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Human-induced hydrological changes and sinkholes in the gypsum karst of Lesina Marina area (Foggia Province, Italy)

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The Lesina Lagoon is located in the East-West-trending northern cost of Gargano (southern Italy). The lagoon is fed by springs draining the northern side of the Gargano Mesozoic carbonate aquifer and is connected with the sea by three channels, including the 2.2 km long Acquarotta Canal with a N-S orientation. The sea-side mouth of this canal was frequently clogged by sand accumulation. In 1927, the path of the northern section of this canal was changed to improve the water exchange between the lagoon and the Adriatic Sea for environmental and fish-farming purposes. The new portion of the canal, 8.5 m wide and 1.5 m deep, was excavated in evaporite bedrock and in a small outcrop of igneous rocks situated in the coast that inhibits sand accumulation. The Acquarotta Canal conveys water in both directions depending on the relative water levels of the lagoon and the sea. Initially the reach of the canal dug in gypsum was lined with concrete, which was replaced in 1993 by gabions for scenery improvement.

The northern reach of the canal is dug in Upper Triassic gypsiferous sediments of the Burano Anhydrite Formation. The evaporite bedrock is mantled by unconsolidated deposits a few meters thick, largely made up of loose sand. The exposures found in the banks of the canal and in some sinkholes reveal that the gypsum has a high density of dissolutional conduits and cavities. Locally, it also shows open fractures and brecciated structure (crackle, mosaic and chaotic packbreccias) caused by dissolution-induced collapse processes. These voids, either of solutional or mechanical origin, are partially filled with detrital sediments derived from the mantling deposits. These features seem to correspond to a paleokarst, probably developed at several depths controlled by different and much lower sea level stands during the Quaternary.

The construction Acquarotta Canal has caused significant changes in the local hydrology. According to the piezometric series recorded at several points distributed over a large area around the canal and the results of numerical simulations, the main hydrological changes include: (1) Incorporation of new boundary conditions. The groundwater flow, previously controlled by the oscillating sea level and by the lagoon level, has been altered introducing a line of minimum potential along the canal. The water level in the canal oscillates according to the variations in the levels of the sea and the lagoon. (2) The gypsum bedrock that behaves as an anisotropic aquifer, is drained by a channel in which the flow, essentially controlled by the tidal regime, discharges two times a day towards the sea and towards the lagoon. (3) The canal that works as a drainage trench, has caused the lowering of the water table. The local distortion of the piezometric surface has modified the flow direction and increased the gradient and flow rate. At the flanks of the canal, the groundwater that used to flow towards the sea, now has been captured by the excavation and circulates towards the canal. The sense of this flow is influenced by the piezometric changes caused by the tidal variations. (4) As a consequence of the lowering of the water table (of the order of a few decimetres) near the banks of the canal, slow subhorizontal phreatic flows have been replaced by more rapid downward vadose flows.

These hydrological changes have induced the reactivation-acceleration of internal erosion and collapse processes leading to the generation of a large number of sinkholes in the vicinity of the canal. The lowering in the water table involves an increase in the effective weight of the sediments previously situated in the saturated zone due to the loss of buoyancy. Additionally, downward vadose flows and more rapid water circulation in the saturated zone towards the canal favour the flushing out of the sediments filling voids and the downward migration of cover material towards the underlying paleokarst. Most likely the continuous oscillations of the piezometric level and the associated bidirectional changes of the groundwater flow in the vicinity of the canal play a relevant role in the

internal erosion processes. The low cohesion of the sandy cover determines to a great extent the high speed at which suffosion processes and the generation-enlargement of sinkholes are taking place.

Subsidence activity has affected the canal since its construction. To our knowledge, the first account of a sinkhole occurrence in the adjacent area corresponds to an official report dating back to 1990. The great majority of the sinkholes are located within the canal and on two relatively narrow bands situated on its flanks. The sinkholes tend to form clusters and alignments with a prevalent N145E orientation. The Lesina Marina residential area, whose construction in the western side of the canal started around 1980, is currently suffering from subsidence damage, including the occurrence of collapse sinkholes in streets, destruction of pathways and cracking of walls. Boreholes and geophysical surveys performed in the area reveal the presence of abundant cavities up to 9 m in height, cave fills and collapse breccias in the strongly karstified bedrock. Most of the depressions can be classified as cover suffosion and collapse sinkholes generated by the downward migration of the loose sandy cover through voids in the bedrock. The lack of basal support caused by piping may lead to the gradual settlement of the cover and/or its collapse through the development of failure planes. These sinkholes are typically less than 1 m across and 2-3 m deep at the initial stages. However, they typically grow very rapidly by mass wasting processes acting on their edges until they reach the repose angle of the detrital mantle. Consequently, clusters of small sinkholes tend to evolve into a smaller number of large depressions up to 20 m meters across resulting from the coalescence of several dolines. Some sinkholes are related to the breakdown of cavities situated within the bedrock. These bedrock and cover collapse sinkholes are generally deeper reaching up to 7 m in depth.

Detailed surveys carried out in 1999, 2005 and 2007 indicate that the area affected by sinkholes is increasing exponentially. These data indicate that the subsidence area has increased at a mean rate of 1000 m2/year between 1999 and 2007. The spatio-temporal evolution pattern of the phenomenon strongly suggests that subsidence will affect to a progressively larger area in the future. Given the proximity of some buildings to rapidly growing sinkhole clusters, it seems highly probable that some structures will be severely damaged by subsidence. Restoring the original hydrological situation would help to reduce the sinkhole hazard. However, the rapid increase that is undergoing the rock mass permeability due to the reactivation of the paleokarst may hamper the effectiveness of this measure.