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Development and validation of sinkhole susceptibility models in mantled karst settings. A case study from the Ebro Valley alluvial evaporite karst (NE Spain)

J.P. Galve (1), F. Gutiérrez (1), J. Remondo (2), J. Bonachea (2), A. Cendrero (2), J. Guerrero (1), P. Lucha (1), M. Gutiérrez (1) and J.A. Sánchez (1)

(1) Earth Sciences Department, Univ. of Zaragoza, Spain, (2) DCITIMAC, Univ. of Cantabria, Spain (fgutier@unizar.es / Phone: +34-976-761090)

This research forms part of a 3-year project (CGL2004-02892) founded by the Spanish Government and the FEDER that investigates whether it is possible to generate sound sinkhole susceptibility zonations analysing the statistical relationships between the known sinkholes in a given area and the available potential causal variables and assessing quantitatively the reliability of the predictive models through the application of cross-validation techniques. At this stage, a spatial database on sinkholes and potential causal variables has been already compiled. The project is on the point of starting the development and validation of sinkhole susceptibility models. Will the models provide a reasonably good prediction?

Sinkhole activity caused by the suballuvial karstification of halite and glauberite-bearing evaporites produces substantial economic losses in the Ebro River valley, upstream and downstream of Zaragoza city (NE Spain). This study is focused on a reach of the Ebro River valley around 70 km^2 in area located downstream of Zaragoza city. Here, the Ebro Valley is excavated in a horizontally lying gypsiferous sequence underlain by a shale and marl unit. The thickness of the gypsum bedrock beneath the valley bottom diminishes towards the downstream margin of the study area where the alluvium rests directly on the impervious shale and marl unit. The Quaternary alluvium has a highly variable thickness and locally fills dissolution-induced basins more than 50 m deep generated by synsedimentary subsidence. Three different geomorphic sectors have been differentiated: (1, 2) Alluvial fans and lower Ebro River terrace (+10-14 m above the current channel) in the northern and southern margins of the valley. The slightly cemented terrace gravels are interdigitated and overlain by alluvial fan facies primarily composed of gypsiferous silts; (3) Ebro River flood plain with two subsectors: a) The Ebro River channel and a belt of abandoned meandering channels locally hosting oxbow lakes that were active in historical times; b) The relatively inactive sector of the flood plain.

(1) *Alluvial fans and lower Ebro River terrace in the northern sector:* Although a highly active collapse sinkhole field has been studied in this geomorphic sector very close to the study area (158 sinkholes in 0.25 km^2), no evidence of modern subsidence has been detected.

(2) *Ebro River flood plain:* Around 100 sinkholes have been mapped in this sector. The density of sinkholes and the percentage of the area affected by sinkholes are remarkably lower in the meander belt than in the rest of the flood plain. Two types of sinkholes have been identified in this sector: a) Shallow and diffuse-edged depressions up to 1 km long generated by progressive bending. These flood-prone large subsidence depressions are commonly colonised by palustrine or halophilous (*Suaeda vera*) vegetation and are frequently used for the illegal disposal of wastes. From 1956, the area of these basins has been reduced by anthropogenic fill from 50 to 2 ha, covering 7% and 3% of the flood plain area, respectively. b) Collapse sinkholes 30-40 m across and 4-6 m deep filled with highly concentrated phreatic waters (up to 6.5 mS/cm). This type of sinkholes occur solely in the upstream sector of the flood plain, probably because the gypsum sequence in the downstream sector is not thick enough for the development of large cavities. Recently, the reactivation of a filled collapse sinkholes engulfed a tractor.

(3) *Alluvial fans and lower Ebro River terrace in the northern sector:* Some 400 collapse sinkholes have been mapped in this area, commonly around 1.5 m in diameter with overhanging margins. The probability of occurrence of sinkholes is above 40 sinkholes/km^2year. The majority occur associated with canals, irrigation ditches and leakages from service pipes. It seems that the anthropogenic water input promotes the migration of the alluvial cover through previously existing solution pipes. In a downstream direction the density of sinkholes shows a marked increase followed by an abrupt decrease to cero. This seems to reflect a downstream concentration of the underground flow lines caused by the thinning of the karstic bedrock which gives way to an impervious substratum. On the other hand, the downstream portion of the alluvial fans show a relatively higher sinkhole density. This may be explained by the influence of the inclination of the valley on the flow of the groundwaters derived from the adjacent drainage basins. Damage caused by sinkholes in this area include: (a) The construction of the Imperial Canal was interrupted in 1790, 50 km before its final point; (b) Derailment of a train in the 90´s caused by a flood-induced sinkhole in a

ditch culvert (Km 360.7), speed limitations and frequent repair works; (c) Recurrent sinkholes in the N-232 road, commonly associated with ditch culverts; (d) Frequent leakage-induced sinkholes in a residential estate. The replacement of the water pipe network had a total cost of 1 million euros; (e) Continuous damages in the irrigation network and crop fields. The Irrigation Union estimate losses of around 80 euros/ha year; (f) Serviceability of water tanks affected by sinkholes.