Integrating geomorphological mapping, trenching, InSAR and GPR for the identification and characterization of sinkholes: a review and application in the mantled evaporite karst of the Ebro Valley (NE Spain)

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Abstract

This contribution illustrates the advantages of integrating conventional geomorphological methods with InSAR, ground penetrating radar and trenching for sinkhole mapping and characterization in a mantled evaporite karst area, where a significant proportion of the karstic depressions have been obliterated by artificial fills. The main practical aim of the investigation was to elucidate whether buried sinkholes overlap the areas planned for the construction of buildings and services, in order to apply a preventive planning strategy. Old aerial photographs and detailed topographic maps were the most useful sources of information for the identification of sinkholes and helped to obtain information on their chronology, either a minimum age or bracketing dates. The InSAR technique provided subsidence rate values ranging from 4.4 to 17.3 mm/yr consistent with the spatial distribution of the mapped sinkholes. This quantitative deformation data helped corroborating independently the existence of active buried sinkholes and improving the delineation of their limits. The GPR profiles contributed to the precise location of sinkhole edges, provided information on the geometry of buried sinkholes and deformation structures and helped to site trenches and to rule out the existence of sinkholes in particular areas. The main input derived from the trenches includes: (1) Confirming or ruling out anomalies of the GPR profiles attributable to subsidence. (2) Precise location of the edge of some filled sinkholes. (3) Information on subsidence mechanisms recorded by various deformation structures and cumulative subsidence magnitude. (4) Calculating minimum long-term subsidence rates using radiocarbon dates obtained from deformed sinkhole deposits. (5) Unequivocal evidence of active subsidence in areas assigned for the construction of buildings.

Keywords: sinkhole inventory, trenching, InSAR, ground penetrating radar, subsidence rates

1. Introduction

The most important step in sinkhole hazard analysis is the construction of a comprehensive sinkhole cartographic inventory. The reliability of sinkhole susceptibility and hazard maps and the effectiveness of the mitigation measures depend largely on the completeness, accuracy and representativeness of the sinkhole inventories on which they are based (Galve et al., 2009a, b; Gutiérrez, 2010). Sinkhole data bases constructed for planning purposes should preferably include information on the following aspects: (1) Precise location of the limits of the sinkholes and the underlying subsidence structures. This is essential to define accurately the unstable areas, including a setback distance around the sinkholes (Zhou and Beck, 2008). It is important to bear in mind that the subsidence structures and the sectors affected by settlement may cover a larger area than the mapped topographic depressions (i.e. Gutiérrez et al., 2009). (2) Morphometric parameters. These data constitute the basis on which to analyse the magnitude and frequency relationships of sinkholes, of great importance for hazard assessment. (3) Geological, geomorphological and hydrological setting. A good understanding of the local and regional geological context may provide clues on the causal factors and relative chronology of the sinkholes. (4) Genetic type; that is subsidence mechanisms and material affected by subsidence (Williams, 2004; Beck, 2005; Waltham et al., 2005; Gutiérrez et al., 2008a). This is a crucial aspect since the subsidence mechanism determines the applicability and effectiveness of different corrective measures and the capability of the sinkholes to cause damage. Catastrophic collapse, unlike progressive sagging, may lead to human life losses. (5) Chronology, either relative or numerical ages. The latter is indispensable to calculate rates of sinkhole occurrence and hazard estimates in terms of spatial and temporal probability. (6) Active or inactive character. This distinction may be determined through the identification of fresh morphological features and deformed human structures, comparing aerial photographs of different dates and from accounts provided by local people. However, in many cases it is necessary to apply geodetic measurements that generally cover a limited temporal window. Additionally, it may be difficult to define the limit between active and inactive sinkholes; for example the maximum age of the most recent displacement episode for a sinkhole to be considered as active. (7) Kinematical regime (gradual, episodic or mixed). This type of information may be obtained studying the stratigraphy and structure of the sinkholes (Gutiérrez et al., 2008b, 2009) and from relatively long geodetic records. (8) Current and long-term subsidence rates. Contemporaneous subsidence rates may be obtained applying geodetic methods and using deformed structural markers of known age. The calculation of long-term subsidence rates requires the analysis of the sinkhole structure and deposits and the application of geochronological methods.

Sinkholes are commonly mapped using conventional geomorphological methods like aerial photographs, topographic maps, DEMs and field surveys. However, the effectiveness of this approach may be quite 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 aforementioned practical aspects requires the application of other techniques like those presented below.

Synthetic Aperture Radar Interferometry (InSAR) is a geodetic method that may be applied to measure the displacement of the ground surface using the phase difference between two radar acquisitions (Massonet and Feigl, 1998; Rott, 2009). Although levelling is an accurate technique for subsidence monitoring, it has significant drawbacks (Ketelaar, 2009): (1) It provides deformation data for a limited number of points. (2) It requires time-consuming field work. (3) It is expensive when applied to extensive areas and/or during long periods of time. Conversely, InSAR, under favourable conditions, allows the measurement of subcentimetric deformation occurring over time spans of days or years, covering extensive areas with a high temporal and spatial resolution and without the need of conducting field work. Moreover, interferometry may be applied to obtain retrospective deformation values using radar scenes from historical satellite archives. The main limitations of the InSAR technique are: (1) The errors introduced by atmospheric artefacts due to the microwave propagation conditions (e.g., vapour content) and the troposphere heterogeneities between the different image acquisitions. (2) The loss of coherence due to decorrelation in agricultural fields and vegetated areas (Ferretti et al., 2001, Hanssen, 2001; Castañeda et al., 2010). For this reason, the areas with human structures and rock outcrops are generally the most favourable for the application of this technique. Removing the atmospheric phase component can be optimized using advanced techniques which process multiple interferograms derived from a large set of SAR images, allowing us to generate deformation time series to study the temporal evolution of the detected displacements. These techniques are based on the signal of detected scatters using as selection criteria the multilook coherence or the amplitude stability (Ferretti et al., 2000a, 2001; Hooper et al., 2007; Ketelaar, 2009).

Radar interferometry has great potential in the study of geomorphic processes that involve the deformation of the ground surface (Rott, 2009), including dissolution-induced subsidence. The development of advanced techniques and the launching of new SAR missions capable of acquiring images with higher temporal frequency and spatial resolution will partially overcome some of the problems inherent to the sinkhole phenomena, like the limited size of the targets. A significant part of the studies on the application of the InSAR technique to the study of sinkholes have been developed in the Dead Sea coasts of Israel and Jordan. Here, the rapid human-induced decline in the lake level has propitiated the circulation of fresh water in contact with salt deposits, resulting in the continuous generation of sinkholes (Yechieli et al., 2006). Baer et al. (2002) measured subsidence rates ranging between 5 and 20 mm/yr in large shallow depressions attributed to acquitard consolidation induced by the lowering of the water table. In this sector of the Dead Sea coast collapse sinkholes tend to form alignments associated with these large depressions, being the spatial distribution of both types of subsidence features controlled by concealed Quaternary faults (Abelson et al., 2003). Closson et al. (2003, 2005), using ERS images acquired from 1993 to 1999, measured subsidence rates as high as 24 mm/yr in an area where a dike of a salt evaporation pan collapsed in 2000. This work suggests that the InSAR technique may be useful for monitoring vulnerable structures (dams, high-speed railways) and the anticipation of catastrophic collapse sinkholes through the detection of precursory displacements. More recentely, Closson et al. (2010), based on InSAR-derived deformation time series suggest that earthquake shaking and probably the coseismic reactivation of faults play a significant role in the development of sinkholes in the emerged Lynch Strait of the Dead Sea. Ferretti et al. (2000b, 2004) identified a gradual subsidence preceding a catastrophic collapse sinkhole that caused the destruction of several buildings in

Camaiore, Italy. Al-Fares (2005), working in SE Nevada, measured subsidence rates of 3-5 mm/yr in the surroundings of a large collapse that forms part of a sinkhole cluster developed in a mantled carbonate karst. Paine et al. (2009), working in the Delaware Basin, Texas, tested the InSAR technique in an area where there are two large collapse sinkholes (Wink Sink 1 and Wink Sink 2) related to the dissolution of a deep salt formation, induced by oil exploitation boreholes. The authors identified three sectors affected by settlement with diameters ranging from 300 to 850 m and with subsidence rates up to 30 cm/yr. The subsidence rates measured by these authors are one order of magnitude higher that those of the rest of the reviewed papers. One of the subsiding areas surrounds the Wink Sink 1, whereas the others are located close to Wink Sink 2. Castañeda et al. (2009a) analysed the possibilities and limitations of the SBAS (Small Baseline Subset) interferometric technique to the study of sinkholes in the Ebro Valley, NE Spain. These authors used 27 ERS-1 and ERS-2 images with a pixel size of 90 x 90 m acquired over a period of about 5 years (July 1995-December 2000). The main findings of this work include: (1) Deformation values were measured in only 5-10% of the known active sinkholes. This limitation is mainly attributed to the lack of coherence in crop fields and the low spatial resolution of the deformation maps. Movements at subpixel scale result in decorrelation (Zebker and Villasenor, 1992). (2) Most of the detected active subsidence areas correspond to human structures built on artificially filled sinkholes. (3) The interferometric study, although it overlooked a significant proportion of the areas affected by subsidence, complements the geomorphological studies providing valuable quantitative deformation data.

The use of the ground penetrating radar (GPR), as non destructive technique to analyse the subsoil, has shown an important development during the last decades. This advance has been largely due to the capability of the technique to investigate environmental and engineering problems (Mellet, 1995). As an example, GPR was used to detect termite nests (voids) inside dikes and earth dams in China (Xu et al., 2010), obtaining satisfactory results. GPR allows the acquiring of information on the subsoil from the response of the materials to high frequency electromagnetic radio waves emitted by an antenna. The receiving antenna records in a radargram the signal reflected at boundaries with different dielectric constants (i.e. stratigraphic contacts, failure planes, cavities, water table). In the last decade the GPR has been applied in a wide variety of geomorphological investigation topics, such as landslides (Sass et al., 2008), moraine deposits (Sadura et al., 2006), and dunes (Girardi and Davis, 2010). However, one the most extended applications of GPR has been the detection of subsurface cavities and deformation structures.

The quality of the results obtained by means of GPR depends on the characteristics of the subsurface materials and our ability to site the profiles in the most favourable sectors, which is mainly a function of our knowledge of the local geomorphology and geology. The main performance limitations of the technique include: (1) Relatively low penetration, conditioned by the electrical conductivity of the ground materials and the frequency of the radiated energy. Higher frequency waves have lower penetration but give better resolution. As the electrical conductivity of the ground increases, the penetration depth decreases. Clayey terrains and wet or salt-contaminated soils dissipate the electromagnetic energy more rapidly, causing a loss of signal at depth (Schrott and Sass, 2008). (2) The signal may be masked by the presence of external electromagnetic fields. GPR also offers important advantages: (1) It is a non destructive method. (2) Data acquisition is relatively fast and the results may be examined directly in the field. (3) Reflectors may reproduce precisely the geometry of geological features (i.e. stratification, deformation structures, buried depressions, cavities). Concerning the application of GPR in bare and mantled karst terrains, the radargrams may allow identifying shallow cavities (Chamberlain et al., 2000; Ranalli et al., 2004), investigating the epikarst and the geometry of the rockhead (pinnacles, grikes, floaters) (Leucci and De Giorgi, 2005; Neto and Medeiros, 2006), recognizing buried sinkholes (Batayneth et al., 2002) and the location of sinkhole throats (Tanalli et al., 2006), and studying deformation structures (Gutiérrez et al., 2009; Pueyo-Anchuela et al., 2010) in cover sediments related to subsurface dissolution (synforms, faults, tilted strata, fissure fills, cumulative wedge-outs, zones of dilated deposits).

The trenching technique is aimed at obtaining information on recent ground deformation through the analysis and dating of the sediments and structures exposed in excavated trenches. This method has been applied primarily to the study of active faults in order to unravel the associated paleoseismic record and assess their seismogenic potential (McCalpin, 2009). It has been also used satisfactorily in a number of cases in the investigation of landslides (i.e. McCalpin and Irvine, 1995; Onida et al., 2001; McCalpin and Hart, 2003; Gutiérrez et al., 2008d, 2010). However, although this relatively inexpensive technique could provide valuable results in the study of sinkholes, especially in mantled karst settings, its possibilities have been barely explored (Gutiérrez et al., 2008b, 2009). A priori, the most favourable sinkhole types for this technique seem to be the depressions generated by sagging and collapse mechanisms. Presumably, the information that may be obtained from trenches excavated across suffosion sinkholes, related to the downward migration of particles through conduits, should be more limited. Generally, the greatest amount of information should be found at the sinkhole margins. Nevertheless, it is desirable to dig trenches long and deep enough to expose a section from the outer margin to the centre of the depression and reaching the base of the sinkhole fill. The success rate of a trenching program depends largely on the selection of the excavation sites. This key step should be based on a good understanding of the context supported by detailed geomorphological maps (McCalpin, 2009). Geophysical methods like ground penetrating radar or electrical resistivity may help to identify the most adequate locations for the trenches improving the benefit/effort ratio (Gutiérrez et al., 2009). Once the log of the trench has been delineated, the next step is to perform a retrodeformation analysis in order to reconstruct the chronological sequence of deformation and sedimentary episodes. This analysis involves removing or restoring the sedimentary units to their previous position reversing the deformation structures step by step and in reverse chronological order, from younger to older. The resulting retrodeformation sequence illustrates the evolution of the investigated sector of the sinkhole.

The trenching technique may provide useful information about the sinkholes that cannot be obtained by means of conventional geomorphological methods: (1) To elucidate the nature of topographic features and geophysical anomalies of uncertain origin. (2) To define the precise limits of the depressions and the ground affected by subsidence. (3) To establish the subsidence mechanisms analyzing the style of deformation. (4) To measure deformation magnitudes using stratigraphic and geomorphic markers; total cumulative subsidence and the contribution of each structure to the subsidence. (5) To ascertain the kinematical regime; gradual, episodic or mixed. Figure 1 shows several theoretical stratigraphic and structural arrangements indicative of progressive (A, B) and episodic displacement (C, D, E). A: Cumulative wedge-out at the margin of a sagging sinkhole recording progressive synsedimentary subsidence. B: Conformable and monotonous sequence with no evidence of sedimentary breaks juxtaposed to a creeping fault at the margin of a collapse sinkhole. C: Two stacked colluvial wedges associated to the edge of a sinkhole recording two collapse and scarp rejuvenation events. The dashed lines indicate the event horizons. D: Two overlapped fissure fills associated with two unconformable sedimentary packages recording two subsidence events that involve vertical displacement and tilting of the hanging wall. E: Two sedimentary units bounded by an angular unconformity that truncates a fault in the lower sedimentary package. These geometrical relationships can be explained by a minimum of two subsidence events; one which created the accommodation space in which the lower unit was deposited and a subsequent one that deformed the lower unit and created the depression where the younger unit was accumulated. (6) Numerical ages of selected stratigraphic units may provide information on the age of the sinkholes, the timing of subsidence episodes, especially the most recent event (MRE). These events are generally bracketed by maximum and minimum ages obtained from deposits underlying and overlying the event horizons, respectively. The geochronological information combined with deformation values can be used to calculate average rates of subsidence and/or rotation. These long term displacement rates covering a wide time span can be compared with those obtained using geodetic methods. All these data may be used as an objective basis to forecast the behaviour of specific sinkholes and to select the most adequate mitigation measures.

This contribution presents the lessons learnt through the construction of a sinkhole inventory in a sector of the Ebro Valley which constitutes the area in Spain where subsidence due to evaporite dissolution causes the greatest economic losses (Gutiérrez et al., 2008d; Galve et al., 2009c). Here, a large proportion of the karstic depressions have been filled artificially (Galve et al., 2009a) and the vast majority of the subsidence damage occurs on human structures built on pre-existing filled sinkholes. These circumstances justify the need of constructing a sinkhole inventory as complete and accurate as possible complementing traditional geomorphological mapping methods with other techniques like radar interferometry (InSAR), ground penetrating radar (GPR) and trenching.

2. The study area

The study area, covering approximately 27.5 ha, corresponds to a portion of a terrace of the Ebro River upstream of Zaragoza city, NE Spain (Fig. 2). The limits are defined by those of a planning unit of the municipality of Zaragoza (sector F-61-2). It has a triangular geometry elongated in the NW-SE direction and its northeast side coincides with the edge of the N-232 highway (Fig. 2A). A large part of the zone is occupied by crop fields, many of them abandoned, and buildings are relatively scarce. Before this work was undertaken, a building company submitted a development plan for the area (Fig. 2B). The practical aim of producing a detailed sinkhole inventory was to elucidate whether any sinkhole overlaps with the areas planned for the construction of buildings and services.

From the geological perspective, the investigated area is located in the central sector of the Ebro Tertiary Basin, NE Spain. The bedrock is composed of sub-horizontal evaporites of the Oligo-Miocene Zaragoza Gypsum Formation (Quirantes, 1978), which according to oil exploration boreholes reaches around 800 m in thickness (Torrescusa and Klimowitz, 1990). In outcrops, the evaporitic succession exhibits around 300 m of laminated and nodular secondary gypsum with interlayered marls and shales. Borehole data reveal the presence of halite and glauberite ($Na_2Ca[SO_4]_2$) units relatively close to the surface, some of them above the base level (Salvany et al., 2007; Salvany, 2009). Mining exploration boreholes drilled around 10 km southeast of the study area (i.e. borehole A5; Salvany, 2009) have penetrated a 30 m thick glauberite unit just below 200 m a.s.l. and a halite unit 75 m thick between 175 and 100 m a.s.l. The latter displays a rapid increase in thickness towards the north. Considering the sub-horizontal structure of the evaporitic formation and that the study area lies at 205-210 m a.s.l., we may expect the presence of glauberite and halite at shallow depths beneath the alluvium. The existence of glauberite and halite plays a crucial role in the development of the subsidence phenomena. Whereas the equilibrium solubility of gypsum at 25ºC is 2.4 g/l, halite and glauberite solubilities reach 360 and 118 g/l, respectively (Ford and Williams, 2007).

In this sector of the Ebro Basin the Tertiary bedrock is affected by subvertical joints and small-throw normal faults with prevalent WNW-ESE, E-W and N-S trends (Arlegui and Simón, 2001). The most penetrative WNW-ESE joint set plays a significant role in the development of karstic depressions as revealed by the dominant orientation of the major axes and alignments (Gutiérrez et al., 2007; Guerrero, 2008; Galve et al., 2009c). Locally, the evaporitic bedrock displays abundant gravitational deformation (basin structures, collapsed blocks, stratiform breccias and breccia pipes) generated by ductile and brittle subsidence phenomena caused by interstratal karstification, most likely preferential dissolution of halite and glauberite (Guerrero, 2008; Guerrero et al., 2008a, b; Gutiérrez et al., 2008a). These dissolution-induced deformation structures are clearly more abundant in the sectors where the bedrock is overlain by Quaternary alluvium, where the interaction between the bedrock and aggressive groundwater has been more intense.

From the geomorphological point of view, the study area is situated on the lowest terrace of the Ebro River, located on the right margin of the valley at 7-10 m above the channel. Available borehole data indicate that the Quaternary alluvium, mainly composed of channel gravel facies, has a variable thickness ranging from 10 to 30 m (Galve et al., 2009c). The erratic variability in the thickness of the cover is related to spatial changes in the magnitude of the dissolution-induced synsedimentary subsidence that affects the terrace deposits (Benito et al., 1998; Guerrero et al., 2008a). The water table is located at less than 5 m below the ground surface and shows significant seasonal variations, reaching the highest level by the end of the summer due to significant recharge of the alluvial aquifer by summer irrigation.

Galve et al. (2009c) presented an analysis of the sinkholes developed in the lower terraces of the Ebro Valley upstream of Zaragoza city. This work, mainly based on conventional geomorphological mapping, covers a much wider area than that of this study (40.8 km^2 vs 27.5 ha). The main findings of the cartographic analysis carried out by Galve et al. (2009c) include: (1) Sinkholes cover approximately 8.2% of the area in the studied stretch of the Ebro Valley. (2) Three main types of sinkholes have been differentiated following the classification proposed by Gutiérrez et al. (2008a); small cover collapse sinkholes related to the downward migration of alluvium through dissolutional conduits; large cover and bedrock collapse sinkholes (>15 m) caused by upward stoping of cavities developed within the bedrock; and cover and bedrock sagging sinkholes produced by interstratal karstification and downward flexure of the overlying bedrock and cover. (3) Sinkholes show preferred WNW-ESE orientations and alignments and collapse sinkholes tend to form clusters. (4) The geomorphic expression of approximately 70% of the sinkholes identifiable in aerial photographs taken in 1957 has been obliterated by artificial fills, with the consequent disappearance of 137 ha of wetlands. (5) Subsidence causes losses of the order of millions of euros per decade and the vast majority of the damage is concentrated within the boundaries of pre-existing filled sinkholes. These two latter facts justify the need of developing complete and accurate inventories of sinkholes, both visible and obscured, following a multiapproach scheme as the basis for the application of preventive planning strategies.

3. Methodology

This investigation has been carried out in three phases. In the first stage we produced a preliminary cartographic inventory of sinkholes and subsidence evidence interpreting aerial photographs from different dates and with variable scales and resolutions (1927 - 1:10,000; 1957 - 1:33,000; 1984 - 1:30,000; 1998 - 1:5.000; 2003 - 1 m of resolution; 2006 - 10 cm of resolution; Fig. 3), identifying depressions depicted on detailed topographic maps supplied by the municipality of Zaragoza from different dates (1969 – 1:2,000; 1971-72 – 1:1,000, both with contour lines every 1 m; Fig. 4), thorough field surveys, and deformation data provided by an interferometric analysis (Fig. 2C). The field surveys included: (1) Examination of the areas with InSAR deformation points and the subsidence features detected in the aerial photographs and topographical maps. (3) Multiple traverses in each portion of land. (4) Inspection of all of the human structures searching for subsidence-related deformation (Fig. 2C). The subsidence damage on buildings was classified using the ranking proposed by Cooper (2008). (5) Enquiries to local people about the existence of sinkholes and subsidence damage. (6) Bathimetric survey from a boat of a sinkhole that hosts a permanent pond.

The InSAR ground deformation data have been obtained in the frame of the European Terrafirma Project (http://www.terrafirma.eu.com) using 23 ENVISAT images spanning more than five years, from 2 May 2003 to 4 July 2008. The Spanish photogrammetric elevation model “GIS Oleícola”, with 20-m pixel size and a vertical accuracy higher than 5 m, provided by the Spanish Ministry of Agriculture, Fisheries and Food, was applied to generate 54 interferograms. The applied Stable Point Network technique (Arnaud et al., 2003) identified stable points (20-m pixel) with coherence values from 0.62 to 0.98, representing reliable displacement rate measurements (precision 1-3 mm/yr). The mean deformation velocity map provides mean subsidence rate values estimated along the line of sight (LOS) on a limited number of pixels, mainly due to decorrelation and loss of coherence in vegetated areas (Fig. 2C). Nevertheless, this analysis has yielded a significantly higher number of subsidence rate values than the deformation map previously generated through the Small Baseline Subset (SBAS) technique using ERS-1 and ERS-2 images with a pixel size of 90 m (Castañeda et al., 2009a, b).

In the second phase of the investigation, 26 GPR profiles with a total length of 2290 m were acquired with an IDS (Ingegneria Dei Sistemi S.p.A.) georadar equipped with an antenna of 400 MHz (Fig. 2A). The profiles were acquired using the software K2FastWave of IDS using the default configuration: (1) Range of 60 ns for channel 1 with 600 MHz frequency and range of 128 ns for channel 2 with 200 MHz frequency, both with 384 samples per scan. (2) A propagation speed of 10 cm/ns. (3) A wheel pace (step) and resolution of 0.017 m and 0.00283 m, respectively. The processing was carried out with the software GRED of IDS applying the filters: move start time, background removal, vertical bandpass, linear gain.

The objectives of this geophysical investigation, which guided the location of the profiles, were: (1) To define more precisely the limits of the known sinkholes, especially the buried ones, and obtain information about the subsurface geometry and internal structure of the sinkholes. (2) To investigate areas with “suspicious” surface features the possible existence of anomalies attributable to filled sinkholes (synforms, tilted strata, failure planes, local man-made deposits). (3) To select the most appropriate locations for the excavation of the trenches in the subsequent investigation phase.

The third stage of the investigation was focused on the excavation of 13 backhoe trenches with a total length of 323 m and a maximum depth of 2.8 m (Fig. 2A). After cleaning the vertical walls, a reference grid with horizontal and vertical strings spaced 1-2 m apart was placed in one side of the trenches, preferably the most shaded one. The gridded walls were logged with graph paper. Trench TE in sinkhole S12 was not mapped due to the instability of the walls and trench TK, in the same sinkhole, was logged from outside of the excavation for the same reason. Trenches TA, TB and TJ were finally linked into a single excavation. Charcoal fragments were only found in the natural fill of sinkhole S8 in trench TG. The location of the trenches, conditioned by the possibility of obtaining permits from the landowners and the presence of human structures, was based on the following criteria: (1) Investigate areas with InSAR displacement data and evidence of subsidence deformation in human structures (TABJ, TC, TD and TL). (2) Define precisely the limits of filled sinkholes (TF and TK in sinkhole S12). (3) Check whether subtle scarps identified in old aerial photographs and obscured by anthropogenic fill correspond to subsidence deformation features (TG and TH in sinkhole S8). (4) Investigate anomalous geometries (apparent tilted strata) displayed in GPR profiles (TI). (5) Check if filled sinkholes located in the immediate vicinity of the area extend to the sector of interest (TM next to sinkhole S11).

4. The sinkhole inventory

The multiphase and multiapproach investigation carried out has allowed us to map 12 sinkholes (Fig. 2C), two of them located just outside the area of interest (sinkholes S10 and S11). Table 1 presents the typology, morphometry and chronology of the inventoried sinkholes. The mapped karstic depressions cover around 20% of the area. Solely five sinkholes have topographic expression (S3, S4, S5, S6 and S7), whereas the rest have been masked by anthropogenic fills. Eight of the sinkholes form a tightly packed cluster and four of them are nested in the large sinkhole S8, with an area of around 35,500 m^2 (Fig. 5). Moreover, in the northwestern sector of the area, InSAR displacement data, cracks in structures and the deformation mapped in trench TC (open fissure and tilted strata) reveal the existence of an additional subsidence zone in the northwestern sector of the area. However, in spite of the intense investigation carried out by means of GPR and trenching in this sector, we were not able to define the limits of this subsidence area. Consequently, we opted for the delineation of a line linking the edge of the deformation zone of trench TC with the boundary of sinkhole S8, including sinkholes S1, S2 and S3. We propose that the area located east of this line should be considered as affected by sinkholes or particularly prone to subsidence (Fig. 2C).

Sinkhole S5 hosts a permanent lake 65 m long and 40 m wide (Fig. 5). In April 2009 a bathymetric survey of the lake revealed a maximum depth in the central sector of 6.5 m below the water level and 9-10 m below the surrounding ground. The asphalt road and the wall located on the NW margin of this sinkhole are affected by crescentic cracks and conspìcuous bending-related contractional deformation, respectively (Fig. 6). Sinkhole

S9 causes the continuous bending of the N-232 highway forming a large pothole around 100 m long that requires frequent re-asphalting (Fig. 2C).

6. Contribution of the different methods to the sinkhole inventory

6.1. Aerial photographs, topographic maps and field surveys

The aerial photographs and the old and detailed topographic maps from 1969 and 1971-72 have been the most helpful sources of information for the identification of sinkholes. All of the inventoried sinkholes except S12 have been recognized in air photographs (Fig. 3). The most helpful ones happened to be the black and white images taken in 1957 and printed at a scale of 1:33.000. These photographs have the following advantages: (1) Were acquired before the transformation of the landscape (excavation, fill and urbanization) in this sector the Ebro Valley became significant (Galve et al., 2009c). (2) Can be analysed with stereoscope. (3) In spite of their small scale, are very sharp and have a high resolution. The black and white orthoimages from 1927 were not so useful mainly because they are not so clear and cannot be viewed stereoscopically. The contour lines of the 1969 topographic maps at 1:2,000 scale depict 7 sinkholes (S1, S3, S4, S6, S7, S10 and S11), whereas the 1971-72 maps, despite having a larger scale (1:1,000), illustrate only 4 karstic depressions (S4, S5, S6, S10; Fig. 4). One of the advantages of the topographic maps with respect to the non orthorectified aerial photographs is that they allow obtaining quite precise measurements of the axial lengths and area of the depressions and estimating a minimum depth. On the other hand, the use of images and maps from multiple dates gave us the opportunity of bracketing the age of formation and filling of sinkholes. For example sinkhole S1 formed after the acquisition of the 1957 aerial photographs and before the elaboration of the 1969 topographical map and sinkhole S2 was filled between 1927 and 1957 (Figs. 3 and 4). The rest of the sinkholes, except S12, formed before 1927 or 1957, age of the oldest aerial photographs (Table 1). The main contributions of the field surveys to the sinkhole inventory include: (1) Mapping precisely the edges of the non filled sinkholes. (2) Corroborating the presence of filled sinkholes through the identification of man-made deposits and deformed structures (Fig. 6). The latter in some cases induced us to expand the limits of some sinkholes initially mapped with aerial photographs and/or old topographic maps. (3) Farmers indicated the approximate location of the buried sinkhole S12, not recognizable in any remote-sensed image or topographic map.

6.2. InSAR

The radar interferometry analysis performed using ENVISAT images with a pixel size of 20 m and covering approximately 5 years, has provided a limited number of measurements, mainly due to decorrelation caused by the high percentage of the area covered by crop fields and vegetation. Most of the pixels with data occur associated with buildings and paved surfaces. Subsidence rates in the 6 points with measured deformation range from 17.3 to 4.4 mm/yr. All of these points are situated within the limits of the inventoried sinkholes and subsidence areas, whereas the 25 “no deformation” points fall outside those areas (Fig. 2C). Most probably, the lack of ground displacement data on the N-232 road in the active sinkhole S9 is related to the loss of coherence caused by the continuous levelling of the infrastructure by re-asphalting. InSAR displacement data provided consistent quantitative displacement velocity data helping to corroborate objectively the existence of active buried sinkholes and to define their limits. The “no deformation” points served as independent data for the identification of stable areas.

6.3 Ground penetrating radar

The quality of the GPR profiles was very variable. A significant number of the profiles displayed very low penetration. This circumstance is attributed to the high humidity of the soils in crop fields due to sheet-flooding irrigation and the high content of clay in the man-made ground that covers the terrace surface to a great extent. An additional pitfall is that some profiles showed tilted reflectors that turned out to be artefacts after the excavation of trenches (Profiles C, D, S and T and trenches TF, TK, TI and TM). Conversely, some GPR profiles provided highly useful information. The profile H allowed us to confirm the existence of sinkhole S2, interpreted with a limited level of confidence with the 1927 orthoimage (Fig. 7). This profile shows a reflector with a synformal geometry 35 m long ascribed to the base of an artificial fill around 1 m thick filling a sinkhole, most likely dominated by sagging subsidence. The GPR profiles P, Bal 3 and Bal 4 facilitated the mapping of the edges of sinkhole S9. The profile P, obtained along the NE shoulder of the N-232 highway, captured a synform around 70 m long coinciding with the re-asphalted portion of the infrastructure in sinkhole S9. Additionally, this profile did not show any evidence of deformation in the stretch of the highway shoulder opposite to sinkhole S10, allowing us to map the limits of that karstic depression outside of our study area. The profiles Bal 3 and Bal 4, carried out in the garden of a private property, displayed a sharp change in the electrical impedance of the subsoil coinciding with a degraded scarp, attributed to a change from natural ground to a clay-rich artificial sinkhole fill and the edge of the sinkhole S9, respectively. The profile B, acquired along an asphalt road, allowed us to corroborate sinkhole S12 and locate it more precisely (Fig. 7). The existence and rough position of this buried sinkhole was indicated by the local farmers. The reflectors of this profile show a synform 30 m long affected by synthetic normal faults, consistent with the geometrical relationships observed in the trenches TF and TK dug in the subsequent phase of the investigation.

6.4. Trenching

Six trenches (TA, TB, TC, TD, TJ, TL) with a total length of 143 m were excavated in the northwestern sector of the study area (Fig. 2A). Here, the InSAR analysis provided subsidence rates for three pixels from 12.7 to 17.3 mm/yr and conspicuous damage on human structures was observed in the field (Fig. 2C). The aim of these trenches was to map and characterize the active subsidence structure with no geomorphic expression. Unfortunately, evidence of deformation was only found in trench TC and consequently we were not able to define precisely the limits of the area affected by subsidence. This is probably because dissolution-induced subsidence is primarily accommodated by ductile sagging, creating an open basin structure with very low dips difficult to identify in the trenched poorly stratified terrace gravel deposits. Trench TC exposed terrace gravels with a N035E trending open fissure 1 cm wide that does not affect the overlying man-made fill (Fig. 8). The gravels situated to the SE of the fissure show an apparent dip of 7-11° towards the SE edge of the trench, as measured on lenticular sand beds. An additional artificial fill unit 35 cm thick was mapped overlying the tilted gravels that wedges out towards the fissure. Most likely the fissure corresponds to a bending-moment fracture developed at the margin of a sagging basin, the zone of maximum flexure, and the wedge-shaped artificial deposit to an accumulation dumped to level the ground deformed by subsidence. The area assigned for the construction of one of the buildings overlaps the fissure and the tilted gravels (Fig. 2B).

The synform captured in the GPR profile B, acquired along an asphalt road, pinpointed the location of the edge of the buried sinkhole S12 in two points (Fig. 7B). In order to map this sinkhole more precisely and obtain information about its internal structure, two aligned trenches perpendicular to the road and on both sides of the infrastructure were excavated (TF and TK). The edges of the trenches were located coinciding with the core of the synform detected in the GPR profile B (Fig. 2A). In the walls of trench TF we identified a synthetic normal fault dipping towards the centre of the sinkhole and an antithetic fissure. The fault juxtaposes fluvial sediments against man-made deposits and shows a minimum vertical throw of 50 cm (Fig. 8). The fissure has a horizontal separation of around 1 cm and could correspond to an incipient dome-shaped failure related to loss of basal support. In trench TK a synthetic normal fault dipping towards the centre of the sinkhole at a distance of 25 m from the fault identified in trench TF was identified. Unfortunately, it was not possible to deepen this trench and it had to be studied from outside due to the instability of the walls on the man-made ground. The integration of the information gained with the GPR profile B and the trenches TF and TK suggests that sinkhole S12 is a subcircular depression with a diameter of 25-30 m generated by collapse and probably sagging.

Active subsidence in sinkhole S11 affects the N-232 highway and a factory situated on the northestern flank of the linear infrastructure (Fig. 2C). The trench TM was sited on the opposite side of the highway and with a perpendicular orientation with the aim of elucidating whether the edge of the sinkhole S11 is located beneath the highway or in our study area (Fig. 2A). The lack of deformation in the trench, which exposed horizontally lying gravels, led us to infer that this sinkhole does not affect the area of interest.

Before the creation of the sinkhole inventory, the construction of buildings overlapping the SE sector of sinkhole S8 had been projected. This sinkhole shows abundant evidence of active subsidence; deformed human structures and InSAR displacement points with subsidence rates of 11.3 and 6.5 mm/yr (Fig. 2C). However, the location of the SE edge of the sinkhole, mapped following a subtle scarp identified in the 1957 aerial photographs, but obscured by later artificial fill, was challenged. In order to corroborate or relocate the edge of the sinkhole in this sector and to obtain additional information on the subsidence depression, two trenches perpendicular to the presumed sinkhole boundary were excavated (TG and TH; Fig. 2A).

Five stratigraphic units have been mapped in the 48 m long and 2.8 m deep trench TG (Fig. 9). Rounded, polymictic and stratified fluvial gravels with an apparent dip of 3-4° to the NW between the reference vertical lines 0 and 33 (unit 1). A sandy silt unit 85 cm thick that wedges out to the SE, interpreted as a natural sinkhole deposit generated by sheet wash (unit 2). Two layers of artificial fill that wedge out to the SE (units 3 and 4). These two units, with recent human objects, were most likely accumulated after 1957, when the sinkhole still had topographic expression. Units 2, 3 and 4 are restricted to the sector where the terrace gravels are tilted and the feather edge of unit 3 is located next to an extensional structure in the terrace deposits. Finally, unit 5 corresponds to a tabular man-made deposit with no evidence of deformation, that can be traced along the whole length of the trench. Between the vertical reference lines 32 and 33, the terrace gravels of unit 1 are affected by a keystone graben 1.1 m wide controlled by a NW-dipping master synthetic normal fault and a secondary antithetic fault (Fig. 9). Both failure planes are defined by shear zones 5-10 cm wide in which the clasts show obvious reoriented fabrics. The upper part of the secondary fault shows a 35 cm long fissure filled with unit 5 deposits, suggesting that when this artificial unit was accumulated, presumably after 1957, the fissure was opened. However, unit 5 truncates the two normal faults, indicating that they have not undergone any appreciable displacement since the accumulation of that unit. The origin of the graben seems to be related to the collapse of a wedge-shaped block from the hanging-wall induced by its tilting and lateral displacement towards the centre of the sinkhole. The absence of distinguishable stratigraphic markers in the faulted gravel unit precludes estimating the magnitude of the subsidence caused by this structure. Between the vertical reference lines 35 and 36 the gravel unit 1 is affected by another NW-dipping normal fault, expressed as a shear zone with reoriented fabrics and truncated by unit 5. Since the gravels do not show any evidence of deformation SE of the reference line 36, we have situated the “structural limit” of the buried sinkholes at this reference line, roughly coinciding with the location of the edge of the sinkhole mapped with the 1957 aerial photographs.

Two charcoal samples were obtained from the natural sinkhole fill (unit 2) at 200 cm (TG2a) and 140 cm (TG2c) below the ground surface (Fig. 9). Poznan Radiocarbon Laboratory provided AMS radiocarbon ages in correct stratigraphic order; 2010±35 yr BP (46 cal yr BC-26 cal yr AD) and 1685±30 cal yr BP (408-336 cal yr AD); error at 1σ and calibration following CALIB v6.0 by Reimer et al. (2009). These dates allow the calculation of an average sedimentation rate of 1.3-1.9 mm/yr between the accumulation of the two sampled deposits. Assuming that the sediments in which the samples have been collected where deposited at the current position of the topographic surface, we can estimate average subsidence rates of 0.9-1.0 and 0.8 mm/yr using the dates of samples TG2a and TG2c with an error margin at 1σ , respectively. It is important to take into account that these values have been obtained close to the margin of the sinkhole. The stratigraphy in the depocentral sector of the sinkhole would yield higher cumulative subsidence values and subsidence rates.

The stratigraphy of the 34 m long trench TH is similar to that of trench TG (Fig. 9). In trench TH the fluvial gravels show a NW-facing open monoclinal flexure between the vertical reference lines 28 and 30. Northwest of this flexure the gravels show an apparent dip of 4-5° to the NW, whereas they display a horizontal structure to the SE. The natural sinkhole fill (unit 2) and the artificial fill units 3 and 4 wedge out towards the SE, and the location of the feather edge of unit 2 coincides with that of the upper hinge of the monocline in the terrace gravels.

The stratigraphic and structural relationships observed in the trenches TG and TH indicate that subsidence in the investigated sector of sinkhole S8 has been mainly produced by sagging, with a secondary collapse component accommodated by small-throw normal faults. Assuming that the top of the gravel unit was originally horizontal, we can estimate that this unit has undergone a cumulative vertical displacement by sagging of 1.5 and 1.8 m in trenches TG and TH, respectively. A significantly higher cumulative subsidence may be expected in the depocentral sector of the sinkhole. The obtained long-term subsidence velocity values in trench TH are much lower than those measured by InSAR in sinkhole S8. This difference may be related to the following non-exclusive factors: (1) There has been an acceleration in the subsidence velocity in recent times. (2) Subsidence rates have significant spatial variations within sinkhole S8. (3) The InSAR values account for the sum of the subsidence caused by both, evaporite dissolution and the compaction of the recent man-made deposits accumulated to fill the sinkhole.

7. Discussion and conclusions

Sinkhole risk management commonly involves three main steps, each one built upon the previous one/s: (1) Identification and characterization of the existing sinkholes. (2) Spatial and temporal prediction of future sinkholes. (3) Design and application of mitigation measures. The prognostic capability of the susceptibility and hazard models developed in step 2 and the effectiveness of the mitigation strategies applied in step 3 largely depend on the completeness and quality of the sinkhole inventory constructed in step 1. This data base should include as much information as possible on the inventoried sinkholes (location, morphometry, typology, chronology, relation to causal factors, kinematic regime, subsidence rates). Incomplete and inaccurate sinkhole inventories very probably will lead to the delineation of safe areas in sectors affected by sinkholes or prone to subsidence. Consequently, one of the main challenges is to improve the existing methodologies used for the recognition and characterization of sinkholes. This is particularly important in areas where the sinkholes have been masked by natural and/or anthropogenic processes. Under these circumstances conventional geomorphological studies should be complemented by other techniques like InSAR, GPR or trenching. These methods, as the presented study illustrates, help not only to recognize and map sinkholes, but also to improve their characterization obtaining additional practical information.

In the studied area, where a significant proportion of the sinkholes have been filled during the last decades, aerial photographs taken in 1957 and old and detailed topographic maps from 1969 and 1971-72 have been the most helpful sources of information for the identification of sinkholes (Figs. 3 and 4). The use of remote-sensed images and maps from different dates may allow bracketing the age of the sinkholes. In this investigation, except sinkhole S1 that formed between 1957 and 1969, only a very lose minimum age can be provided for the rest of the sinkholes, that may be as old as several centuries or millennia. Detailed field surveys were essential for a more precise mapping of the sinkholes with geomorphic expression and corroborating buried sinkholes. One of the sinkholes (S12) was not overlooked thanks to the interviews carried out with local people, who indicated the approximate location of this buried karstic depression. These conventional sources of information allowed us to construct a reasonably complete sinkhole inventory, answering several questions relevant for a proper preventive planning required the application of InSAR, GPR and trenching.

As this study illustrates, the InSAR technique has the advantage of providing remotely accurate measurements of the displacement of the ground and human structures in extensive areas with a high spatial and temporal resolution. Additionally, the radar technique may be applied to obtain deformation values retrospectively using scenes acquired in previous dates. However, the loss of coherence, mainly related to the presence of agricultural fields and vegetation, may considerably reduce the density of measurement points. The radar deformation data allow the identification of active sinkholes and subsidence areas that have been overlooked by conventional mapping methods due to their subtle geomorphic expression or their buried character. The subsidence rates provided by the interferometric analysis in the NW sector of the study area were instrumental in the identification of a previously unknown subsidence area (Fig. 2C). Additionally, deformation data, consistent with the preliminary sinkhole and subsidence damage map helped us to determine or corroborate the active nature of some of the sinkholes and in some cases to improve the location of the sinkhole edges. Gaining average displacement velocity values and time series of deformation is a great advance for the following reasons: (1) It may provide a quantitative measurement of the activity of sinkholes, generally more convincing than other geomorphic data for planners and decision makers. In filled sinkholes those rates may account for the contributions of both dissolution-induced deformation and compaction. (2) Coherent points with “no deformation” values may support the definition of *a priori* stable areas. (3) Accurate subsidence values may serve to evaluate if the strain rate is tolerable by a specific structure and to design structures capable of accommodating the deformation. (4) Time deformation series may be used to analyse the impact of several factors on sinkhole activity (i.e. earthquakes, water table changes, floods, irrigation, rainfall events). (5) The InSAR technique might be useful for monitoring vulnerable structures (dams, high-speed railways) and the anticipation of catastrophic collapse sinkholes through the detection of precursory displacements (Ferretti et al., 2000b; Closson et al., 2003; Castañeda et al., 2009a).

The ground penetration radar (GPR), although it has a limited penetration capacity and its performance is adversely affected by the presence of clayey soils and water, allows investigating the subsoil in a rapid way imaging the profiles directly in the field. Some of the potential contributions of GPR for the identification and characterization of sinkholes are: (1) Identifying shallow cavities. (2) Determine the depth of the rockhead and water table and the geometry of the former. (3) Locating buried sinkholes and delineating precisely the position of their edges. In the study area, the GPR profile B was essential for situating sinkhole S12, whose position was roughly indicated by local people (Fig. 7). Profile H helped to refine the previously mapped edge of sinkhole S2. (4) Ruling out the presence of sinkholes in particular sectors. GPR profiles P and G strongly suggest that sinkholes S10 and S11 do not affect the study area. (5) Investigating the geometry of filled sinkholes and subsurface deformation structures. Some of the geometries that may be observed include synforms, tilted and faulted reflectors, units with lateral wedge-outs, onlaps or local interruptions in the reflectors or changes in the electromagnetic behaviour attributable to loosened or collapsed material. In some cases it may be necessary to investigate the meaning of some of these GPR signals by intrusive methods. For example the inclined reflectors of some profiles turned out to be artefacts via trenching. (6) Deciding about the most favourable location for trenching or drilling. This may be done just before digging the trenches examining the GPR profiles in the field. For example, in this investigation trenches TK and TF were sited on the basis of the geometries observed in the GPR profile B.

The data gained by means of the trenching technique were especially useful for the urban planning process. Trench TM, in agreement with the GPR profile Q, revealed that sinkhole S11 does not extend into the study area. Trench TC allowed us to locate precisely in a particular sector the edge of a subsidence area identified by means of InSAR displacement data and subsidence damage in human structures. It also demonstrated that two of the areas selected for the construction of buildings overlap active subsidence structures. Trenches TF and TK contributed to define the edges of the filled sinkhole S12 and to determine the subsidence mechanism; collapse controlled by synthetic normal faults. Trenches TG and TH were dug perpendicularly to the SE edge of sinkhole S8 as mapped following a subtle scarp identified in the 1957 aerial photographs. The position of the limit of this sinkhole, which overlaps the planned area for new buildings, was challenged. However, the deformation observed in these trenches corroborated the aerial photograph interpretation and helped to map the limit of the area affected by subsidence more precisely. The stratigraphic and structural relationships of these trenches revealed that subsidence in sinkhole S8 in this sector is accommodated by sagging and a secondary collapse component recorded by normal faulting. Cumulative subsidence values of 1.5 and 1.8 m were measured in trenches TG and TH, respectively. Additionally, two radiocarbon dates obtained from charcoal fragments collected from a natural sinkhole fill deposit in trench TG (46 cal yr BC-26 cal yr AD and 408-336 cal yr AD) allowed us to obtain a minimum age for the sinkhole and to calculate long-term subsidence rates ranging from 0.8 to 1 mm/yr. Both the deformation magnitude and subsidence rates must be considered as minimum values since they were not obtained in the depocentral sector of the sinkhole. A very important advantage of the trenches was that they allowed the planners to put their eyes on the failure planes that define the margins of sinkholes, providing unquestionable evidence for the existence of buried active sinkholes.

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Figure captions

Figure 1. Theoretical stratigraphic and structural arrangements at sinkhole margins indicative of progressive (A, B) and episodic (C, D, E) subsidence. See explanation in text.

Figure 2. Location of the study area. A: Spatial distribution of old buildings, GPR profiles and trenches. B: Building planning proposed before this study and mapped sinkholes and subsidence areas. C: Map showing the distribution of inventoried sinkholes, subsidence areas, deformation in human structures and InSAR ground displacement data.

Figure 3. Aerial photographs of the study area from different dates. Most of the inventoried sinkholes are recognizable in the 1957 images. Sinkhole S1 formed between 1957 and 1984 and by the latter date the geomorphic expressions of several sinkholes was obliterated by artificial fills.

Figure 4. Detailed topographic maps of the study area from 1969 and 1971-72; contour interval is 1 m. Both maps provided complementary information of the location and morphometry of the sinkholes.

Figure 5. Oblique aerial view of a portion of the study area taken in May 2008. By that date, sinkholes S1 and S2 had been filled by man-made deposits and the infill of sinkhole S3 had started from its right side. Sinkholes S6 and S7 are hidden by poplar trees.

Figure 6. Cracks in the asphalt road and contractional deformation in the wall located on the west margin of sinkhole S5. The shortening seems to be related to compression in the central sector of the area affected by bending. Image taken in April 2009.

Figure 7. GPR profiles acquired across sinkholes S2 (profile H) and S12 (profile B). Both helped to locate the edges of the filled sinkholes and obtain information on their subsurface geometry. Profile B determined the location of trenches TF and TK. See location of profiles in Figure 2A.

Figure 8. Logs of trenches TC and TF. See location in Figure 2A and explanation in text. Inset photograph of trench TC.

Figure 9. Logs of trenches TG and TH. See location in Figure 2A and explanation in text. Inset photograph of trench TG.

Sinkhole	*Type*	*Length-width or diameter(m)*	*Depth(m)*	*Area(m^2)*	*Age*
S1	collapse	55-60	1,5?	2827	1957-1969
S2	sagging	70x25	1?	1374	pre-1927
S3	collapse	20-25	2,5-3	490	pre-1927
S4	collapse	25-30	5	706	pre-1927
S5	collapse	65x40	9-10	2042	pre-1927
S6	collapse	40	4?	1256	pre-1927
S7	collapse	20	4?	314	pre-1927
S8	sagging /collapse	-	1-1,5	35,500	pre-1927
S9	sagging /collapse	110-120	2-3?	11,309	pre-1957
S10	collapse?	70	2-3	3846	pre-1927
S11	¿	110x?	¿	¿	pre-1927
S12	collapse	25-30	¿	490	>40 years

Table 1. Typology, morphometry and chronology of the inventoried sinkholes.