

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

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12
13 **Abstract**

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

34 radiocarbon dates obtained from deformed sinkhole deposits. (5) Unequivocal evidence
35 of active subsidence in areas assigned for the construction of buildings.

36

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

39

40 **1. Introduction**

41 The most important step in sinkhole hazard analysis is the construction of a
42 comprehensive sinkhole cartographic inventory. The reliability of sinkhole
43 susceptibility and hazard maps and the effectiveness of the mitigation measures depend
44 largely on the completeness, accuracy and representativeness of the sinkhole inventories
45 on which they are based (Galve et al., 2009a, b; Gutiérrez, 2010). Sinkhole data bases
46 constructed for planning purposes should preferably include information on the
47 following aspects: (1) Precise location of the limits of the sinkholes and the underlying
48 subsidence structures. This is essential to define accurately the unstable areas, including
49 a setback distance around the sinkholes (Zhou and Beck, 2008). It is important to bear
50 in mind that the subsidence structures and the sectors affected by settlement may cover
51 a larger area than the mapped topographic depressions (i.e. Gutiérrez et al., 2009). (2)
52 Morphometric parameters. These data constitute the basis on which to analyse the
53 magnitude and frequency relationships of sinkholes, of great importance for hazard
54 assessment. (3) Geological, geomorphological and hydrological setting. A good
55 understanding of the local and regional geological context may provide clues on the
56 causal factors and relative chronology of the sinkholes. (4) Genetic type; that is
57 subsidence mechanisms and material affected by subsidence (Williams, 2004; Beck,
58 2005; Waltham et al., 2005; Gutiérrez et al., 2008a). This is a crucial aspect since the
59 subsidence mechanism determines the applicability and effectiveness of different
60 corrective measures and the capability of the sinkholes to cause damage. Catastrophic
61 collapse, unlike progressive sagging, may lead to human life losses. (5) Chronology,
62 either relative or numerical ages. The latter is indispensable to calculate rates of
63 sinkhole occurrence and hazard estimates in terms of spatial and temporal probability.
64 (6) Active or inactive character. This distinction may be determined through the
65 identification of fresh morphological features and deformed human structures,
66 comparing aerial photographs of different dates and from accounts provided by local
67 people. However, in many cases it is necessary to apply geodetic measurements that

68 generally cover a limited temporal window. Additionally, it may be difficult to define
69 the limit between active and inactive sinkholes; for example the maximum age of the
70 most recent displacement episode for a sinkhole to be considered as active. (7)
71 Kinematical regime (gradual, episodic or mixed). This type of information may be
72 obtained studying the stratigraphy and structure of the sinkholes (Gutiérrez et al.,
73 2008b, 2009) and from relatively long geodetic records. (8) Current and long-term
74 subsidence rates. Contemporaneous subsidence rates may be obtained applying geodetic
75 methods and using deformed structural markers of known age. The calculation of long-
76 term subsidence rates requires the analysis of the sinkhole structure and deposits and the
77 application of geochronological methods.

78

79 Sinkholes are commonly mapped using conventional geomorphological methods like
80 aerial photographs, topographic maps, DEMs and field surveys. However, the
81 effectiveness of this approach may be quite limited in areas where the geomorphic
82 expression of sinkholes has been obliterated by natural processes or anthropogenic fill.
83 Additionally, gaining data on some of the aforementioned practical aspects requires the
84 application of other techniques like those presented below.

85

86 Synthetic Aperture Radar Interferometry (InSAR) is a geodetic method that may be
87 applied to measure the displacement of the ground surface using the phase difference
88 between two radar acquisitions (Massonet and Feigl, 1998; Rott, 2009). Although
89 levelling is an accurate technique for subsidence monitoring, it has significant
90 drawbacks (Ketelaar, 2009): (1) It provides deformation data for a limited number of
91 points. (2) It requires time-consuming field work. (3) It is expensive when applied to
92 extensive areas and/or during long periods of time. Conversely, InSAR, under
93 favourable conditions, allows the measurement of subcentimetric deformation occurring
94 over time spans of days or years, covering extensive areas with a high temporal and
95 spatial resolution and without the need of conducting field work. Moreover,
96 interferometry may be applied to obtain retrospective deformation values using radar
97 scenes from historical satellite archives. The main limitations of the InSAR technique
98 are: (1) The errors introduced by atmospheric artefacts due to the microwave
99 propagation conditions (e.g., vapour content) and the troposphere heterogeneities
100 between the different image acquisitions. (2) The loss of coherence due to decorrelation
101 in agricultural fields and vegetated areas (Ferretti et al., 2001, Hanssen, 2001; Castañeda

102 et al., 2010). For this reason, the areas with human structures and rock outcrops are
103 generally the most favourable for the application of this technique. Removing the
104 atmospheric phase component can be optimized using advanced techniques which
105 process multiple interferograms derived from a large set of SAR images, allowing us to
106 generate deformation time series to study the temporal evolution of the detected
107 displacements. These techniques are based on the signal of detected scatters using as
108 selection criteria the multilook coherence or the amplitude stability (Ferretti et al.,
109 2000a, 2001; Hooper et al., 2007; Ketelaar, 2009).

110

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

136 Camaione, Italy. Al-Fares (2005), working in SE Nevada, measured subsidence rates of
137 3-5 mm/yr in the surroundings of a large collapse that forms part of a sinkhole cluster
138 developed in a mantled carbonate karst. Paine et al. (2009), working in the Delaware
139 Basin, Texas, tested the InSAR technique in an area where there are two large collapse
140 sinkholes (Wink Sink 1 and Wink Sink 2) related to the dissolution of a deep salt
141 formation, induced by oil exploitation boreholes. The authors identified three sectors
142 affected by settlement with diameters ranging from 300 to 850 m and with subsidence
143 rates up to 30 cm/yr. The subsidence rates measured by these authors are one order of
144 magnitude higher than those of the rest of the reviewed papers. One of the subsiding
145 areas surrounds the Wink Sink 1, whereas the others are located close to Wink Sink 2.
146 Castañeda et al. (2009a) analysed the possibilities and limitations of the SBAS (Small
147 Baseline Subset) interferometric technique to the study of sinkholes in the Ebro Valley,
148 NE Spain. These authors used 27 ERS-1 and ERS-2 images with a pixel size of 90 x 90
149 m acquired over a period of about 5 years (July 1995-December 2000). The main
150 findings of this work include: (1) Deformation values were measured in only 5-10% of
151 the known active sinkholes. This limitation is mainly attributed to the lack of coherence
152 in crop fields and the low spatial resolution of the deformation maps. Movements at
153 subpixel scale result in decorrelation (Zebker and Villasenor, 1992). (2) Most of the
154 detected active subsidence areas correspond to human structures built on artificially
155 filled sinkholes. (3) The interferometric study, although it overlooked a significant
156 proportion of the areas affected by subsidence, complements the geomorphological
157 studies providing valuable quantitative deformation data.

158
159 The use of the ground penetrating radar (GPR), as a non-destructive technique to analyse
160 the subsoil, has shown an important development during the last decades. This advance
161 has been largely due to the capability of the technique to investigate environmental and
162 engineering problems (Mellet, 1995). As an example, GPR was used to detect termite
163 nests (voids) inside dikes and earth dams in China (Xu et al., 2010), obtaining
164 satisfactory results. GPR allows the acquiring of information on the subsoil from the
165 response of the materials to high frequency electromagnetic radio waves emitted by an
166 antenna. The receiving antenna records in a radargram the signal reflected at boundaries
167 with different dielectric constants (i.e. stratigraphic contacts, failure planes, cavities,
168 water table). In the last decade the GPR has been applied in a wide variety of
169 geomorphological investigation topics, such as landslides (Sass et al., 2008), moraine

170 deposits (Sadura et al., 2006), and dunes (Girardi and Davis, 2010). However, one the
171 most extended applications of GPR has been the detection of subsurface cavities and
172 deformation structures.

173

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

196

197 The trenching technique is aimed at obtaining information on recent ground
198 deformation through the analysis and dating of the sediments and structures exposed in
199 excavated trenches. This method has been applied primarily to the study of active faults
200 in order to unravel the associated paleoseismic record and assess their seismogenic
201 potential (McCalpin, 2009). It has been also used satisfactorily in a number of cases in
202 the investigation of landslides (i.e. McCalpin and Irvine, 1995; Onida et al., 2001;
203 McCalpin and Hart, 2003; Gutiérrez et al., 2008d, 2010). However, although this

204 relatively inexpensive technique could provide valuable results in the study of
205 sinkholes, especially in mantled karst settings, its possibilities have been barely
206 explored (Gutiérrez et al., 2008b, 2009). A priori, the most favourable sinkhole types
207 for this technique seem to be the depressions generated by sagging and collapse
208 mechanisms. Presumably, the information that may be obtained from trenches
209 excavated across suffosion sinkholes, related to the downward migration of particles
210 through conduits, should be more limited. Generally, the greatest amount of information
211 should be found at the sinkhole margins. Nevertheless, it is desirable to dig trenches
212 long and deep enough to expose a section from the outer margin to the centre of the
213 depression and reaching the base of the sinkhole fill. The success rate of a trenching
214 program depends largely on the selection of the excavation sites. This key step should
215 be based on a good understanding of the context supported by detailed
216 geomorphological maps (McCalpin, 2009). Geophysical methods like ground
217 penetrating radar or electrical resistivity may help to identify the most adequate
218 locations for the trenches improving the benefit/effort ratio (Gutiérrez et al., 2009).
219 Once the log of the trench has been delineated, the next step is to perform a
220 retrodeformation analysis in order to reconstruct the chronological sequence of
221 deformation and sedimentary episodes. This analysis involves removing or restoring the
222 sedimentary units to their previous position reversing the deformation structures step by
223 step and in reverse chronological order, from younger to older. The resulting
224 retrodeformation sequence illustrates the evolution of the investigated sector of the
225 sinkhole.

226

227 The trenching technique may provide useful information about the sinkholes that cannot
228 be obtained by means of conventional geomorphological methods: (1) To elucidate the
229 nature of topographic features and geophysical anomalies of uncertain origin. (2) To
230 define the precise limits of the depressions and the ground affected by subsidence. (3)
231 To establish the subsidence mechanisms analyzing the style of deformation. (4) To
232 measure deformation magnitudes using stratigraphic and geomorphic markers; total
233 cumulative subsidence and the contribution of each structure to the subsidence. (5) To
234 ascertain the kinematical regime; gradual, episodic or mixed. Figure 1 shows several
235 theoretical stratigraphic and structural arrangements indicative of progressive (A, B)
236 and episodic displacement (C, D, E). A: Cumulative wedge-out at the margin of a
237 sagging sinkhole recording progressive synsedimentary subsidence. B: Conformable

238 and monotonous sequence with no evidence of sedimentary breaks juxtaposed to a
239 creeping fault at the margin of a collapse sinkhole. C: Two stacked colluvial wedges
240 associated to the edge of a sinkhole recording two collapse and scarp rejuvenation
241 events. The dashed lines indicate the event horizons. D: Two overlapped fissure fills
242 associated with two unconformable sedimentary packages recording two subsidence
243 events that involve vertical displacement and tilting of the hanging wall. E: Two
244 sedimentary units bounded by an angular unconformity that truncates a fault in the
245 lower sedimentary package. These geometrical relationships can be explained by a
246 minimum of two subsidence events; one which created the accommodation space in
247 which the lower unit was deposited and a subsequent one that deformed the lower unit
248 and created the depression where the younger unit was accumulated. (6) Numerical ages
249 of selected stratigraphic units may provide information on the age of the sinkholes, the
250 timing of subsidence episodes, especially the most recent event (MRE). These events
251 are generally bracketed by maximum and minimum ages obtained from deposits
252 underlying and overlying the event horizons, respectively. The geochronological
253 information combined with deformation values can be used to calculate average rates of
254 subsidence and/or rotation. These long term displacement rates covering a wide time
255 span can be compared with those obtained using geodetic methods. All these data may
256 be used as an objective basis to forecast the behaviour of specific sinkholes and to select
257 the most adequate mitigation measures.

258

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

269

270 **2. The study area**

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

281

282 From the geological perspective, the investigated area is located in the central sector of
283 the Ebro Tertiary Basin, NE Spain. The bedrock is composed of sub-horizontal
284 evaporites of the Oligo-Miocene Zaragoza Gypsum Formation (Quirantes, 1978), which
285 according to oil exploration boreholes reaches around 800 m in thickness (Torrescusa
286 and Klimowitz, 1990). In outcrops, the evaporitic succession exhibits around 300 m of
287 laminated and nodular secondary gypsum with interlayered marls and shales. Borehole
288 data reveal the presence of halite and glauberite ($\text{Na}_2\text{Ca}[\text{SO}_4]_2$) units relatively close to
289 the surface, some of them above the base level (Salvany et al., 2007; Salvany, 2009).
290 Mining exploration boreholes drilled around 10 km southeast of the study area (i.e.
291 borehole A5; Salvany, 2009) have penetrated a 30 m thick glauberite unit just below
292 200 m a.s.l. and a halite unit 75 m thick between 175 and 100 m a.s.l. The latter displays
293 a rapid increase in thickness towards the north. Considering the sub-horizontal structure
294 of the evaporitic formation and that the study area lies at 205-210 m a.s.l., we may
295 expect the presence of glauberite and halite at shallow depths beneath the alluvium. The
296 existence of glauberite and halite plays a crucial role in the development of the
297 subsidence phenomena. Whereas the equilibrium solubility of gypsum at 25°C is 2.4 g/l,
298 halite and glauberite solubilities reach 360 and 118 g/l, respectively (Ford and Williams,
299 2007).

300

301 In this sector of the Ebro Basin the Tertiary bedrock is affected by subvertical joints and
302 small-throw normal faults with prevalent WNW-ESE, E-W and N-S trends (Arlegui and
303 Simón, 2001). The most penetrative WNW-ESE joint set plays a significant role in the
304 development of karstic depressions as revealed by the dominant orientation of the major

305 axes and alignments (Gutiérrez et al., 2007; Guerrero, 2008; Galve et al., 2009c).
306 Locally, the evaporitic bedrock displays abundant gravitational deformation (basin
307 structures, collapsed blocks, stratiform breccias and breccia pipes) generated by ductile
308 and brittle subsidence phenomena caused by interstratal karstification, most likely
309 preferential dissolution of halite and glauberite (Guerrero, 2008; Guerrero et al., 2008a,
310 b; Gutiérrez et al., 2008a). These dissolution-induced deformation structures are clearly
311 more abundant in the sectors where the bedrock is overlain by Quaternary alluvium,
312 where the interaction between the bedrock and aggressive groundwater has been more
313 intense.

314

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

325

326 Galve et al. (2009c) presented an analysis of the sinkholes developed in the lower
327 terraces of the Ebro Valley upstream of Zaragoza city. This work, mainly based on
328 conventional geomorphological mapping, covers a much wider area than that of this
329 study (40.8 km² vs 27.5 ha). The main findings of the cartographic analysis carried out
330 by Galve et al. (2009c) include: (1) Sinkholes cover approximately 8.2% of the area in
331 the studied stretch of the Ebro Valley. (2) Three main types of sinkholes have been
332 differentiated following the classification proposed by Gutiérrez et al. (2008a); small
333 cover collapse sinkholes related to the downward migration of alluvium through
334 dissolutional conduits; large cover and bedrock collapse sinkholes (>15 m) caused by
335 upward stoping of cavities developed within the bedrock; and cover and bedrock
336 sagging sinkholes produced by interstratal karstification and downward flexure of the
337 overlying bedrock and cover. (3) Sinkholes show preferred WNW-ESE orientations and
338 alignments and collapse sinkholes tend to form clusters. (4) The geomorphic expression

339 of approximately 70% of the sinkholes identifiable in aerial photographs taken in 1957
340 has been obliterated by artificial fills, with the consequent disappearance of 137 ha of
341 wetlands. (5) Subsidence causes losses of the order of millions of euros per decade and
342 the vast majority of the damage is concentrated within the boundaries of pre-existing
343 filled sinkholes. These two latter facts justify the need of developing complete and
344 accurate inventories of sinkholes, both visible and obscured, following a multiapproach
345 scheme as the basis for the application of preventive planning strategies.

346

347 **3. Methodology**

348 This investigation has been carried out in three phases. In the first stage we produced a
349 preliminary cartographic inventory of sinkholes and subsidence evidence interpreting
350 aerial photographs from different dates and with variable scales and resolutions (1927 -
351 1:10,000; 1957 - 1:33,000; 1984 - 1:30,000; 1998 - 1:5.000; 2003 - 1 m of resolution;
352 2006 - 10 cm of resolution; Fig. 3), identifying depressions depicted on detailed
353 topographic maps supplied by the municipality of Zaragoza from different dates (1969 –
354 1:2,000; 1971-72 – 1:1,000, both with contour lines every 1 m; Fig. 4), thorough field
355 surveys, and deformation data provided by an interferometric analysis (Fig. 2C). The
356 field surveys included: (1) Examination of the areas with InSAR deformation points and
357 the subsidence features detected in the aerial photographs and topographical maps. (3)
358 Multiple traverses in each portion of land. (4) Inspection of all of the human structures
359 searching for subsidence-related deformation (Fig. 2C). The subsidence damage on
360 buildings was classified using the ranking proposed by Cooper (2008). (5) Enquiries to
361 local people about the existence of sinkholes and subsidence damage. (6) Bathimetric
362 survey from a boat of a sinkhole that hosts a permanent pond.

363

364 The InSAR ground deformation data have been obtained in the frame of the European
365 Terrafirma Project (<http://www.terrafirma.eu.com>) using 23 ENVISAT images
366 spanning more than five years, from 2 May 2003 to 4 July 2008. The Spanish
367 photogrammetric elevation model “GIS Oleícola”, with 20-m pixel size and a vertical
368 accuracy higher than 5 m, provided by the Spanish Ministry of Agriculture, Fisheries
369 and Food, was applied to generate 54 interferograms. The applied Stable Point Network
370 technique (Arnaud et al., 2003) identified stable points (20-m pixel) with coherence
371 values from 0.62 to 0.98, representing reliable displacement rate measurements
372 (precision 1-3 mm/yr). The mean deformation velocity map provides mean subsidence

373 rate values estimated along the line of sight (LOS) on a limited number of pixels,
374 mainly due to decorrelation and loss of coherence in vegetated areas (Fig. 2C).
375 Nevertheless, this analysis has yielded a significantly higher number of subsidence rate
376 values than the deformation map previously generated through the Small Baseline
377 Subset (SBAS) technique using ERS-1 and ERS-2 images with a pixel size of 90 m
378 (Castañeda et al., 2009a, b).

379

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

389

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

397

398 The third stage of the investigation was focused on the excavation of 13 backhoe
399 trenches with a total length of 323 m and a maximum depth of 2.8 m (Fig. 2A). After
400 cleaning the vertical walls, a reference grid with horizontal and vertical strings spaced
401 1-2 m apart was placed in one side of the trenches, preferably the most shaded one. The
402 gridded walls were logged with graph paper. Trench TE in sinkhole S12 was not
403 mapped due to the instability of the walls and trench TK, in the same sinkhole, was
404 logged from outside of the excavation for the same reason. Trenches TA, TB and TJ
405 were finally linked into a single excavation. Charcoal fragments were only found in the
406 natural fill of sinkhole S8 in trench TG. The location of the trenches, conditioned by the

407 possibility of obtaining permits from the landowners and the presence of human
408 structures, was based on the following criteria: (1) Investigate areas with InSAR
409 displacement data and evidence of subsidence deformation in human structures (TABI,
410 TC, TD and TL). (2) Define precisely the limits of filled sinkholes (TF and TK in
411 sinkhole S12). (3) Check whether subtle scarps identified in old aerial photographs and
412 obscured by anthropogenic fill correspond to subsidence deformation features (TG and
413 TH in sinkhole S8). (4) Investigate anomalous geometries (apparent tilted strata)
414 displayed in GPR profiles (TI). (5) Check if filled sinkholes located in the immediate
415 vicinity of the area extend to the sector of interest (TM next to sinkhole S11).

416

417 **4. The sinkhole inventory**

418 The multiphase and multiapproach investigation carried out has allowed us to map 12
419 sinkholes (Fig. 2C), two of them located just outside the area of interest (sinkholes S10
420 and S11). Table 1 presents the typology, morphometry and chronology of the
421 inventoried sinkholes. The mapped karstic depressions cover around 20% of the area.
422 Solely five sinkholes have topographic expression (S3, S4, S5, S6 and S7), whereas the
423 rest have been masked by anthropogenic fills. Eight of the sinkholes form a tightly
424 packed cluster and four of them are nested in the large sinkhole S8, with an area of
425 around 35,500 m² (Fig. 5). Moreover, in the northwestern sector of the area, InSAR
426 displacement data, cracks in structures and the deformation mapped in trench TC (open
427 fissure and tilted strata) reveal the existence of an additional subsidence zone in the
428 northwestern sector of the area. However, in spite of the intense investigation carried
429 out by means of GPR and trenching in this sector, we were not able to define the limits
430 of this subsidence area. Consequently, we opted for the delineation of a line linking the
431 edge of the deformation zone of trench TC with the boundary of sinkhole S8, including
432 sinkholes S1, S2 and S3. We propose that the area located east of this line should be
433 considered as affected by sinkholes or particularly prone to subsidence (Fig. 2C).

434

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

440 S9 causes the continuous bending of the N-232 highway forming a large pothole around
441 100 m long that requires frequent re-asphalting (Fig. 2C).

442

443 **6. Contribution of the different methods to the sinkhole inventory**

444 *6.1. Aerial photographs, topographic maps and field surveys*

445 The aerial photographs and the old and detailed topographic maps from 1969 and 1971-
446 72 have been the most helpful sources of information for the identification of sinkholes.

447 All of the inventoried sinkholes except S12 have been recognized in air photographs
448 (Fig. 3). The most helpful ones happened to be the black and white images taken in
449 1957 and printed at a scale of 1:33.000. These photographs have the following

450 advantages: (1) Were acquired before the transformation of the landscape (excavation,
451 fill and urbanization) in this sector the Ebro Valley became significant (Galve et al.,
452 2009c). (2) Can be analysed with stereoscope. (3) In spite of their small scale, are very
453 sharp and have a high resolution. The black and white orthoimages from 1927 were not
454 so useful mainly because they are not so clear and cannot be viewed stereoscopically.

455 The contour lines of the 1969 topographic maps at 1:2,000 scale depict 7 sinkholes (S1,
456 S3, S4, S6, S7, S10 and S11), whereas the 1971-72 maps, despite having a larger scale
457 (1:1,000), illustrate only 4 karstic depressions (S4, S5, S6, S10; Fig. 4). One of the

458 advantages of the topographic maps with respect to the non orthorectified aerial
459 photographs is that they allow obtaining quite precise measurements of the axial lengths
460 and area of the depressions and estimating a minimum depth. On the other hand, the use
461 of images and maps from multiple dates gave us the opportunity of bracketing the age
462 of formation and filling of sinkholes. For example sinkhole S1 formed after the
463 acquisition of the 1957 aerial photographs and before the elaboration of the 1969
464 topographical map and sinkhole S2 was filled between 1927 and 1957 (Figs. 3 and 4).

465 The rest of the sinkholes, except S12, formed before 1927 or 1957, age of the oldest
466 aerial photographs (Table 1). The main contributions of the field surveys to the sinkhole

467 inventory include: (1) Mapping precisely the edges of the non filled sinkholes. (2)
468 Corroborating the presence of filled sinkholes through the identification of man-made
469 deposits and deformed structures (Fig. 6). The latter in some cases induced us to expand

470 the limits of some sinkholes initially mapped with aerial photographs and/or old
471 topographic maps. (3) Farmers indicated the approximate location of the buried
472 sinkhole S12, not recognizable in any remote-sensed image or topographic map.

473

474 6.2. *InSAR*

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

489

490 6.3 Ground penetrating radar

491 The quality of the GPR profiles was very variable. A significant number of the profiles
492 displayed very low penetration. This circumstance is attributed to the high humidity of
493 the soils in crop fields due to sheet-flooding irrigation and the high content of clay in
494 the man-made ground that covers the terrace surface to a great extent. An additional
495 pitfall is that some profiles showed tilted reflectors that turned out to be artefacts after
496 the excavation of trenches (Profiles C, D, S and T and trenches TF, TK, TI and TM).
497 Conversely, some GPR profiles provided highly useful information. The profile H
498 allowed us to confirm the existence of sinkhole S2, interpreted with a limited level of
499 confidence with the 1927 orthoimage (Fig. 7). This profile shows a reflector with a
500 synformal geometry 35 m long ascribed to the base of an artificial fill around 1 m thick
501 filling a sinkhole, most likely dominated by sagging subsidence. The GPR profiles P,
502 Bal 3 and Bal 4 facilitated the mapping of the edges of sinkhole S9. The profile P,
503 obtained along the NE shoulder of the N-232 highway, captured a synform around 70 m
504 long coinciding with the re-asphalted portion of the infrastructure in sinkhole S9.
505 Additionally, this profile did not show any evidence of deformation in the stretch of the
506 highway shoulder opposite to sinkhole S10, allowing us to map the limits of that karstic
507 depression outside of our study area. The profiles Bal 3 and Bal 4, carried out in the

508 garden of a private property, displayed a sharp change in the electrical impedance of the
509 subsoil coinciding with a degraded scarp, attributed to a change from natural ground to
510 a clay-rich artificial sinkhole fill and the edge of the sinkhole S9, respectively. The
511 profile B, acquired along an asphalt road, allowed us to corroborate sinkhole S12 and
512 locate it more precisely (Fig. 7). The existence and rough position of this buried
513 sinkhole was indicated by the local farmers. The reflectors of this profile show a
514 synform 30 m long affected by synthetic normal faults, consistent with the geometrical
515 relationships observed in the trenches TF and TK dug in the subsequent phase of the
516 investigation.

517

518 6.4. Trenching

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

538

539 The synform captured in the GPR profile B, acquired along an asphalt road, pinpointed
540 the location of the edge of the buried sinkhole S12 in two points (Fig. 7B). In order to
541 map this sinkhole more precisely and obtain information about its internal structure, two

542 aligned trenches perpendicular to the road and on both sides of the infrastructure were
543 excavated (TF and TK). The edges of the trenches were located coinciding with the core
544 of the synform detected in the GPR profile B (Fig. 2A). In the walls of trench TF we
545 identified a synthetic normal fault dipping towards the centre of the sinkhole and an
546 antithetic fissure. The fault juxtaposes fluvial sediments against man-made deposits and
547 shows a minimum vertical throw of 50 cm (Fig. 8). The fissure has a horizontal
548 separation of around 1 cm and could correspond to an incipient dome-shaped failure
549 related to loss of basal support. In trench TK a synthetic normal fault dipping towards
550 the centre of the sinkhole at a distance of 25 m from the fault identified in trench TF
551 was identified. Unfortunately, it was not possible to deepen this trench and it had to be
552 studied from outside due to the instability of the walls on the man-made ground. The
553 integration of the information gained with the GPR profile B and the trenches TF and
554 TK suggests that sinkhole S12 is a subcircular depression with a diameter of 25-30 m
555 generated by collapse and probably sagging.

556

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

564

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

574

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

604

605 Two charcoal samples were obtained from the natural sinkhole fill (unit 2) at 200 cm
606 (TG2a) and 140 cm (TG2c) below the ground surface (Fig. 9). Poznan Radiocarbon
607 Laboratory provided AMS radiocarbon ages in correct stratigraphic order; 2010±35 yr
608 BP (46 cal yr BC-26 cal yr AD) and 1685±30 cal yr BP (408-336 cal yr AD); error at 1σ

609 and calibration following CALIB v6.0 by Reimer et al. (2009). These dates allow the
610 calculation of an average sedimentation rate of 1.3-1.9 mm/yr between the accumulation
611 of the two sampled deposits. Assuming that the sediments in which the samples have
612 been collected where deposited at the current position of the topographic surface, we
613 can estimate average subsidence rates of 0.9-1.0 and 0.8 mm/yr using the dates of
614 samples TG2a and TG2c with an error margin at 1σ , respectively. It is important to take
615 into account that these values have been obtained close to the margin of the sinkhole.
616 The stratigraphy in the depocentral sector of the sinkhole would yield higher cumulative
617 subsidence values and subsidence rates.

618

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

626

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

641

642 **7. Discussion and conclusions**

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

661

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

676

677 As this study illustrates, the InSAR technique has the advantage of providing remotely
678 accurate measurements of the displacement of the ground and human structures in
679 extensive areas with a high spatial and temporal resolution. Additionally, the radar
680 technique may be applied to obtain deformation values retrospectively using scenes
681 acquired in previous dates. However, the loss of coherence, mainly related to the
682 presence of agricultural fields and vegetation, may considerably reduce the density of
683 measurement points. The radar deformation data allow the identification of active
684 sinkholes and subsidence areas that have been overlooked by conventional mapping
685 methods due to their subtle geomorphic expression or their buried character. The
686 subsidence rates provided by the interferometric analysis in the NW sector of the study
687 area were instrumental in the identification of a previously unknown subsidence area
688 (Fig. 2C). Additionally, deformation data, consistent with the preliminary sinkhole and
689 subsidence damage map helped us to determine or corroborate the active nature of some
690 of the sinkholes and in some cases to improve the location of the sinkhole edges.
691 Gaining average displacement velocity values and time series of deformation is a great
692 advance for the following reasons: (1) It may provide a quantitative measurement of the
693 activity of sinkholes, generally more convincing than other geomorphic data for
694 planners and decision makers. In filled sinkholes those rates may account for the
695 contributions of both dissolution-induced deformation and compaction. (2) Coherent
696 points with “no deformation” values may support the definition of *a priori* stable areas.
697 (3) Accurate subsidence values may serve to evaluate if the strain rate is tolerable by a
698 specific structure and to design structures capable of accommodating the deformation.
699 (4) Time deformation series may be used to analyse the impact of several factors on
700 sinkhole activity (i.e. earthquakes, water table changes, floods, irrigation, rainfall
701 events). (5) The InSAR technique might be useful for monitoring vulnerable structures
702 (dams, high-speed railways) and the anticipation of catastrophic collapse sinkholes
703 through the detection of precursory displacements (Ferretti et al., 2000b; Closson et al.,
704 2003; Castañeda et al., 2009a).

705
706 The ground penetration radar (GPR), although it has a limited penetration capacity and
707 its performance is adversely affected by the presence of clayey soils and water, allows
708 investigating the subsoil in a rapid way imaging the profiles directly in the field. Some
709 of the potential contributions of GPR for the identification and characterization of
710 sinkholes are: (1) Identifying shallow cavities. (2) Determine the depth of the rockhead

711 and water table and the geometry of the former. (3) Locating buried sinkholes and
712 delineating precisely the position of their edges. In the study area, the GPR profile B
713 was essential for situating sinkhole S12, whose position was roughly indicated by local
714 people (Fig. 7). Profile H helped to refine the previously mapped edge of sinkhole S2.
715 (4) Ruling out the presence of sinkholes in particular sectors. GPR profiles P and G
716 strongly suggest that sinkholes S10 and S11 do not affect the study area. (5)
717 Investigating the geometry of filled sinkholes and subsurface deformation structures.
718 Some of the geometries that may be observed include synforms, tilted and faulted
719 reflectors, units with lateral wedge-outs, onlaps or local interruptions in the reflectors or
720 changes in the electromagnetic behaviour attributable to loosened or collapsed material.
721 In some cases it may be necessary to investigate the meaning of some of these GPR
722 signals by intrusive methods. For example the inclined reflectors of some profiles
723 turned out to be artefacts via trenching. (6) Deciding about the most favourable location
724 for trenching or drilling. This may be done just before digging the trenches examining
725 the GPR profiles in the field. For example, in this investigation trenches TK and TF
726 were sited on the basis of the geometries observed in the GPR profile B.

727
728 The data gained by means of the trenching technique were especially useful for the
729 urban planning process. Trench TM, in agreement with the GPR profile Q, revealed that
730 sinkhole S11 does not extend into the study area. Trench TC allowed us to locate
731 precisely in a particular sector the edge of a subsidence area identified by means of
732 InSAR displacement data and subsidence damage in human structures. It also
733 demonstrated that two of the areas selected for the construction of buildings overlap
734 active subsidence structures. Trenches TF and TK contributed to define the edges of the
735 filled sinkhole S12 and to determine the subsidence mechanism; collapse controlled by
736 synthetic normal faults. Trenches TG and TH were dug perpendicularly to the SE edge
737 of sinkhole S8 as mapped following a subtle scarp identified in the 1957 aerial
738 photographs. The position of the limit of this sinkhole, which overlaps the planned area
739 for new buildings, was challenged. However, the deformation observed in these
740 trenches corroborated the aerial photograph interpretation and helped to map the limit of
741 the area affected by subsidence more precisely. The stratigraphic and structural
742 relationships of these trenches revealed that subsidence in sinkhole S8 in this sector is
743 accommodated by sagging and a secondary collapse component recorded by normal
744 faulting. Cumulative subsidence values of 1.5 and 1.8 m were measured in trenches TG

745 and TH, respectively. Additionally, two radiocarbon dates obtained from charcoal
746 fragments collected from a natural sinkhole fill deposit in trench TG (46 cal yr BC-26
747 cal yr AD and 408-336 cal yr AD) allowed us to obtain a minimum age for the sinkhole
748 and to calculate long-term subsidence rates ranging from 0.8 to 1 mm/yr. Both the
749 deformation magnitude and subsidence rates must be considered as minimum values
750 since they were not obtained in the depocentral sector of the sinkhole. A very important
751 advantage of the trenches was that they allowed the planners to put their eyes on the
752 failure planes that define the margins of sinkholes, providing unquestionable evidence
753 for the existence of buried active sinkholes.

754

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759

760

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966 **Figure captions**

967

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

971

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

977

978 Figure 3. Aerial photographs of the study area from different dates. Most of the
979 inventoried sinkholes are recognizable in the 1957 images. Sinkhole S1 formed between
980 1957 and 1984 and by the latter date the geomorphic expressions of several sinkholes
981 was obliterated by artificial fills.

982

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

986

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

991

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

995

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

1000

1001 Figure 8. Logs of trenches TC and TF. See location in Figure 2A and explanation in
1002 text. Inset photograph of trench TC.

1003

1004 Figure 9. Logs of trenches TG and TH. See location in Figure 2A and explanation in
1005 text. Inset photograph of trench TG.

1006

<i>Sinkhole</i>	<i>Type</i>	<i>Length-width or diameter(m)</i>	<i>Depth(m)</i>	<i>Area(m²)</i>	<i>Age</i>
<i>S1</i>	collapse	55-60	1,5?	2827	1957-1969
<i>S2</i>	sagging	70x25	1?	1374	pre-1927
<i>S3</i>	collapse	20-25	2,5-3	490	pre-1927
<i>S4</i>	collapse	25-30	5	706	pre-1927
<i>S5</i>	collapse	65x40	9-10	2042	pre-1927
<i>S6</i>	collapse	40	4?	1256	pre-1927
<i>S7</i>	collapse	20	4?	314	pre-1927
<i>S8</i>	sagging /collapse	-	1-1,5	35,500	pre-1927
<i>S9</i>	sagging /collapse	110-120	2-3?	11,309	pre-1957
<i>S10</i>	collapse?	70	2-3	3846	pre-1927
<i>S11</i>	¿	110x?	¿	¿	pre-1927
<i>S12</i>	collapse	25-30	¿	490	>40 years

1007 Table 1. Typology, morphometry and chronology of the inventoried sinkholes.

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