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A probabilistic approach to sinkhole hazard modelling. The case study of the Ebro Valley evaporite karst (NE Spain)

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A method for quantitatively assessing sinkhole susceptibility (spatial probability) and hazard (temporal-spatial probability) has been developed and independently tested in a 50 km^2 sector of the Ebro valley alluvial evaporite karst. The bedrock consists of subhorizontally lying halite and glauberite-bearing evaporites that grade into shales in a downstream direction. Two main morpho-hydrological domains can be differentiated: the floodplain (discharge area), and the low terraces of the Ebro River located on both flanks of the valley (perched aquifers). Three genetic types of sinkholes have been identified: large sagging sinkholes (Type 1) and large collapse sinkholes (Type 2) in the floodplain, and small cover collapse sinkholes (Type 3) located in the southern terrace. A spatial database composed of a sinkhole inventory and 29 thematic layers related to potential conditioning factors has been constructed and implemented in a GIS. The sinkhole inventory includes two temporal populations: 494 sinkholes formed before November 2005 (24, 23 and 447 sinkholes of types 1, 2 and 3, respectively), and 500 type 3 sinkholes formed in the southern terrace between November 2005 and November 2006. The 8 most significant factors were selected by means of visual examination of map overlays and sensitivity analyses: geomorphological units (geomor), lithological gradient (gradient), electrical conductivity of the alluvial aquifer (ec), gypsum saturation index (si_gyp), alluvium thickness (thickness), annual variations of the piezometric surface (piezovar), irrigation network (irriga) and land use (landuse). Multiple susceptibility models were generated analysing the statistical relationships between the sinkholes formed before November 2005 and combinations of factors using Favourability Functions (empirical likelihood ratio models). The ap-

plication of a random split validation method to the models has allowed us to assess their prediction capability and to determine the variables that best explain the spatial distribution of each type of sinkhole, as well as their contribution to the prediction in the study area. In the best susceptibility models of type 2 and 3 sinkholes, more than 90% of the sinkholes of the validation samples occur on the 10% of the pixels with the highest susceptibility. The susceptibility models generated for type 1 sinkholes show a lower prediction capability, with around 80% of the sinkholes of the validation sample occurring on the 20% of the pixels with the highest susceptibility. The best sets of variables are: geomor, gradient, thickness, piezovar, ec, si_gyp for type 1 sinkholes; geomor, thickness, piezovar, ec, si_gyp for type 2 sinkholes; and geomor, gradient, ec, si_gyp, irriga and landuse for type 3 sinkholes. Validation of the models also reveals that the improvement of some thematic layers with high uncertainty does not significantly contribute to increase the quality of the models. Susceptibility models of type 3 sinkholes have been validated with the sinkholes formed between November 2005 and November 2006 (temporal validation). Around 80% of the new sinkholes occur on the 10% of the pixels with the highest susceptibility. In a subsequent step, the best susceptibility model has been transformed into a hazard map considering the mean size of the new sinkholes and the frequency of the new sinkholes. This hazard model provides a minimum probability for a pixel to be affected by a sinkhole in a given period, or the area of each equal-area susceptibility class that may be affected by sinkholes per year (temporal-spatial probability). These results indicate that probabilistic models can provide good predictions on the future spatial and temporal distribution of sinkholes in the study area. The susceptibility and hazard zones identified could be very useful for the effective application of preventive and corrective mitigation measures.