Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Research Programme
– Short Calls, Final Report –

Lead Applicant Name	Eoghan Holohan
Email	Eoghan.holohan@ucd.ie
Host Organisation name	University College Dublin
Project Title	4D Quantification of Salt-related Sinkhole Development and Migration
Contract Number	2017-sc-002

Date: 19/12/2018

This report covers the period November 1st 2017 to October 31st 2018

2. (a) Project information:

Final project report (*max **2500** words, excluding figures and headings*):

(i) *Progress* of objectives and scientific/engineering targets beyond the state of the art & *methods* used

This research project aimed to advance beyond the state of the art by:

(1) Providing new spatiotemporal and volumetric constraints on the rapid development of a sinkhole population formed by dissolution of rock salt.
(2) Attaining new estimates of bulk dissolution rates and kinetics of rock salt.
(3) Generating new morphometric data to test existing hypothesis for the development of the morphology and size distribution of individual sinkholes - e.g. material property control, stochastic control, etc.
(4) Testing existing hypotheses regarding meteorological, hydrogeological and structural geological controls on spatio-temporal development of sinkhole populations in areas underlain by rock-salt.

The study focussed on the area of Ghor al-Haditha on the eastern shore of the Dead Sea (**Figure 1**). Methods used included: (1) remote sensing and mapping based on high resolution satellite and aerial imagery; and (2) morphological analysis of digital surface models derived from close-range aerial photogrammetric survey datasets. Data generated from these approaches were integrated with field observations, with hydro-chemical data and with historical observations from other sources. The methods, and the main findings as noted below, are described in more detail in a manuscript by Watson et al. that is currently under review at the open-access journal Solid Earth (to download this manuscript, see: https://www.solid-earth-discuss.net/se-2018-105/).

Objective 1 has been addressed in our new map of sinkhole and uvala development at the study area from 1967 to 2017 (**Figure 2**). The map shows a clear migration of sinkhole development in space and time, and so enables us to forecast the areas of greatest hazard in future - i.e. those areas to the north and immediately west (seaward) of the most-recently affected areas (marked in red on Figure 2). In particular, the area adjacent the main north-south highway seems now to be the zone of highest risk, given the value and usage of this major infrastructural artery. The hazard here is not only from sinkhole development, but also from enhanced stream channel erosion immediately downstream of the numerous bridges along the highway.

Objectives 2 and 3 were addressed through the analysis of several high-resolution Digital Surface Models (DSMs) for the area. Watson has so far conducted a morphological analysis of stream channels (e.g. **Figure 3**), and sinkholes (**Figure 4**) to identify (or exclude) potential controlling factors such as material properties, hydrological influx etc. A clear material property control emerges for sinkholes, with high width/depth sinkholes generally characteristic of collapses in alluvial fan sediments, whereas low width/depth sinkholes form in the muddy sediments of the former lake bed. Sinkholes in salt-rich sediments of the former seabed have intermediate width/depth ratios (**Figure 4**). For his MSc thesis, Watson will converted the 3D surface data now assembled to bulk dissolution rates by assuming that (1) the mapped surface features have not changed much since their formation, and (2) that surface volume loss equates to sub-surface volume loss.

Objective 4 is the examination of three factors hypothesised to control the spatio-temporal development of sinkholes in the study area:
(a) intersection of salt deposits in the subsurface with a major, active regional tectonic fault;
(b) variations in fresh groundwater influx to the salt deposits linked to changes in rainfall-related aquifer recharge;
(c) migration of a saltwater-freshwater interface through subsurface salt deposits due to the fall in hydrological base-level.

Regarding (a), our new more temporally extensive data (**Figure 2**) is less consistent with a strong control of regional structures on the sinkholes' spatial distribution than the more temporally restricted data presented by previous authors. In particular, the spatial distribution is far less linear on a sub-km-scale, and hence less consistent with direct fault control, than shown in previous studies. Rather the spatial distribution of sinkholes seems more likely to reflect the initial rather curvilinear distribution of soluble material in the sub surface.

Regarding (b), the new mapping data, integrated with data from old Jordanian reports, has been converted to a first time-series of sinkhole development for the study area (**Figure 5**). This shows an initial exponential growth of the sinkhole population from 1987-2009, followed by a linear growth from 2010-2017. Initial comparison to available metrological data does not show a clear temporal link between marked accelerations in sinkhole development to annual precipitation in the region. This contrasts with findings for recently published sinkhole population growth time-series on the Israeli side.

Regarding (c), the mapping data shows a pronounced seaward migration of sinkhole development with time (**Figure 2**). This qualitatively consistent with theory regarding the impact of the fall of the hydrological base level and is the first time this has been demonstrated for the study area. A more quantitative assessment of the consistency of our observations with hydrological theory is currently underway.

(ii) Implementation (please include any issues with timelines, milestones, management etc. or deviations from the original implementation plan)

Robert Watson was interviewed and recruited as an MSc student shortly after commencement of the project in November 2017. He commenced work in December 2017, and he rapidly achieved the first scientific objectives/milestones of the project. These included the processing and georeferencing of all satellite and aerial imaging data, the compilation of these images within a GIS and the mapping of sinkholes. A preliminary sinkhole map showing spatio-temporal development was produced on schedule by Month 3. Thereafter, Watson not only made his first scientific conference presentation at IGRM, as scheduled, but also presented his work at the EGU General Assembly. In this time, he also wrote his first scientific proposal for data to ESA (see below). For expediency and technical reasons, generation of DSMs from the photogrammetric datasets gathered by Holohan and colleagues in 2015 and 2016 was undertaken by those colleagues at the GFZ-Potsdam. These DSMs were then used by Watson to produce the 3D morphological analysis of the sinkhole population on schedule by Month 9. In addition, Watson expanded the morphological analysis to include other geomorphological features, such as stream channels, the development of which was intertwined with that of the sinkholes and is a hazard in its own right in the area. The joint analysis of fluvial and karstic geomorphological development in the context of the overall base-level fall of the Dead Sea region was submitted as a manuscript to the open-access journal Solid Earth in Month 11, slightly ahead of schedule.

We paused work on the analytical modelling of the freshwater/seawater interface and on preparation of an article for an outreach publication in order to complete the other aspects of the project on schedule. This adjustment was necessitated by Watson being knocked out of action for several weeks in June and July following a very nasty bicycle accident that required hospitalisation and several surgical procedures.

(iii) Outputs (please provide a short description *and* complete the table below)

- Maps of sinkhole spatio-temporal evolution at the study site with estimated current hazard zones.
- 0.2 m resolution digital surface models and 0.2 m resolution orthophotos of the sinkhole area. These have been generated from photogrammetric analysis of images from drone-based aerial surveys in 2015 and 2016 by colleagues in GFZ-Potsdam and analysed by Watson.
- Quantitative morphological analysis of the sinkhole population, and also of the other features and geomorphological processes (such as stream channel incision, alluvial fan growth) in the area, linked to the decline of the Dead Sea. This provides a more complete picture of the hazards in the study area.
- Presentations of results by Watson at IGRM 2018 in Cork, Ireland, at the EGU General Assembly 2018, Vienna, Austria, and at the British Cave Research Association symposium 2018, Bristol, U.K. Presentation of results also by Holohan at the AGU Fall Meeting 2018, San Francisco, USA.
- Manuscript summarising the main project finding submitted for publication in an international, open-access, peer-reviewed journal (Solid Earth).

Task No.	Deliverable description	Planned delivery (as per proposal)	Date of delivery
1	Maps of sinkhole spatio-temporal development from 1970-2018 and current estimated hazard zones	month 3	month 3
2	0.2 m resolution digital surface model and 0.2 m resolution orthophoto of the sinkhole area	month 6	month 6
3	Quantitative morphological analysis of sinkhole population	month 9	month 9
4	Manuscript submitted for peer-review to international, open-access journal (Solid Earth)	month 12	month 11
5	Article submitted to non-peer-reviewed	month 12	month 14

	outreach publication (e.g. 'Geoscientist')		

Publications to date:

[Journal Paper] Watson R. A., Holohan E. P., Al-Halbouni D., Saberi L., Sawarieh A., Closson D., Alrshdan H., Abou Karaki N., Siebert C., Walter T. R., Dahm T., (in review). Sinkholes, stream channels and base-level fall: a 50-year record of spatio-temporal development on the eastern shore of the Dead Sea. *Solid Earth*, URL: https://doi.org/10.5194/se-2018-105

[Conference Publication] Holohan E., Saberi L., Watson R., Al-Halbouni D., Sawarieh A., Closson D., Alrshdan H., Walter T., and Dahm T., Migration of sinkhole development along the eastern shore of the Dead Sea. *EGU General Assembly 2018 – Geophysical Research Abstracts* 20, EGU2018-8701, Vienna, Austria, 13-APR-18. URL: https://meetingorganizer.copernicus.org/EGU2018/EGU2018-8701.pdf

[Conference Publication] Holohan E., Watson R., Al-Halbouni D., Saberi L., Sawarieh A., Closson D., Alrshdan H., Walter T., and Dahm T., Coastal Landscape Evolution in Response to Rapid Base-level Fall at a Hypersaline Lake: a Case Study of Ghor al-Haditha, Dead Sea, Jordan. *AGU Fall Meeting 2018 – Abstract Nr. EP52D-27*, San Francisco, USA, 14-DEC-18. URL: https://agu.confex.com/agu/fm18/meetingapp.cgi/Paper/430785

4. Data/outputs submitted with final report *(please list the documents, presentations, datasets etc. submitted with this report)*

a. Manuscript submitted for peer-review to Solid Earth
b. Presentation by Watson at IGRM 2018
c. Presentation by Watson at EGU General Assembly 2018
d. Presentation by Watson at BCRA Symposium 2018
e. Shapefiles of sinkhole and uvala mapping
f. Morphometric data for mapped sinkholes

SUPPLEMENTARY MATERIAL

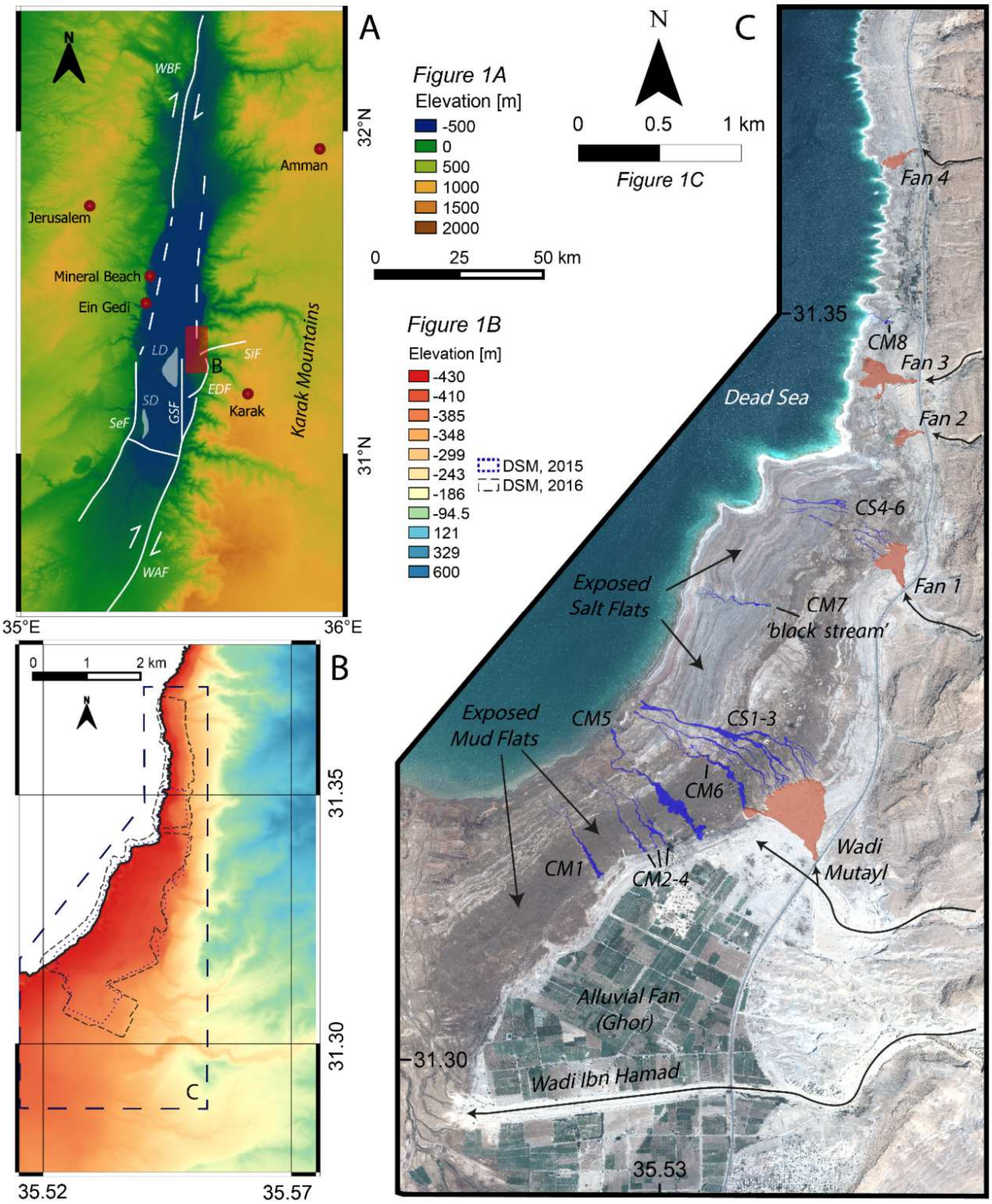

Figure 1: Overview of the Ghor al-Haditha study area. **(A)** JAXA 30m Digital Elevation Model (DEM) of the Dead Sea study area, showing the regional tectonic regime. WBF: Western Boundary Fault; SiF: Siwaqa Fault; LD: Lisan Diapir; EDF: Ed Dhira Flexure; GSF: Ghor Safi Fault; SD: Sedom Diapir; SeF: Sedom Fault; WAF: Wadi Araba Fault. **(B)** JAXA 30m DEM showing relief in the study area, as highlighted in red in (A), along with the footprints of the 2015 and 2016 drone and field surveys. **(C)** Pleiades 2017 satellite image of the study area showing main hydrological and geomorphic features.

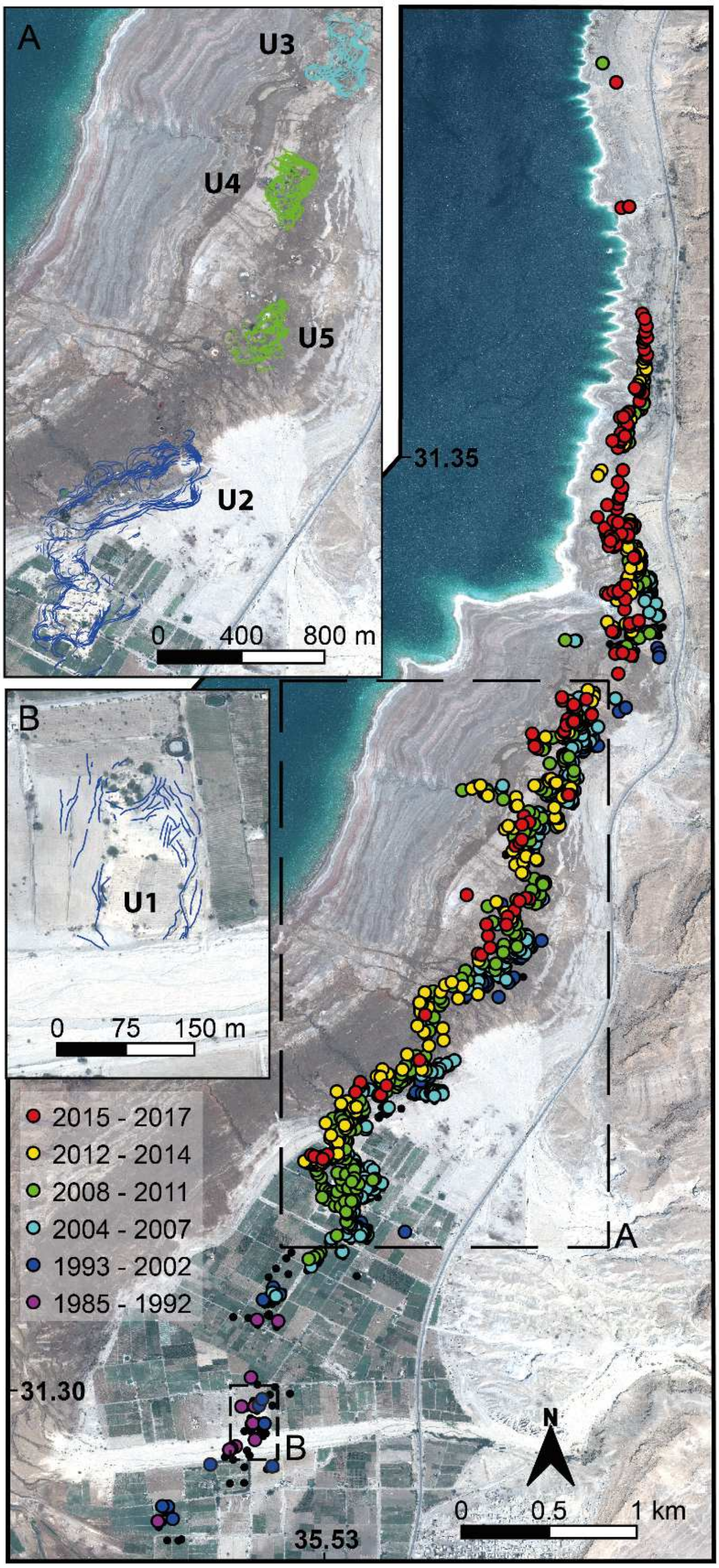

Figure 2: Spatio-temporal development of sinkholes at Ghor al-Haditha in Jordan, as mapped from satellite and aerial imagery. Each sinkhole is colour-coded by year of first sighting in time intervals as labelled. Base image is a pansharpened Pleiades image acquired in April 2017. Smaller black dots are sinkholes that were mapped prior to 2009 by other sources but are not visible in our imagery (mainly because of infilling of those holes by farmers). Insets A and B show the larger-scale depressions ('Uvalas'), as denoted by mapped ground cracks and fractures. For clarity, all fractures for each depression are colour-coded by year of first sighting of any fractures related to that depression. In detail, the fracture formation ages in each large-scale depression span a greater range than shown here.

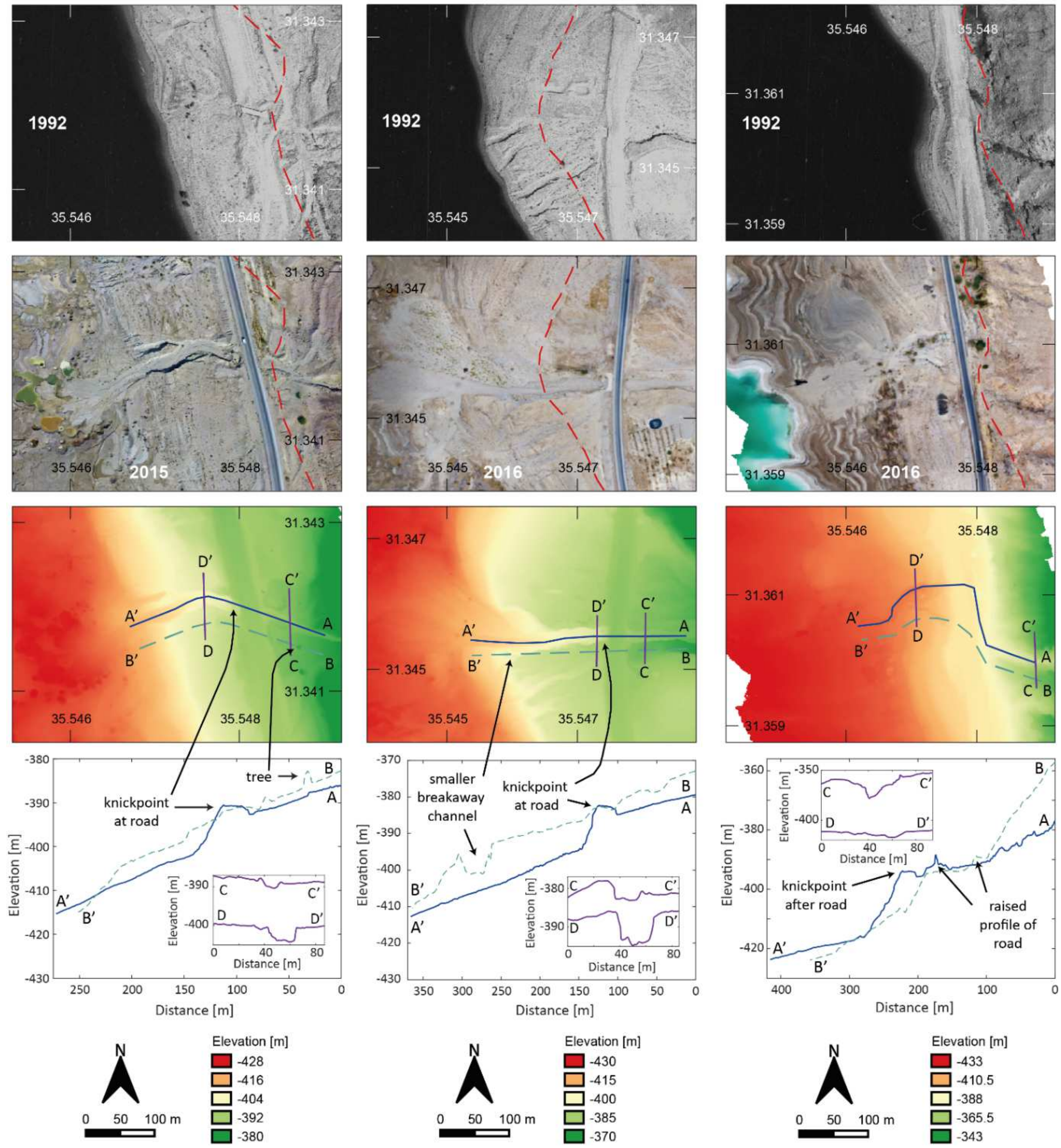

Figure 3: Alluvial channel incision and fan growth proximal to the Dead Sea highway [Jordan Valley Highway 65]. **Top row:** aerial imagery from 1992, taken during the road construction. The dashed red line is the 1967 shoreline. **Second row:** orthophotos from the 2015 (fan 2, fan 3) and 2016 (fan 4) photogrammetric surveys. The channels incise into the old alluvial fan deposits, with fresh deposition of fan material onto the old lake bed. Older alluvial fan deposits appear darker grey in the orthophoto, whereas fresh deposits are lighter coloured. **Third row:** DSMs derived from respective photogrammetric surveys. **Bottom row:** topographic profiles along the channels (A-A’) and along the non-incised fan adjacent the channel (B-B’). Also shown are profiles immediately upstream (C-C’) and downstream (D-D’) of the road bridges.

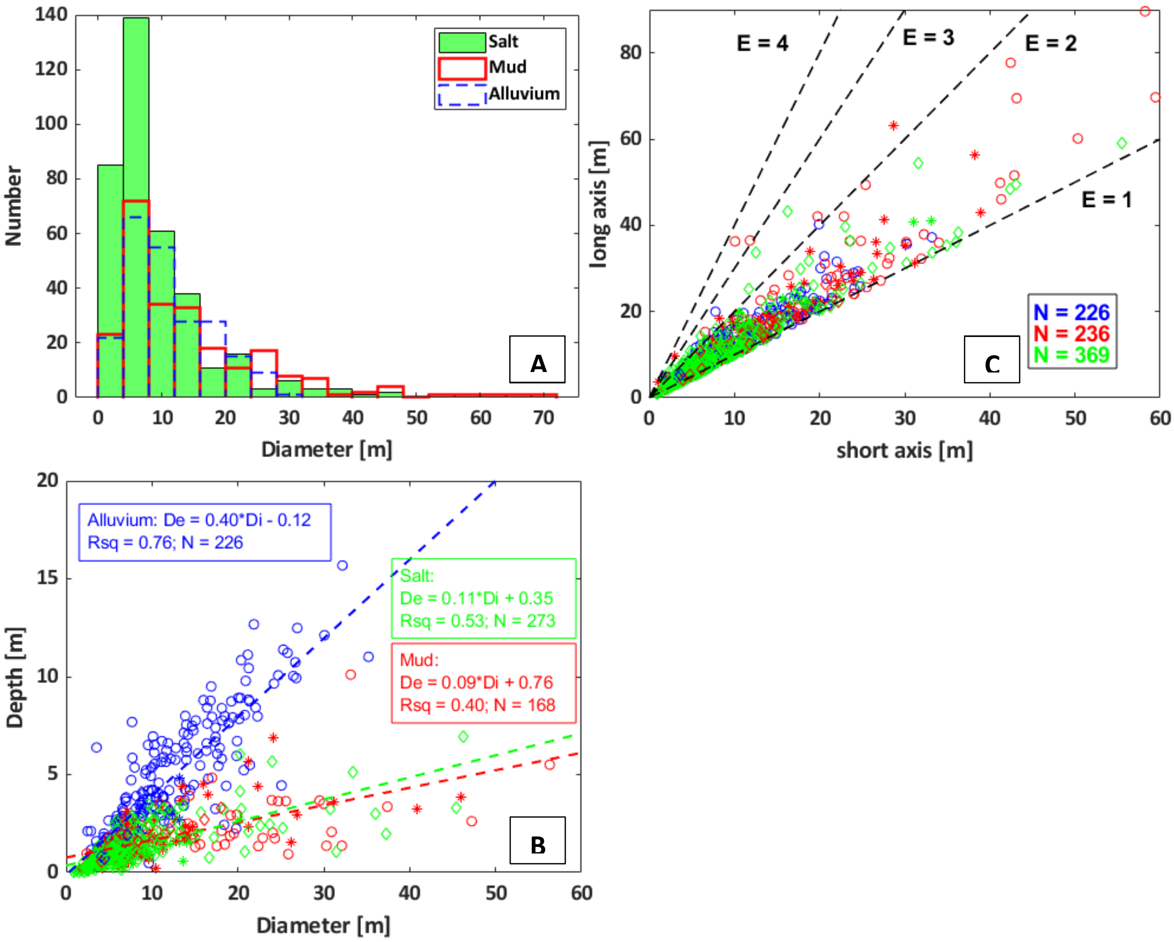

Figure 4: Morphological characteristics of the sinkhole population developed at Ghor Al-Haditha in various sedimentary materials. **(A)** Number of holes binned according to average diameter, **(B)** the relationship between depth and diameter, and **(C)** plan-view eccentricity (longest/shortest diameter). The total number of holes analysed is 226 in the alluvium, 236 in the mud-dominated lacustrine deposits ('mud') and 369 in the salt-dominated deposits ('salt'). Water-filled holes were excluded from the depth/diameter analysis. The depth-diameter plot presents the maximum elevation difference between the rim and the bottom of each sinkhole.

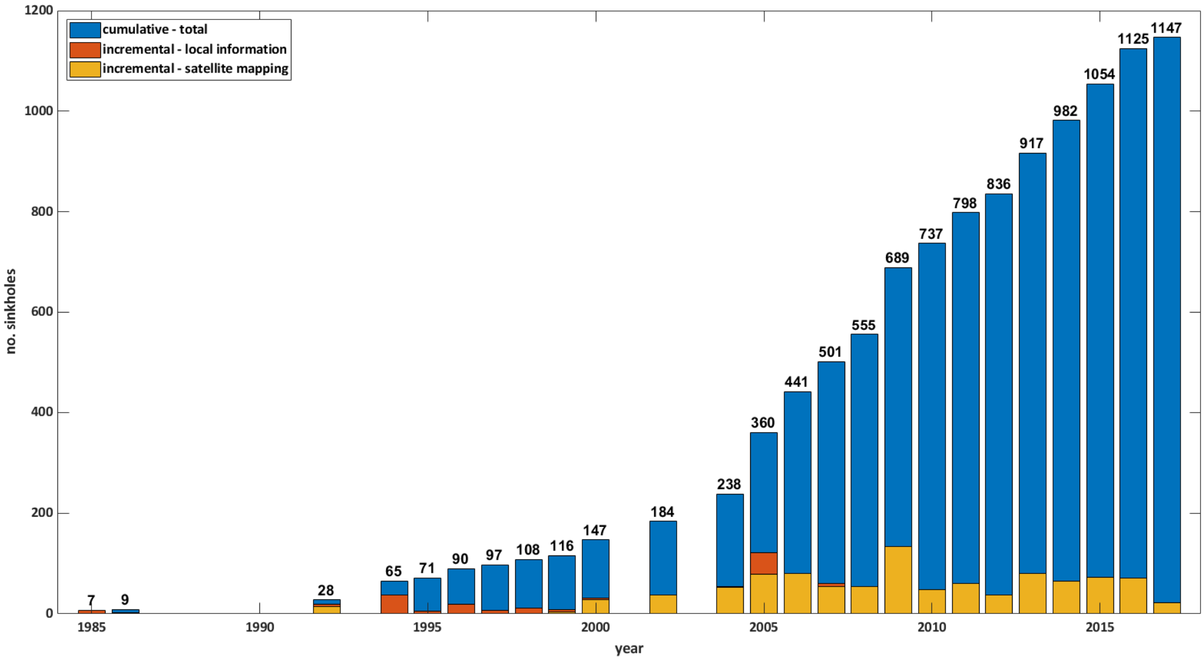

Figure 5: Sinkhole population growth with time in the Ghor al-Haditha study area. 'Local information' constitutes depressions noted in field surveys along with information provided by farmers on sinkholes that were filled in before they were mapped. The total number of sinkholes mapped from satellite imagery alone is 996. The year 2017 appears to have a reduced number of new holes: this is a sampling artefact as there is only a four-month time interval between the 2016 orthophoto and the 2017 satellite image.