GIS-based sinkhole susceptibility mapping in a karst mountain environment: the Vallepietra area and the Holy Trinity Sanctuary (Monti Simbruini, Central Italy)

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Short Note

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ABSTRACT

This study aims to identify areas with high susceptibility to natural sinkholes within a park area of the Municipality of Vallepietra (Rome), surrounding the Sanctuary of the Holy Trinity, a site of significant cultural and religious value and a destination for approximately 500,000 pilgrims per year. The area has been affected by collapse and landslide phenomena, which appear to be associated with intense karst processes. The genesis of sinkholes in the study area is strictly related to karstification, which is amplified and/or triggered by seismic events, as well as by additional factors linked to anthropogenic activities and uncontrolled infiltration, cause the presence of abundant springs and aqueducts.

The analyses indicate that ensuring the safety of the Sanctuary requires multidisciplinary interventions based on a multi-risk assessment approach that considers the interaction among geological, geomorphological, and hydrogeological processes. Within an area of 160 km^2, 215 relict karst landforms were inventoried and georeferenced, supported by three field surveys at Monte Autore (1,669 m a.s.l.). The integration of all datasets within a GIS environment and their use in predictive modelling, through correlations with morphological, geological, and tectonic predictors, allowed the production of a first sinkhole susceptibility map for the Vallepietra area.

Five karst depressions were analyzed in detail above the Sanctuary: three solution sinkholes and two rock-collapse sinkholes. Additionally, five hypogeal karst environments were identified beneath the Sanctuary, partly modified by anthropogenic activity. These features represent a critical element due to intense water infiltration, which may induce sudden roof-collapse phenomena directly beneath the structure. Anthropogenic activities, meteorological events, and seismic activity may act as triggering factors for further collapse events.

KEYWORDS: sinkhole susceptibility, karst geohazards, GIS-based modelling, cultural heritage, Central Italy.

INTRODUCTION

Sinkhole phenomena represent a major geohazard in karst environments worldwide, affecting both natural systems and human activities due to their sudden occurrence and potentially severe impacts on infrastructure and cultural heritage. They are among the most complex geomorphological processes, resulting from the interaction between geological, hydrogeological, and anthropogenic factors (Caramanna et al., 2008; Nisio, 2003, 2008; Nisio et al., 2005). Their occurrence is typically controlled by soluble lithologies, structural discontinuities, groundwater circulation, and triggering mechanisms such as intense rainfall, seismic events, or human activities. These phenomena are particularly critical in areas where natural hazards intersect with cultural heritage and human presence, requiring integrated multi-risk approaches.

In recent years, increasing attention has been devoted to the development of susceptibility models aimed at predicting the spatial occurrence of sinkholes, particularly in areas where direct observations are limited. Several approaches have been proposed, ranging from heuristic methods to statistical and machine-learning models (Gutiérrez et al., 2014; Ciotoli et al., 2015; Bianchini et al., 2022; Wood et al., 2023). The growing availability of spatial datasets and GIS-based techniques has significantly improved the capability to assess sinkhole susceptibility (Ciotoli et al., 2015; Meloni et al., 2013). Among these approaches, presence-only statistical models such as Maximum Entropy (MaxEnt) have proven particularly effective in karst environments characterized by incomplete inventories. However, the application of such methods requires a robust geological and geomorphological framework, as well as a detailed understanding of local processes.

Within this international framework, the present study contributes to ongoing research by applying a GIS-based susceptibility analysis to a karst area of the central Apennines (Italy), characterized by both active geomorphological processes and significant human presence. Despite the increasing number of studies on sinkhole susceptibility, a clear gap remains in the integration of field-based geomorphological data, historical information, and predictive modelling in mountain karst environments, especially in areas of high cultural value.

The study area is located in the Municipality of Vallepietra (RM), within the Monti Simbruini Regional Natural Park, and includes the Sanctuary of the Holy Trinity. This site is not only of great geological interest but also of exceptional cultural and religious importance, attracting hundreds of thousands of pilgrims each year. According to historical sources, the origins of the Sanctuary date back to the early medieval period, with the earliest documented evidence from the 11th century, while the development of the cult is associated with later ecclesiastical documents.

A key element of the local cultural framework is represented by the so-called "legend of the Sanctuary," which recounts a sudden subsidence or collapse event interpreted as miraculous and considered the origin of the religious worship at the site (Ciociaria in Tour website; Parco Naturale Regionale dei Monti Simbruini website; Santuario della SS. Trinità website; Vallepietra Planet website). Although traditionally framed within a spiritual context, this narrative may reflect the memory of an actual geomorphological event, likely related to sinkhole formation processes. From a scientific perspective, the described sudden ground failure and vertical displacement are consistent with collapse processes typical of karst environments and are compatible with the development of a rock-collapse sinkhole, generated by the failure of cavity roofs within carbonate bedrock. Such processes are commonly controlled by structural discontinuities and groundwater fluctuations (Nisio, 2010, 2014; Amirante & Nisio, 2023). Therefore, the legend may represent a geomorphological memory of a past collapse event, later reinterpreted within a religious context. The integration of historical accounts with geological evidence represents an important aspect in understanding the long-term evolution of hazard in the area.

Within this context, the identification of sinkhole susceptibility is not limited to the recognition of high-risk areas, but represents a fundamental tool for understanding the spatial distribution of predisposing conditions controlling sinkhole development. The classification into low-, medium-, and high-susceptibility classes allows the evaluation of the relative importance of geological, geomorphological, and hydrogeological factors, providing a more comprehensive interpretation of the processes governing sinkhole occurrence. This approach enhances the scientific significance of the analysis and supports both hazard assessment and land-use planning.

The Vallepietra area, hosting the Sanctuary of the Holy Trinity, represents a particularly relevant case study due to the coexistence of active karst processes, hypogeal cavities, and intense anthropogenic pressure. In this framework, the aim of this study is to reconstruct the geological–structural, hydrogeological, and geomorphological setting of the area through the integration of field data, historical information, and GIS-based modelling. The ultimate goal is to identify the concurrence of predisposing and triggering factors controlling sinkhole development and to produce a first susceptibility map that can support both local risk mitigation strategies and broader applications in karst environments of the central Apennines.

STUDY AREA

The study area lies within the Monti Simbruini Regional Natural Park, one of the largest protected areas in the Lazio Region, characterized by elevations exceeding 2,100 m a.s.l. The Monti Simbruini ridge represent a major hydrogeological system of the central Apennines, hosting extensive carbonate aquifers and a well-developed karst network.

From a geological standpoint, the area belongs to the "Lazio–Abruzzi" carbonate platform succession, composed of thick Mesozoic shallow-marine deposits, mainly limestones and dolostones, locally overlain by more terrigenous units (Servizio Geologico d'Italia, 1997; D'Orefice et al., 2019). This succession, reaching thicknesses of several thousand meters, developed in a passive margin setting and was later affected by compressional tectonics associated with the Apennine orogeny.

The structural framework is characterized by fault systems and fracture networks that strongly influence both the morphology and the hydrogeological behaviour of the area. These discontinuities control groundwater circulation and contribute to the development of karst cavities and dissolution features.

Karstification processes are particularly intense due to the combination of soluble lithologies, high permeability, and abundant water availability. The area hosts numerous epigeal and hypogeal karst forms, including dolines, sinkholes, caves, and underground drainage systems. The presence of deep aquifers and artesian conditions further enhances dissolution processes and contributes to the instability of underground cavities.

The Sanctuary of the Holy Trinity is located approximately 12 km from the town of Vallepietra at an elevation of 1,373 m a.s.l. (Fig. 1a), at the base of a steep limestone cliff approximately 300 m high (Colle della Tagliata; Chiessi, 2023a, b; Fraccica, 2024). This geomorphological setting represents a critical condition, as the interaction between gravitational processes (rockfalls), karstification, and groundwater dynamics creates a highly complex hazard scenario.

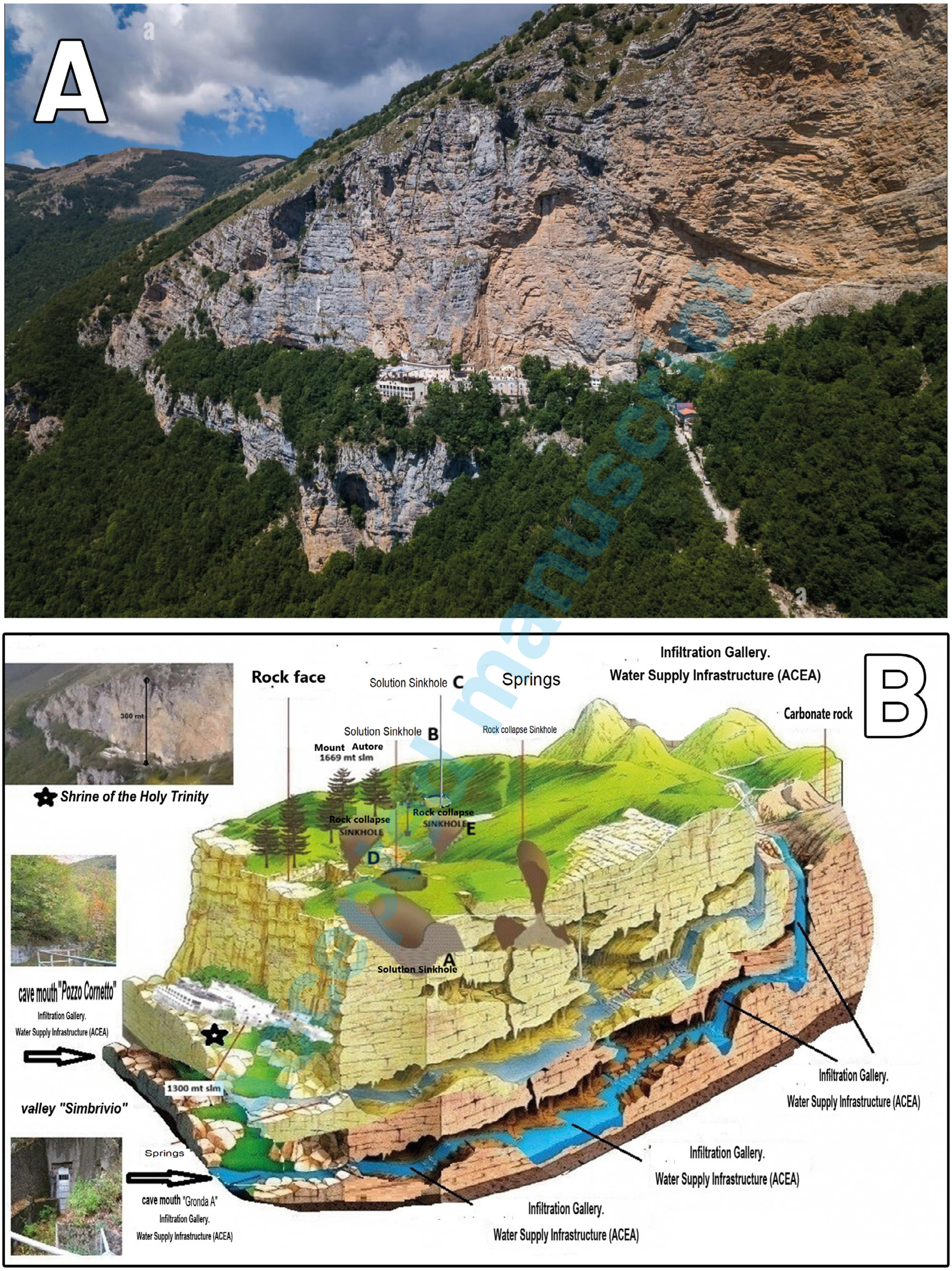

Fig. 1 - a) The Holy Trinity Sanctuary (Vallepietra, Central Italy) located at the base of the Monte Autore limestone cliff. The site represents a major religious destination (~500,000 visitors per year) and is characterized by a complex geomorphological setting where karst processes, rockfall activity, and groundwater circulation interact. b) Conceptual model of the karst system at Monte Autore. The scheme illustrates the relationships between epigeal karst landforms (dolines and sinkholes), hypogeal cavities (karst galleries), structural discontinuities (faults), and groundwater circulation. The position of the Holy Trinity Sanctuary at the base of the cliff highlights its exposure to potential collapse and subsidence processes.

MATERIALS AND METHODS

A Digital Terrain Model (DTM) with a spatial resolution of 10 m (https://tinitaly.pi.ingv.it/) was used to reconstruct the morphology of the study area, together with topographic and thematic maps provided by the Park Authority. In addition, a comprehensive inventory of sinkholes across the entire Simbruini Mountains Regional Park was carried out. The area was further analyzed through photogrammetry and high-resolution orthophotos to identify karst landforms and relict karst features. Moreover, detailed geological and geomorphological field surveys were conducted within the selected study area.

Karst landforms were distinguished from relict karst landform features through an integrated analysis of geomorphological, morphometric, and field-based criteria. Active karst features were identified based on the presence of well-defined morphological expressions, sharp boundaries, and clear connections with present-day hydrological processes, such as infiltration pathways, drainage patterns, and associated karst springs. These features typically show fresh morphologies, limited infilling, and direct interaction with the current karst system (Calligaris et al., 2017a, b, 2019, 2020).

In contrast, relict karst features were recognized as relict landforms, characterized by subdued morphology, partial or complete infilling, and a lack of direct connection with the present hydrological network. Additional criteria included their spatial relationship with ancient geomorphological surfaces, evidence of sedimentary filling, and their occurrence in areas disconnected from active karst processes. Field surveys played a key role in validating these interpretations, allowing the assessment of internal structure, degree of weathering, and sediment infill.

The distinction between active karst and relict karst landforms is essential for susceptibility analysis, as only active or recently reactivated forms are directly related to present-day sinkhole hazard, while relict karst features mainly provide information on the long-term evolution of the karst system. Field surveys allowed the validation and classification of the inventoried sinkholes. In addition, direct investigations were conducted at the base of the slope to inventory and characterize hypogeal karst features (galleries).

A first conceptual model was developed (Fig. 1b), providing a preliminary framework for identifying areas potentially exposed to geological hazards.

Bibliographic and cartographic data were digitized and integrated into a GIS environment in order to produce a first sinkhole susceptibility map. Predictive modelling was carried out using the MaxEnt (Maximum Entropy) algorithm, a statistical approach widely applied in geohazard studies (Galve et al., 2009; Wu et al., 2019). The choice of this method was motivated by its ability to effectively handle presence-only data (dolines and sinkholes), its strong predictive performance, robustness against overfitting, and its capability to estimate probability distributions even with relatively small datasets. Furthermore, MaxEnt provides easily interpretable outputs in the form of probability maps, which are particularly useful for hazard assessment.

Sinkholes identified in the study area were classified according to the genetic classification proposed by Caramanna et al. (2008), Nisio et al. (2007), Nisio (2023) which distinguishes solution, collapse sinkholes based on their formation mechanisms. This classification scheme was selected due to its relative simplicity and applicability in field-based studies, as well as its reduced dependence on subjective interpretation compared to more complex classification approaches. In particular, the adopted scheme minimizes operator-related bias, allowing a more consistent and reproducible classification of sinkholes. Moreover, it enables comparison with other karst regions at both national and international scales.

RESULTS

Within the study area, extending over approximately 160 km^2, an inventory of sinkholes in the Regional Park of the Simbruini Mountains was carried out (Fig. 2). A total of 215 karst depressions were identified, analyzed, and classified according to the framework developed in Italian case studies by ISPRA (Caramanna et al., 2008; Nisio, 2003, 2008; Nisio et al., 2005; Nisio, 2023).

The analysis led to the recognition of two main sinkhole typologies—solution sinkholes (12 sinkholes) and rock collapse sinkholes (203 sinkholes)—classified following the schemes proposed by Nisio et al. (2007) and Caramanna et al. (2008).

A detailed study area was selected in the surroundings of the Sanctuary of the Holy Trinity (highlighted by a red square in Fig. 2), where detailed geological and geomorphological surveys were carried out.

In this area, located above the cliff overlooking the Sanctuary, five sinkholes were documented and subjected to morphometric analyses, including two of them classified as rock-collapse sinkholes and three as solution sinkholes. Beneath the Sanctuary, five hypogeal environments were inventoried, two of which are used for anthropogenic purposes as drainage galleries. In Fig. 1b, three of the identified sinkholes are indicated by points above A, B and C.

Particular concern is associated with rock-collapse sinkholes D and E, which are directly connected to the hypogeal gallery "Gronda A" located beneath the Sanctuary.

This hypogeal environment consists of a gallery approximately 220 m in length, partly modified by anthropogenic activity and enlarged for aqueduct-related uses. The presence and activity of a fault system in the vicinity of sinkholes A and B represents an additional cause for concern regarding groundwater circulation within the network of these structural discontinuities. The occurrence of past rock-collapse phenomena is further supported by historical analyses documenting a legend of a subsidence event upon which the Sanctuary was built (Santuario della SS Trinità website).

With regard to the hydrogeological setting, field surveys confirmed the presence of pressurized groundwater exerting an upward support force on the roofs of karst cavities and a hydrostatic confining pressure within the overlying unconsolidated alluvial aquifer levels above the carbonate lithologies. These supporting actions cease when piezometric or phreatic levels drop, and the loss of hydraulic "support" promotes the collapse of cavities

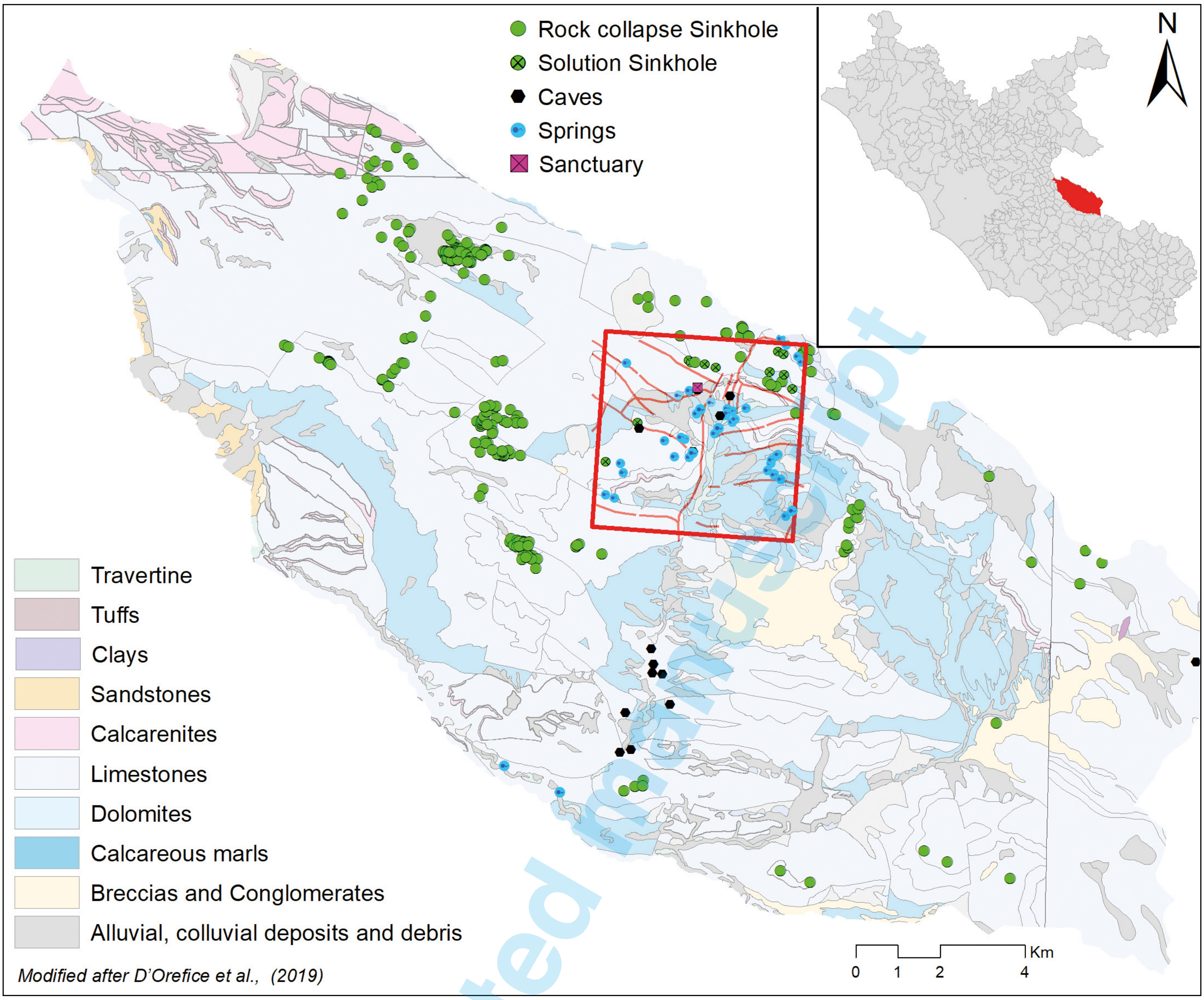

Fig. 2 - Lithological map and inventory of karst sinkholes within the Regional Park of the Simbruini Mountains. The red square highlights the detailed study area, where high-resolution geological and geomorphological surveys were conducted.

within the limestone basement and subsidence phenomena in the overlying cover sediments. Subsequently, all risk levels (multi-risk analysis) were assessed in relation to the potential instabilities and the identified hypogeal and epigeal karst landforms (Chiessi, 2023a, b).

The results of the susceptibility analysis are presented below, including model performance and spatial distribution of sinkhole-prone areas.

Susceptibility Analysis

A preliminary susceptibility model was developed (Ciotoli et al., 2015; Meloni et al., 2013), which can be further refined through the integration of additional data, as new variables may provide increasingly detailed information and analyses. The following data layers were included in the GIS project: surface karst landforms, hypogeal karst features (galleries), springs, surface hydrography, faults, lithology, and the DEM.

Predictive modelling was carried out using MaxEnt (Maximum Entropy), which is based on the principle of maximum entropy: among all probability distributions that satisfy the constraints imposed by the known data, the one with the maximum entropy is selected (i.e., the least “informative” or least assumption-driven distribution). Figure 3 shows the graphs, and Table 1 provides a summary of the analyzed variables. The ROC curve indicates the reliability of the selected model with the listed variables (Fig. 3).

Table 1 shows that elevation, lithology and TPI jointly explain more than 70% of the model contribution.

The response curves of the main variables indicate that the DTM (continuous variable), lithology, and topographic position index (TPI) alone explain nearly 75% of the variance. In addition, the presence of karst galleries appears to play an important role.

A detailed geological–structural survey of the study area was conducted (see Figure 4 a), providing the fundamental dataset for the susceptibility analysis. The integration of structural features,

Table 1 - Contribution and permutation importance of the environmental variables used in the MaxEnt model. Elevation (DTM), lithology, and topographic position index (TPI) are the most influential predictors, jointly accounting for the majority of the model contribution. The relatively high importance of karst caves and faults highlights the role of subsurface karst development and structural control in sinkhole formation, whereas hydrographic variables show a negligible influence.

Variable	Percent contribution (%)	Permutation importance (%)
Elevation (DTM)	26.8	39.0
Lithology	25.3	12.3
Topographic Position Index (TPI)	23.6	15.4
Karst caves	12.8	14.8
Faults	8.7	14.0
Slope	2.0	3.6
Hydrography	0.4	0.0
Springs	0.4	0.9

lithological variability, and field-mapped elements—such as sinkholes and spring locations—enabled a robust assessment of the spatial predisposition to ground instability.

A first sinkhole susceptibility map was therefore produced, from which a medium-to-high susceptibility (the highest class within the Vallepietra area) is inferred for the Sanctuary area (Fig. 4 b).

The ring-shaped patterns identified in the susceptibility map, highlighted by the red-circled areas, can be interpreted as significant geomorphological features associated with the development of the karst system. These configurations likely represent the surface expression of underlying karst networks, where dissolution processes are controlled by structural discontinuities such as faults and fracture systems. In this context, the ring-shaped distribution may indicate zones of progressive subsurface void development, where cavities evolve and expand over time along preferential pathways. Such areas are therefore particularly relevant from a hazard perspective, as they may correspond to sectors in which collapse processes are ongoing or may occur in the future. The recognition of these spatial patterns provides additional insight into the dynamic evolution of the karst system and contributes to a more detailed interpretation of sinkhole susceptibility.

DISCUSSION

The results of the susceptibility analysis highlight the strong control exerted by geological and geomorphological factors on the spatial distribution of sinkholes in the Vallepietra area. In particular, the dominant contribution of lithology, elevation (DTM), and topographic position index (TPI) indicates that sinkhole development is closely associated with carbonate substrates and morphologically depressed areas, where water accumulation and infiltration processes are more effective. These findings confirm that morphostructural and lithological conditions represent primary controls on sinkhole occurrence.

A relevant aspect emerging from the analysis is the role of hypogeal karst systems, especially those modified by anthropogenic activities. The galleries identified beneath the Sanctuary, particularly the "Gronda A" system, act as preferential pathways for groundwater circulation and may significantly reduce the mechanical stability of the overlying rock mass. This condition is further enhanced by the presence of fault systems, which increase permeability and promote hydraulic connectivity within the karst network, thus facilitating dissolution processes and cavity enlargement.

The hydrogeological framework plays a key role in controlling sinkhole formation mechanisms. Field observations suggest that pressurized groundwater conditions may temporarily stabilize cavity roofs through hydraulic support. However, fluctuations in piezometric levels can lead to a sudden loss of this support, triggering collapse processes within the carbonate bedrock and subsequent subsidence in the overlying deposits. This mechanism is consistent with processes described in similar karst environments (Caramanna et al., 2008; Nisio, 2008; Ciotoli et al., 2015; Parise, 2019), confirming the importance of groundwater dynamics in sinkhole evolution.

The spatial distribution of susceptibility values also reveals the occurrence of localized patterns characterized by medium-to-high susceptibility, in some cases arranged in ring-shaped configurations. These patterns may reflect the presence of underlying karst systems developing along preferential pathways controlled by structural discontinuities. Such configurations could indicate zones of progressive subsurface void development, where collapse phenomena may occur at different stages, highlighting the dynamic and evolving nature of karst processes in the study area.

An additional aspect of interest is the correspondence between geological evidence and historical accounts. The legend associated with the origin of the Sanctuary may represent the cultural memory of a real subsidence event, likely related to collapse processes in the karst system. The integration of historical information with field data and susceptibility modelling provides a more comprehensive perspective on the temporal evolution of sinkhole hazards.

Overall, the results indicate that the Sanctuary is located within a medium-to-high susceptibility zone, where multiple factors—including lithology, structural setting, groundwater dynamics, and anthropogenic modifications—interact to increase the probability of sinkhole occurrence. This highlights the need for a multidisciplinary approach to hazard assessment, integrating geological, geophysical, and geochemical investigations. In particular, geophysical methods (Electrical resistivity tomography - ERT) may help delineate subsurface voids, while geochemical analyses can provide insights into active dissolution processes, thus supporting more effective risk mitigation strategies.

Although the analysis is focused on the Vallepietra area, the results have broader implications for karst regions of the central Apennines. The methodological approach adopted in this study can be applied to other carbonate massifs characterized by similar geological and hydrogeological settings, contributing to regional-scale hazard assessment and land management strategies.

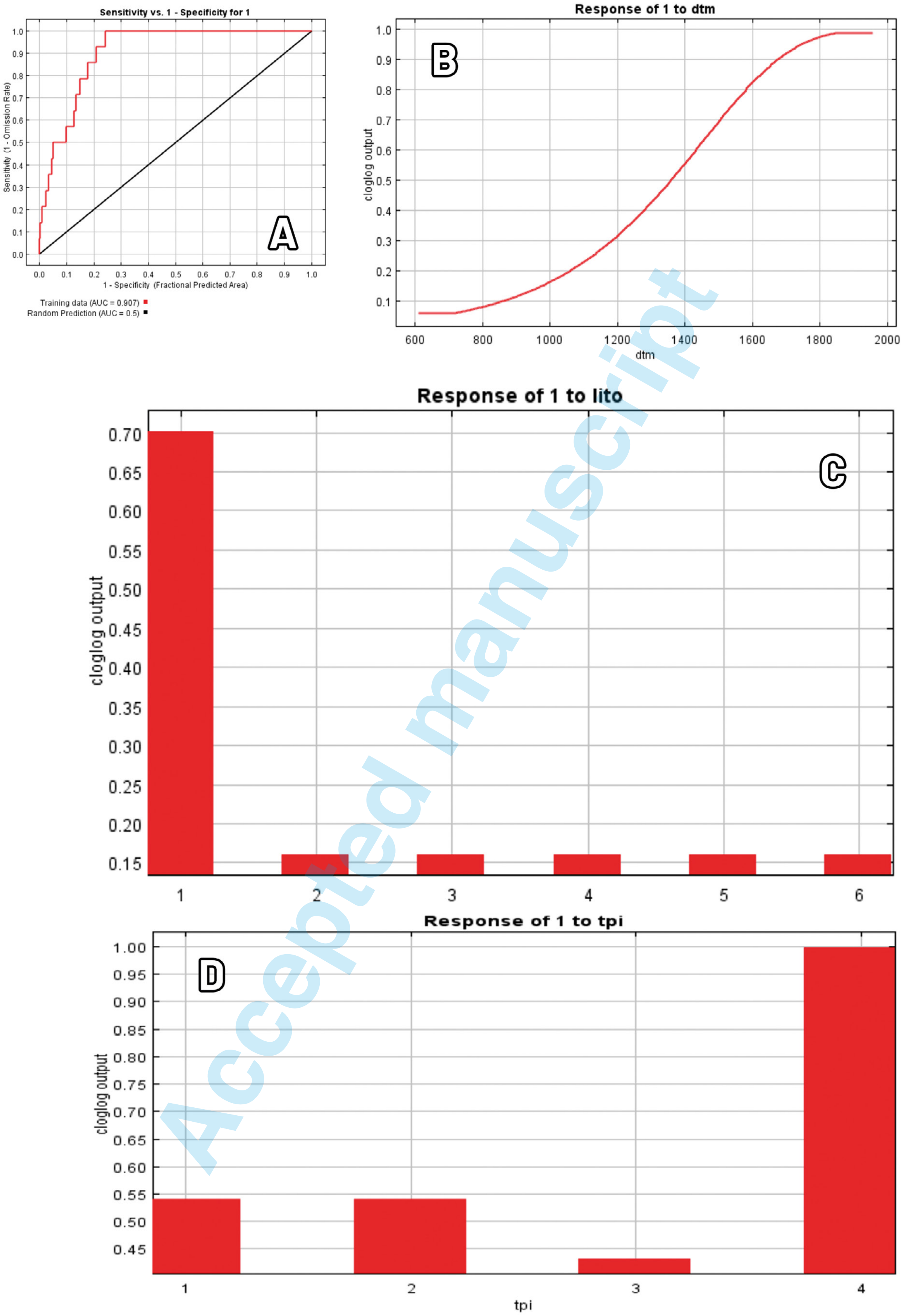

Fig. 3 - Results of the MaxEnt modelling. (a) ROC curve showing model performance and predictive reliability; (b–d) response curves of the most influential variables, including elevation (DTM), lithology, and topographic position index (TPI). The results indicate a strong correlation between sinkhole occurrence and carbonate lithologies, as well as morphologically depressed areas. In particularly 3b — The graph shows a positive relationship with elevation; 3c — Lithology, categorical variable. The graph shows a positive relationship with carbonate lithologies (calcilutites–calcirudites), suggesting collapse-related origins. 3d — TPI, categorical variable. The graph shows a strong relationship with depressed areas (code 4) compared to ridges (code 1) and sloping areas (codes 2 and 3).

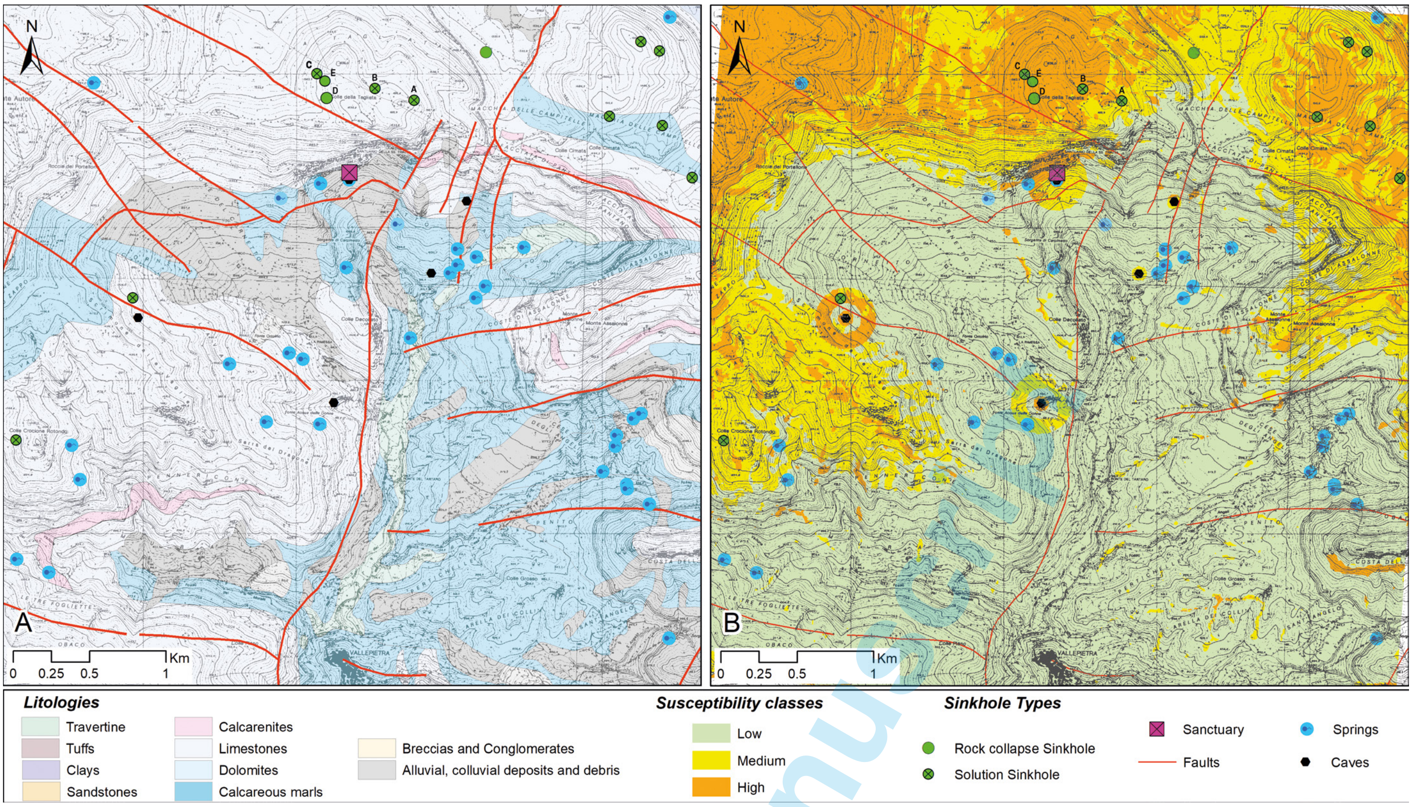

Fig. 4 - a) Geological–structural framework of the study area, showing the mapped sinkholes and documented spring locations. b) - Sinkhole susceptibility map of the Vallepietra area obtained through MaxEnt modelling. The map highlights areas classified into different susceptibility levels, from low to high. The Holy Trinity Sanctuary is located within a medium-to-high susceptibility zone, indicating a significant potential for collapse phenomena related to karst processes and subsurface cavities.

Despite the promising results, the susceptibility model presents some limitations. The use of a DTM with a spatial resolution of 10 m may not adequately capture small-scale geomorphological features, potentially affecting the identification of minor depressions. Furthermore, the relatively limited number of mapped sinkholes may influence model robustness and predictive capability. Future improvements should include higher-resolution datasets, the integration of additional environmental variables, and the incorporation of subsurface data derived from geophysical investigations.

These results are consistent with previous studies on sinkhole-prone karst environments in Italy and elsewhere, confirming the key role of lithological, structural, and hydrogeological controls in governing sinkhole occurrence (Caramanna et al., 2008; Nisio, 2008).

Despite the robustness of the adopted approach, the susceptibility model presents several limitations that should be considered when interpreting the results. The use of a Digital Terrain Model (DTM) with a spatial resolution of 10 m may not fully capture small-scale geomorphological features, potentially affecting the identification of minor depressions and subtle karst landforms. In addition, the relatively limited number of mapped sinkholes and the reliance on presence-only data may influence model performance and introduce uncertainties in the prediction of susceptibility patterns. Furthermore, some relevant factors, such as subsurface heterogeneity and temporal variations in groundwater conditions, are not fully represented in the model.

Notwithstanding these limitations, the proposed methodology demonstrates a high degree of applicability to karst environments characterized by incomplete datasets, as it integrates field observations, geomorphological analysis, and GIS-based modelling. The approach can be effectively transferred to other carbonate areas of the central Apennines, where similar geological and hydrogeological conditions occur, thus contributing to regional-scale assessments of sinkhole susceptibility.

From an applied perspective, the susceptibility map represents a valuable tool for hazard assessment and land-use planning. It provides a spatial framework for identifying areas potentially prone to collapse phenomena, supporting decision-making processes related to infrastructure development, cultural heritage protection, and risk mitigation strategies. When integrated with site-specific investigations and monitoring systems, such susceptibility analyses can contribute to the development of more comprehensive and proactive hazard management plans.

CONCLUSIONS

This study represents the first systematic attempt to assess sinkhole susceptibility in the Vallepietra area through the integration of field surveys, historical analysis, and GIS-based modelling. The results demonstrate that sinkhole formation in the study area is controlled by a complex interplay of karst processes, structural features, and hydrogeological conditions, further influenced by anthropogenic factors. These findings highlight the importance of considering both natural and human-induced processes in the assessment of sinkhole hazards.

The susceptibility map indicates that the area surrounding the Sanctuary of the Holy Trinity is characterized by medium-to-high susceptibility levels, mainly due to the presence of extensive hypogeal karst systems and active groundwater circulation. These conditions represent a significant hazard not only for the natural environment but also for the cultural and religious heritage of the site, which is subject to intense anthropogenic pressure.

Future research should focus on improving the current model through the acquisition of higher-resolution datasets and the integration of additional variables. In particular, geophysical surveys are essential to accurately delineate subsurface cavities and characterize the internal structure of the karst system. Electrical resistivity tomography (ERT) and other geo-electrical methods represent the most suitable techniques in this context, as they allow the detection of resistivity anomalies associated with voids, fractured zones, and water-saturated levels within carbonate rocks. These methods provide high-resolution imaging of subsurface heterogeneities, enabling the identification of potential collapse-prone zones. In parallel, soil gas geochemical analyses (e.g., CO_2, He, H_2S, Rn, methane) may provide key insights into the processes driving sinkhole formation (Annunziatellis et al., 2004; Nisio, 2003, 2008; Nisio et al., 2007). In particular, CO_2 and radon (Rn) are effective tracers of gas migration along fault and fracture systems, while helium anomalies may indicate deep-seated fluid contributions. The spatial distribution and alignment of soil gas anomalies can therefore be used to detect hidden structural discontinuities and zones of enhanced permeability, which represent preferential pathways for fluid circulation and potential triggers for collapse processes. (Annunziatellis et al., 2004; Nisio, 2003, 2008; Nisio et al., 2007). These approaches would contribute to a more detailed characterization of subsurface conditions and to a better understanding of the mechanisms controlling collapse processes.

Furthermore, the implementation of monitoring systems capable of detecting ground deformation in real time is strongly recommended. The early detection of precursory subsidence phenomena would allow the activation of warning procedures and mitigation measures, contributing to the protection of both human activities and cultural heritage.

Although focused on the Vallepietra area, the methodological framework proposed in this study can be applied to other karst environments characterized by limited sinkhole inventories. In this context, the integration of field data, historical information, and predictive modelling represents a valuable tool for improving hazard assessment and supporting land-use planning and risk management strategies at both local and regional scales.

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