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Integrating geomorphological mapping, InSAR, GPR and trenching for the identification and investigation of buried sinkholes in the mantled evaporite karst of the Ebro Valley (NE Spain)

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The first and most important step in sinkhole hazard analysis is the construction of a cartographic sinkhole inventory. The effectiveness of the mitigation measures and the reliability of the susceptibility and hazard maps will depend on the completeness and accuracy of the sinkhole inventories on which they are based. Sinkhole data bases preferably should include information on the following aspects: (1) Precise location of the sinkholes edges. (2) Morphometric parameters. (3) Geomorphological and hydrological context. (4) Genetic type; that is subsidence mechanisms and material affected by subsidence. (5) Chronology; this information is essential to calculate probability of occurrence values. (6) Active or inactive character. (7) Kinematical regime (gradual, episodic or mixed). (8) Current and/or long-term subsidence rates. (9) Evolution of the subsidence and its relationship with causal factors. Sinkholes are generally mapped using conventional geomorphological methods like aerial photographs, topographic maps and field surveys. However, the usefulness of these methods may be limited in areas where the geomorphic expression of sinkholes has been obliterated by natural processes or anthropogenic fill. Additionally, gaining data on some of the practical aspects indicated above requires the application of other techniques.

In this contribution we present the main findings learnt through the construction of a sinkhole inventory in a terrace of the Ebro River valley (NE Spain). The study area covers around 27.5 ha and is located west of Zaragoza city. The bedrock consists of subhorizontal evaporites including gypsum, halite and glauberite. The terrace is situated at 7-10 m above the channel and the alluvium, 10-30 m thick, is composed of unconsolidated gravels and subordinate fines. Previous studies carried out in this sector of the valley reveal that: (1) Three main types of sinkholes may be differentiated: cover collapse, cover and bedrock collapse, and cover and bedrock sagging. (2) Around 70% of the sinkholes have been filled by man-made ground. (3) Subsidence has caused severe damage to many human structures, primarily due to the ongoing activity of pre-existing buried sinkholes. Consequently, the identification of sinkholes is the key for preventive planning and the delineation of the main risk areas. A total of eleven sinkholes (S1-S11) covering around 20% of the study area were mapped. Six of the sinkholes were buried and the largest one (S8), which occupies approximately 35,500 m2, partially coincides with the area previously selected for the construction of a housing state.

The investigation was developed in three main phases. A preliminary sinkhole map was produced in phase I using: (a) aerial photographs and satellite images from different dates (1927, 1957, 1984, 2003, 2006, 2007), (b) detailed topographical maps from 1969 (1:2000) and 1971-73 (1:1000) with contour intervals of 1 m, (c) thorough field surveys including interviews to local people and inspection to human structures, and (d) radar interferometry. Deformation measurements were obtained from 54 interferograms generated by means of the Stable Point Network technique with 23 ENVISAT images acquired from May 2003 to July 2008. The InSAR analysis provides data on the temporal evolution of the subsidence (magnitude and rate) for coherent 20 m-sized pixels. During phase II, 26 GPR profiles with a total length of 2,290 m were conducted using a 400 MHz antenna. In phase III, 13 backhoe trenches up to 2.8 m deep and totalling 323 m were investigated following the methodology commonly used in paleoseismological studies. Two samples were obtained for radiocarbon dating in a trench dug at the margin of sinkhole S8.

The aerial photographs, specially the stereoscopic images taken in 1957, were the most useful tool for the identification of buried sinkholes. They allowed us the detection of 9 sinkholes out of 11. The topographical maps depict 7 of the inventoried sinkholes. Field surveys through the identification of damage to structures and accounts from local people provided clues on the location of one of the sinkholes not detected with aerial photographs and topographic maps. The InSAR technique was instrumental in discovering an additional sinkhole and provided deformation data for a number of pixels in 2 sinkholes; subsidence rates range from 6.5 to 17.3 mm/yr. The main limitation of this technique was that it provided subsidence data for a quite limited number of pixels, mainly roads and buildings. This was mainly due to the lack of coherence in the irrigated crop fields that occupy great part of the area. The main contributions of the GPR profiles were: (1) Revealing the precise limits and internal structure (subsidence mechanism) of some sinkholes. (2) Ruling out areas initially considered as probable sinkholes. (3) Identifying the most adequate sites for the excavation of trenches. Some GPR profiles showed tilted reflectors that were demonstrated to be artefacts via trenching. The trenching technique helped us to gain practical data on some sinkholes including the precise location of their edges, the internal structure and subsidence mechanism. Deformation evidence observed in the trenches include: normal faults, keystone grabens, extensional fissures, tilted strata, a monoclinal flexure and natural and artificial sinkhole fills wedging out towards the margins of the depressions. The charcoal samples collected in sinkhole S8 at 200 and 140 cm below the surface yielded conventional AMS radiocarbon ages of 2010$\pm$35 yr BP (1924-1995 cal. yr BP, CALIB 5.1.0) and 1685$\pm$30 yr BP (1542-1614 cal. yr BP), respectively. These values indicate a mean subsidence rate for the last two millennia of ca. 1 mm/yr at this site. The InSAR data provides subsidence rates of 11.3 and 6.5 mm/yr in other points of this large sinkhole. A very important advantage of the trenches dug in sinkhole S8 is that they allowed the planners to virtually “put their eyes” on the failure planes that define the margins of the sinkholes, providing unequivocal evidence for the existence of this buried active sinkhole.