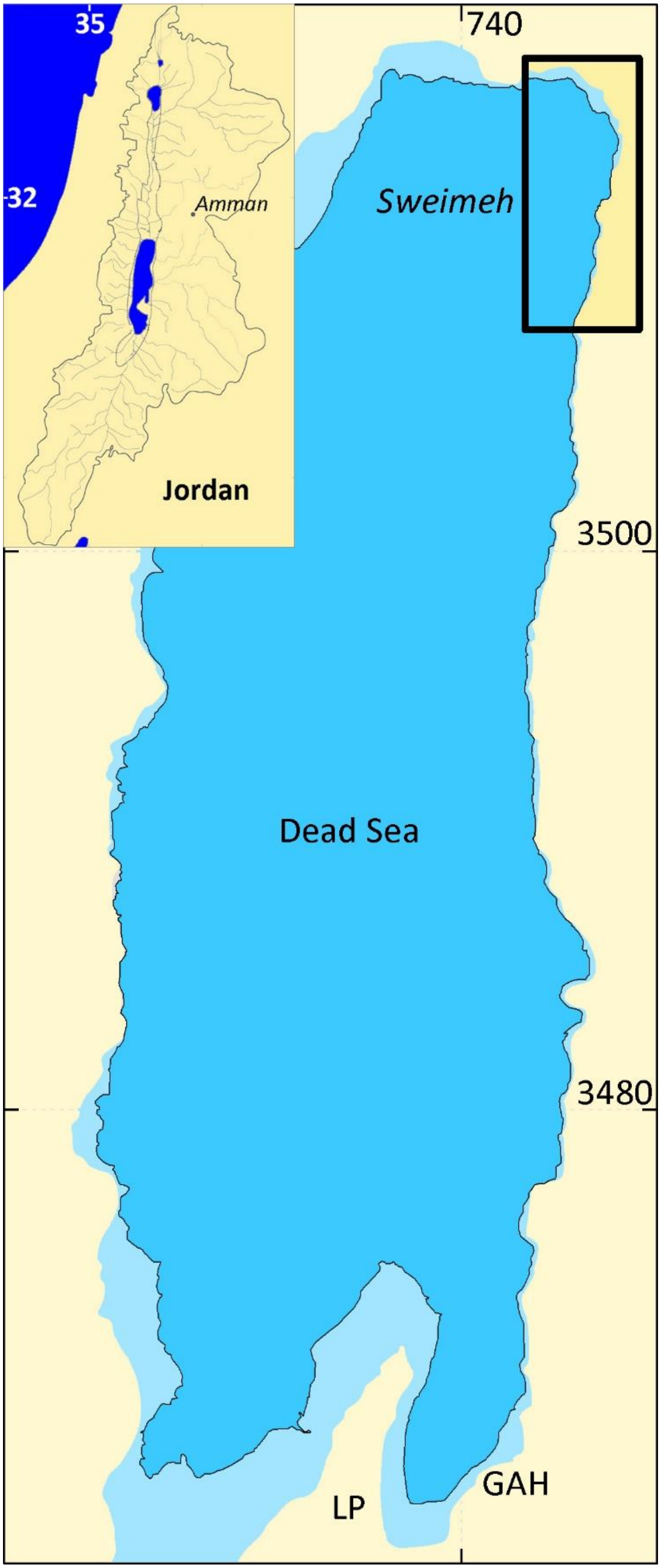
35
32
Amman
Jordan
740
Sweimeh
3500
Dead Sea
3480
GAH
LP

Figure 1. Inset: the Dead Sea (DS) watershed (coordinates in degrees). Main map: location and extent of the Dead Sea. The study area (Sweimeh) is located in the north-eastern part and marked with the black box. The extension of the lake in the 1960s appears in light blue colour. The black line indicates the present-day shoreline (2018). In the figure are also showed the main sinkhole sites: the Lisan Peninsula (LP) and Ghor Al Haditha (GAH) (coordinates in UTM 36 (km), WGS 84).

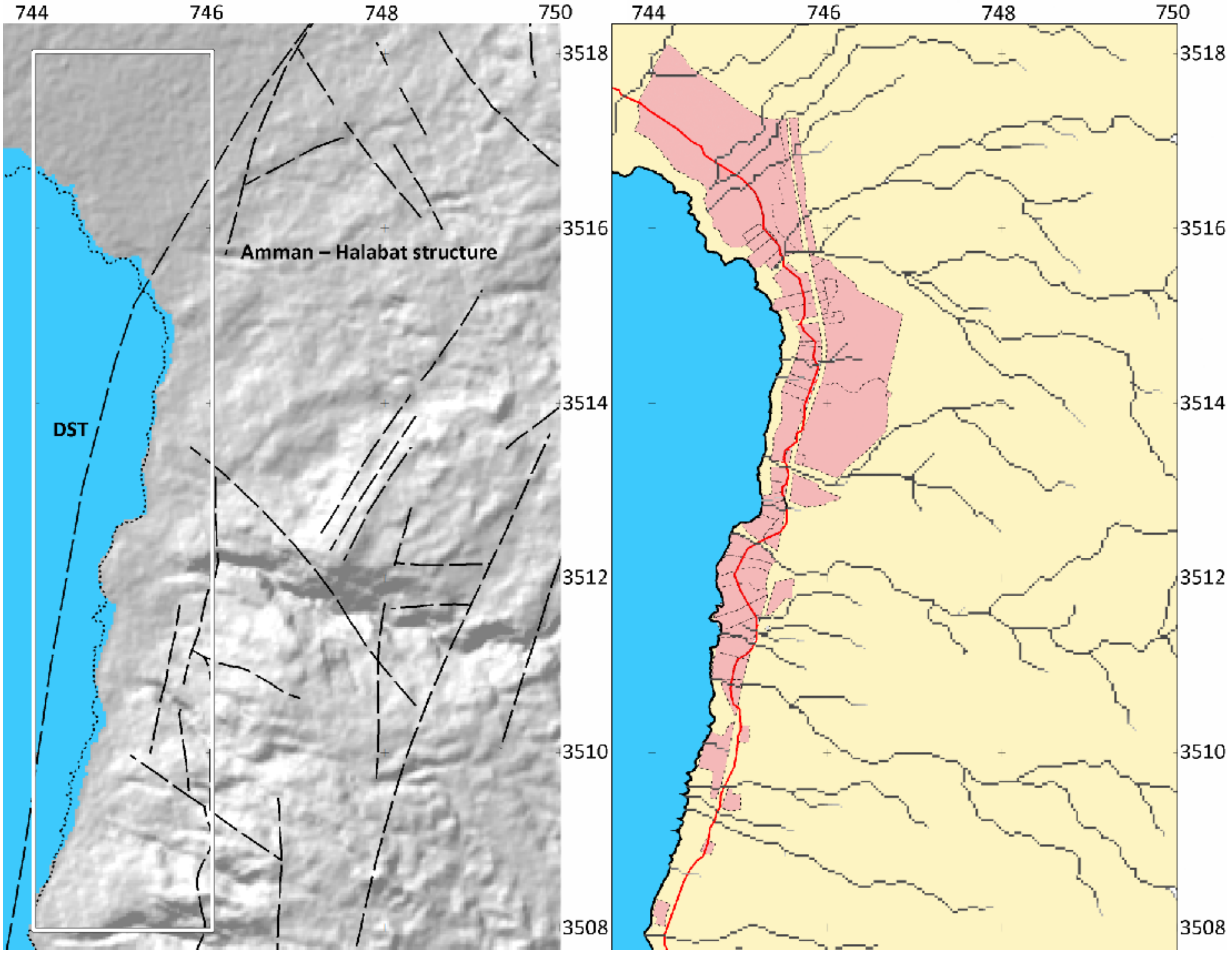

Figure 2. Hydrogeological setting of the Sweimeh area. Coordinates system: UTM 36 (km), WGS84. Left: structural features (from Al-Awabdeh, 2015). The Dead Sea Transform (DST) crosses the area of interest (white rectangle). The black dotted line is the coastline in 2018. The hill shade relief derived from the SRTM Digital Elevation Model shows the coastline in February 2000. Right: the red line shows the coastline in 1959. The pink colour represents the cadastral parcels that are either already built-up or selected for future urban development. The black lines represent the thalwegs network.

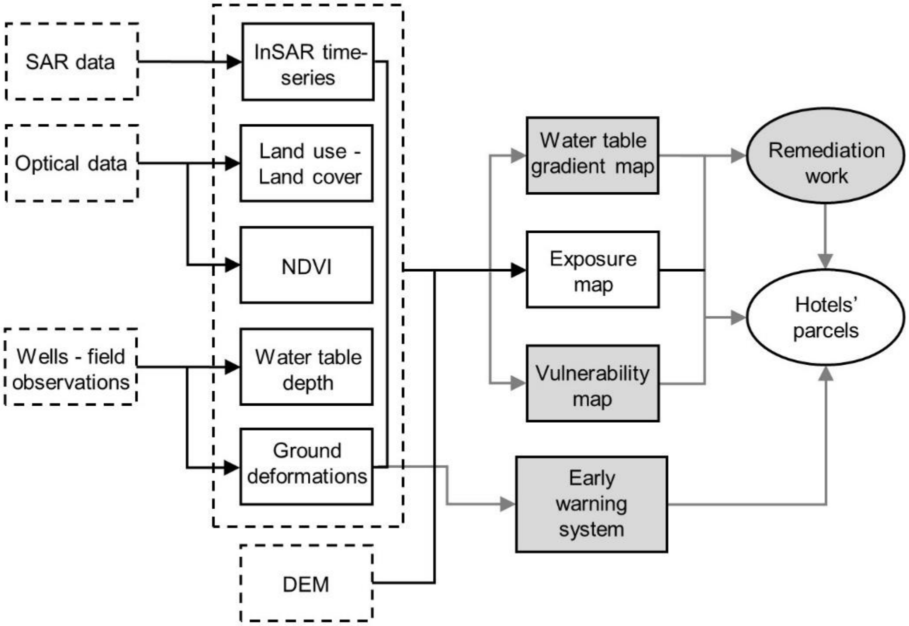

Figure 3. Flow chart of the methodology applied in this research (black colour). Grey colour indicates the next targets: early warning system and water table gradient map to support remediation work.

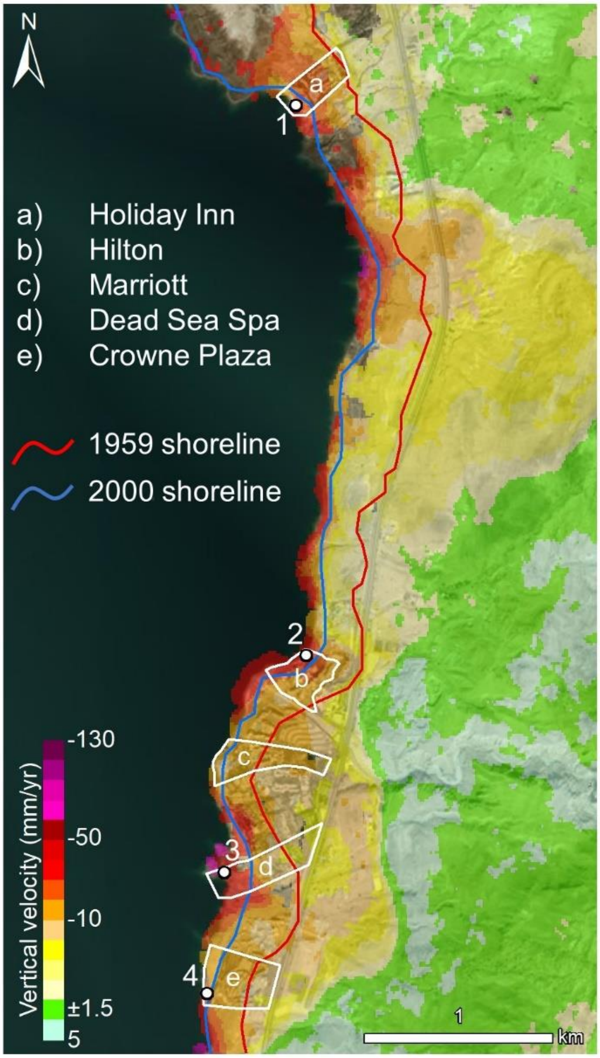

Figure 4. Vertical velocity map of the study area obtained from the SBAS processing of Sentinel-1A/B images. The white dots labelled with numbers are the points select to extract the displacement time-series presented in Fig. 5.

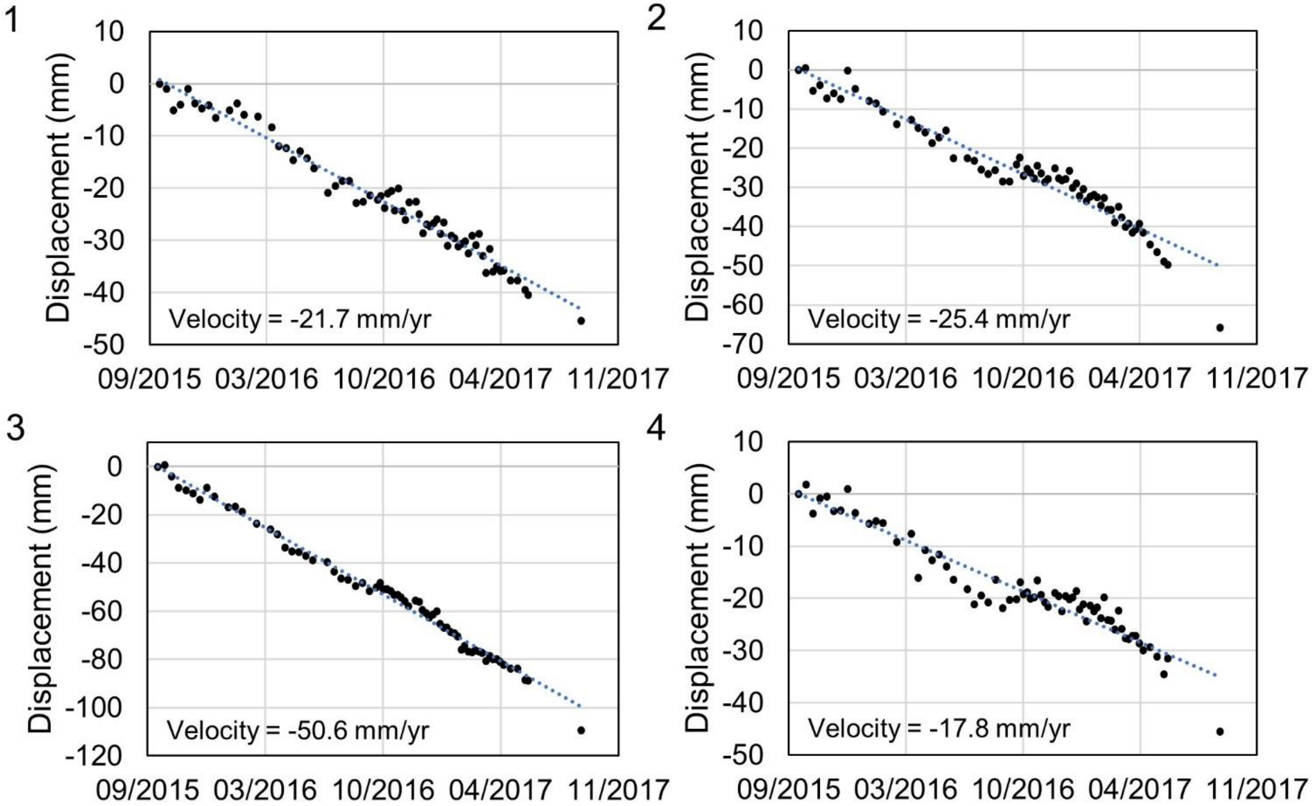

Figure 5. Displacement time-series of four points selected in the hotels' cadastral parcels.

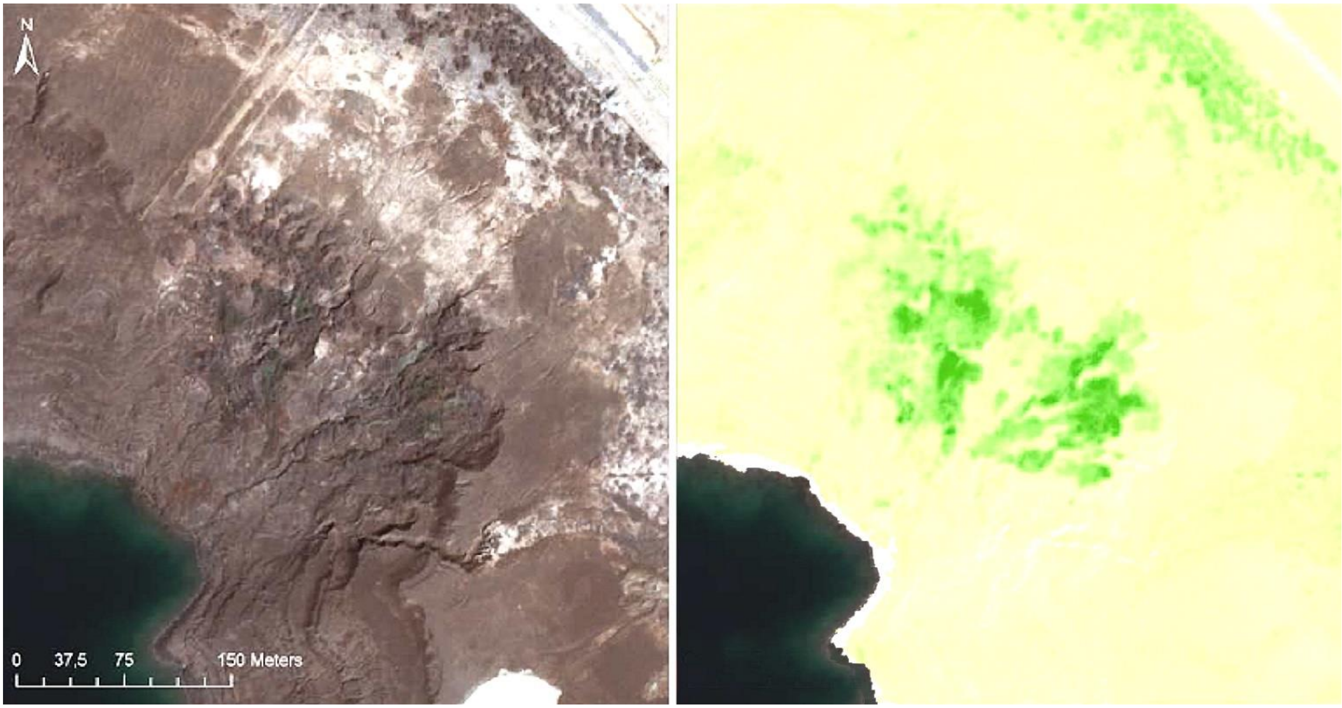

Figure 6. Comparison between optical and NDVI images over a landslide area. Left: optical image (RGB) showing a seepage area. The muddy sediments impregnated with water and salt (white patches) flowed towards the lake and created an amphitheatre. Right: in evidence the vegetation (green) that develops only near the springs.

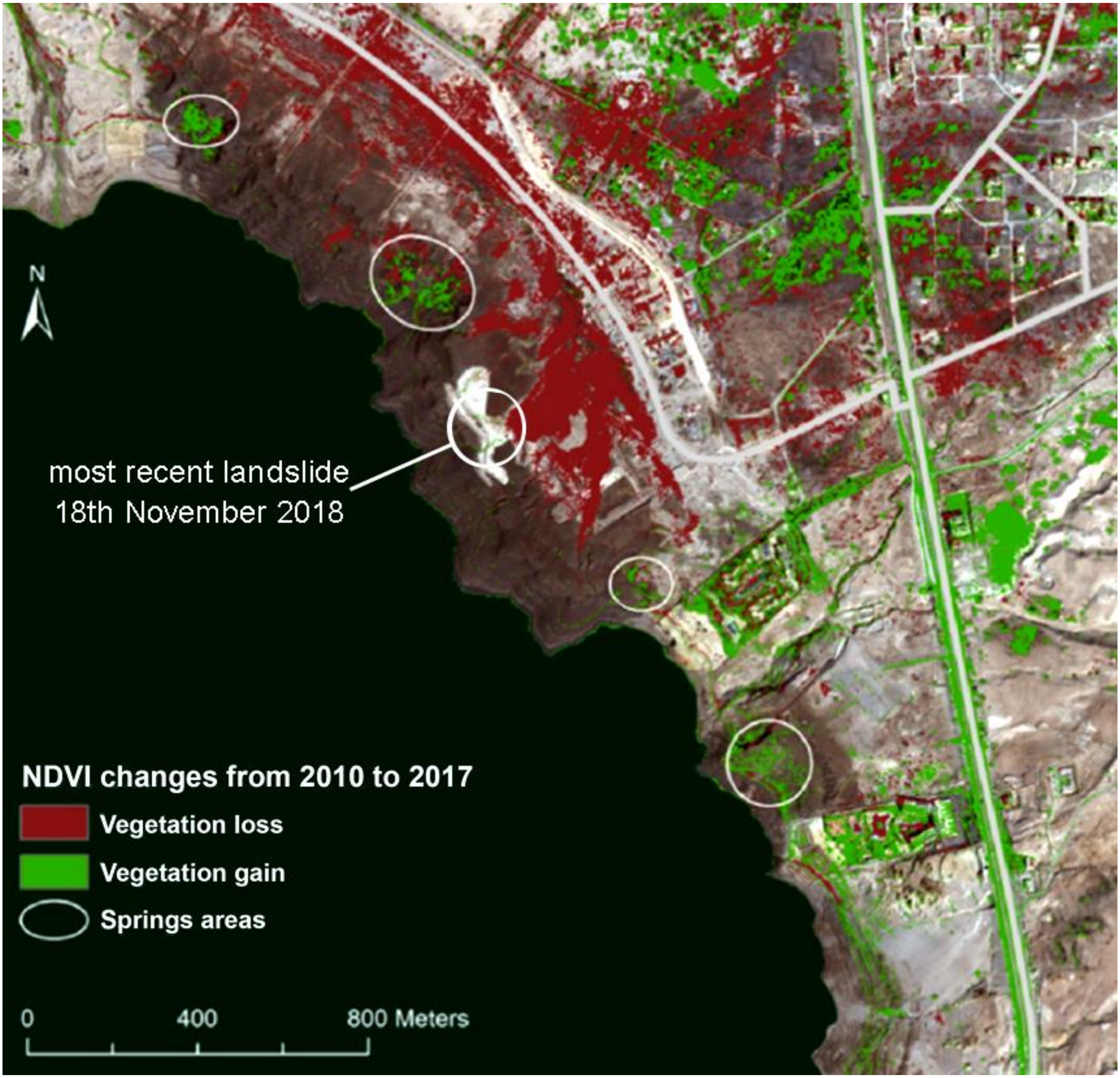

Figure 7. Vegetation change detection map obtained from NDVI difference between 2010 to 2017 in the north-eastern part of the study area. The white circles highlight the areas where new springs appeared in correspondence of vegetation gain along the coastline.

Figure 8. Examples of damage (left) and of quick repair (right) that are common in the front beaches of the hotels along the DS coastline.

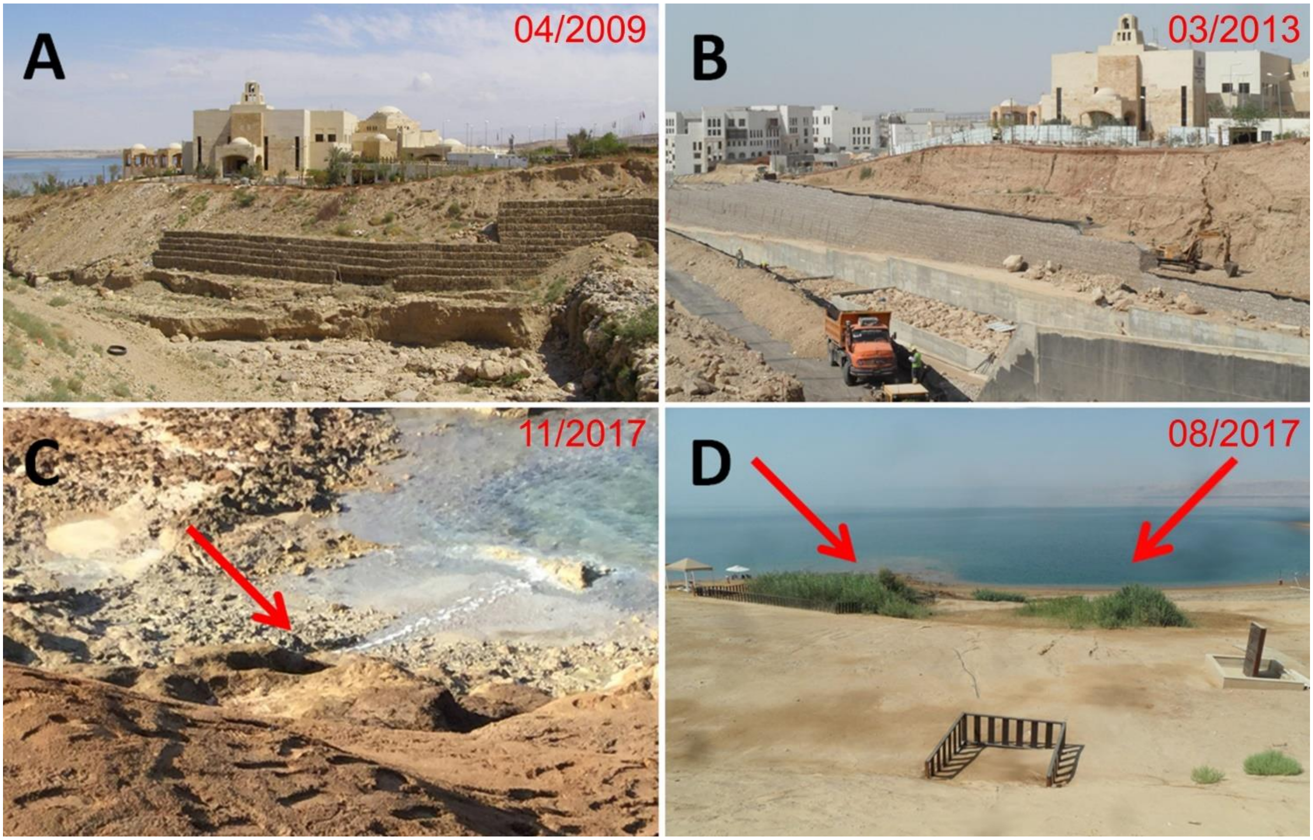

Figure 9. The King Hussein bin Talal convention centre and surrounding areas. a and b: the river next to the conference centre is entrenching at the same pace as the DS level lowering. c and d: below the hotels, underground waters are flowing until reaching the base level. When the flow path remains stable and the water is unsaturated with respect to salt, then vegetation can grow (d).

Figure 10. Example of a bridge along the Dead Sea motorway damaged by progressive erosion of the sediments. All bridges along the DS coast are affected by the rapid incision of the river bed. Each year, the available energy released during erosion process is more important (square function).

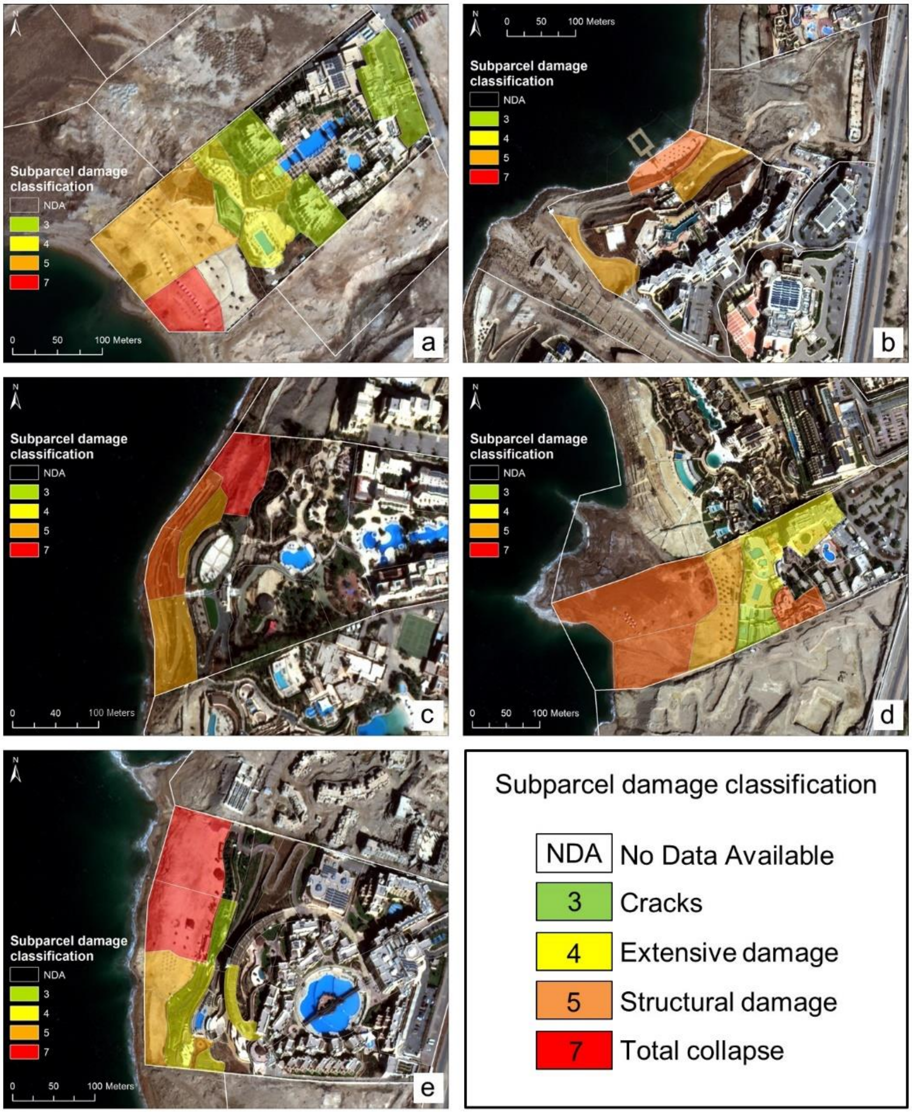

Figure 11. Damage exposure map of five main hotels in the study area. a: Holiday Inn; b: Hilton; c: Marriott; d: Dead Sea Spa; e: Crowne plaza.

Table 1. Specifications of the Sentinel-1A/B images used in this study.

Satellite	Acquisition mode	Band/wavelength (cm)	Revisit time (days)	Native ground resolution (m)	Incidence angle range (degrees)
Sentinel-1A/B	Interferometric Wide Swath (IW)	C/5.6	12/6	~4 x 14 (range and azimuth)	41.33-41.49

Table 2. VHR optical images specifications.

WV-2 VHR (Year)	2017	2011	2010
Collection date	2017-02-19	2011-04-02	2010-06-04
Off-Nadir angle (°)	23	17	15
Panchromatic resolution (m)	0.46 at Nadir, 0.52 at 20° Off-Nadir		
Multispectral resolution (m)	1.84 at Nadir, 2.4 at 20° Off-Nadir		