

# Sinkholes in volcanic areas of Central and Southern Italy: inventory update and occurrence of natural and anthropogenic processes



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## Short Note

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## ABSTRACT

Volcanic plateaus in central and southern Italy, particularly in Lazio and Campania, have long been considered suitable for urban, industrial, and infrastructural developments due to their apparent stability and generally favourable geomorphological and geotechnical characteristics. However, both natural and anthropogenic sinkholes occur widely in these settings and are still largely underestimated in hazard assessment and land-use planning, as sinkhole processes are commonly associated only with karst and pseudokarst environments.

Data from the Italian Sinkhole Database (ISPRA), updated within the framework of the Geosciences-IR project, highlight the significant occurrence of sinkholes in volcanic areas, including sectors hosting strategic infrastructure. Natural sinkholes are mainly related to groundwater-level fluctuations, gas emissions, structural discontinuities, and the presence of karstifiable travertine layers interbedded within pyroclastic successions. Anthropogenic sinkholes are also widespread, especially in urban and peri-urban areas, where they are associated with long-standing underground networks such as cuniculi, aqueducts, catacombs, and quarries, often reactivated or exacerbated by hydraulic failures and intense rainfall events.

The updated inventory emphasises the need to consider sinkhole hazard as a relevant geological risk also in volcanic terrains and to incorporate dedicated mitigation strategies into land-use planning and infrastructure management.

**KEYWORDS:** sinkhole, volcanic areas, anthropogenic cavities, morphological convergence, hazard assessment.

## INTRODUCTION

In volcanic areas, long-lasting and intensive anthropogenic modification of the landscape—driven by agriculture, urban

expansion, and the concentration of industrial activities—has progressively obliterated many surface morphological features that would otherwise allow the recognition of sinkhole-related processes. These transformations have also masked subtle neotectonic indicators and surface expressions linked to late-stage volcanic activity, which are often rapidly levelled, infilled, or incorporated into the modern land surface.

Natural sinkholes in volcanic settings are commonly associated with specific subsurface conditions, including volcanic gas emissions, fluctuations in groundwater levels, fault systems, and rock fracturing. These processes may significantly compromise the structural integrity of infrastructure, particularly facilities designed to host hazardous materials, raising concerns for both public safety and environmental protection. In addition, in areas affected by Quaternary volcanism, secondary volcanic processes involving the circulation of mineral and hydrothermal fluids may occur. These processes have produced extensive carbonate deposits, often in the form of travertine layers interbedded within volcanic successions. Such lithotypes are highly karstifiable and are frequently involved in the development of cave-collapse sinkholes.

Circular depressions in volcanic terrains represent a highly heterogeneous group of geomorphological features that, despite their similar morphology, may originate from fundamentally different processes. This phenomenon, known as morphological convergence, reflects those distinct genetic mechanisms, both endogenic and exogenic, can produce analogous landforms, thereby complicating

their classification. The main causative processes include volcanic activity, structural collapse, piping, and anthropogenic excavation. Consequently, morphological analysis alone is insufficient to determine the origin of sub-circular depressions; instead, a multidisciplinary approach integrating geological, lithological, morphometric, and geochemical data is required.

A representative example of this ambiguity is provided by the comparison between sinkholes and maars. Although these landforms may appear similar in shape and size, they originate from fundamentally different processes. In volcanic areas, sinkholes develop through the collapse of subsurface cavities within soils or lava flows, or through piping processes affecting loose or fractured pyroclastic deposits. They are non-ejective features, characterised by the absence of material emission, the lack of a raised rim, and a predominantly gravitational or hydrogeological evolution. In contrast, maars are volcanic craters formed by explosive events, typically related to magma–water interaction. They are ejective landforms, characterised by the production and deposition of pyroclastic material forming a ring around the depression. The presence of such deposits, together with specific lithological and geochemical signatures, represents a key diagnostic criterion for distinguishing maars from piping sinkholes (Nisio, 2003, 2008; Caramanna et al., 2008). Table 1 summarises the main genetic, morphological, and process-related differences between piping sinkholes, collapse sinkholes, and maars, highlighting how similar surface expressions may correspond to fundamentally different processes (subsidence versus explosive volcanism), and emphasising the need for multidisciplinary criteria for their correct identification.

Several studies have documented sinkhole hazards affecting densely populated and industrialised volcanic plateaus in southern Italy, particularly in Campania, including the middle and upper Volturno Valley, the foothills of the Roccamonfina volcanic complex, the Forino Plain, and the Falerno Plain (Scherillo et al., 1965, 1966, 1968; Gasparini, 1965, 1966; Del Prete et al., 2004; Nisio, 2003, 2008). Most of these sinkholes formed in historical times, with some possibly dating back to the Roman period, as inferred from historical and cartographic sources. In several cases, their formation appears to have been triggered or accelerated by external factors such as seismic events, groundwater fluctuations, and intense hydrological processes.

The genetic interpretation of sinkholes in volcanic settings has long been debated. Early studies interpreted some sub-circular depressions, including the Fosse Falerne and the lakes of Corrèe, as volcanic maars related to late phreatomagmatic or gaseous activity associated with the final eruptive phases of Roccamonfina volcanism. This interpretation was mainly based on morphological characteristics and their alignment along regional tectonic lineaments such as the Monte Massico fault system (Scherillo et al., 1965, 1966, 1968; Gasparini, 1965, 1966). However, subsequent investigations, consistent with early historical descriptions (Gussone & Tenore, 1835; Scacchi, 1885), have progressively favoured a collapse- or piping-sinkhole origin that occurred after the cessation of volcanic activity (Del Prete et al., 2004; Nisio, 2003, 2008).

Recent sinkhole events, such as those documented in the Forino Plain in 2022, have provided direct evidence of natural cavity formation within pyroclastic and alluvial deposits, driven by erosional processes associated with upward-moving groundwater, thus supporting a natural piping mechanism (Nisio, 2008). In several cases, sinkhole development has involved sandy–silty or reworked pyroclastic layers, locally affected by liquefaction processes (Nisio, 2008).

Another poorly investigated mechanism concerns the presence of natural cavities within volcanic units, particularly lava flows. Volcanic caves, including lava tubes, crevice caves, rheogenetic and eruptive fissure caves, and vertical conduits, are well documented in the Etna volcanic area (Licitra, 1982; Bonaccorso & Mageri, 1999), but are rarely considered in sinkhole studies in other Italian volcanic districts, with only sporadic reports from Lazio (Battiato et al., 1999) and Sardinia (De Waele & Muntoni, 1999). In many cases, such cavities may be buried beneath thick pyroclastic covers, and their potential role in sinkhole susceptibility remains largely unexplored.

Overall, natural sinkholes in volcanic areas are commonly associated with tectonically controlled depressions filled with Quaternary pyroclastic and alluvial deposits, bounded by major regional faults that are likely still active and characterised by high seismicity (Celico, 1983; Nisio, 2008). These conditions, combined with complex hydrogeological interactions, highlight the need for integrated geological, geomorphological, hydrogeological, and historical analyses to correctly interpret sinkhole genesis in volcanic terrains.

**Table 1 - This table summarizes the principal genetic, morphological, and process-related differences among piping sinkholes, collapse sinkholes, and maars, highlighting how similar surface expressions may reflect fundamentally distinct formation mechanisms (subsidence versus explosive volcanism), and underscoring the need for multidisciplinary criteria for their correct identification.**

Feature	Piping Sinkhole	Collapse Sinkhole	Maar
Genesis	Inversion erosion (piping)	Roof collapse of underground cavities	Volcanic explosion
Process type	Non-ejective	Non-ejective	Ejective
Material emission	Rarely possible (muddy flows, sediment discharge)	Absent	Present (pyroclasts, mud, gases)
Surrounding deposits	Absent or very limited	Absent	Ring of volcanic deposits
Relationship with magma	Absent	Absent	Direct or indirect
Evolution	Progressive or sudden	Sudden (catastrophic)	Rapid and violent
Shape	Cylindrical	Irregular, widening downward	Cylindrical

Conversely, millennia of human occupation in volcanic areas have led to the widespread excavation of underground spaces within volcanic rocks for various purposes. These anthropogenic cavities, often unrecorded or forgotten, represent a major predisposing factor for the development of anthropogenic sinkholes, particularly in densely urbanised and peri-urban areas (Guarino & Nisio, 2012; Basso et al., 2013; Ciotoli et al., 2013, 2015). The combined effects of surface modification and subsurface excavation, therefore, contribute to both the underestimation of sinkhole hazard and the increasing occurrence of collapse phenomena in volcanic settings.

Volcanic rocks are widely distributed in Italy and are commonly considered suitable for a broad range of civil and industrial applications due to their favourable technical properties. As a result, extensive volcanic plateaus have increasingly been used for the development of critical infrastructure, often characterised by a gently sloping morphology. However, these areas are not free from geological hazards, including both natural and anthropogenic sinkhole processes.

## MATERIALS AND METHODS

A comprehensive inventory of natural sinkholes in volcanic areas was carried out by integrating heterogeneous spatial and non-spatial datasets within a GIS environment. The analysis was primarily based on the Italian Sinkhole Database (ISPRA), updated within the framework of the PNRR Geosciences-IR project (WP 3.2). The database includes georeferenced information on both natural and anthropogenic sinkholes derived from previous studies, technical reports, and newly collected data.

The inventory update focused on harmonising and validating multiple data sources, including geological and geomorphological maps, hydrogeological datasets, land-use information, and available digital elevation models (DEMs). Additional information was obtained from historical and archaeological sources, such as ancient maps, cadastral records, archival documents, and excavation reports, which are particularly relevant in volcanic areas characterised by long-term human occupation. These datasets enabled the identification of past collapse events, buried cavities, abandoned quarries, tunnels, and hydraulic structures, as well as the reconstruction of the temporal evolution of sinkhole occurrence.

Recent sinkhole events were documented through the analysis of technical reports, civil protection archives, and journalistic sources, providing information on timing, triggering factors, and impacts. All datasets were critically evaluated, georeferenced, and standardised to ensure consistency within the national database.

The identification and classification of sinkholes were based on the integration of geomorphological, geological, and hydrogeological criteria. Circular to subcircular depressions, structural discontinuities, and areas affected by groundwater fluctuations or gas emissions were considered indicative of natural sinkhole processes. In contrast, the presence of underground cavities and historical subsurface networks (e.g., cuniculi, aqueducts, catacombs, and quarries) was used to identify anthropogenic sinkhole-prone areas.

Field surveys and targeted investigations were conducted in selected case studies to validate the interpretations and improve the characterisation of both natural and anthropogenic features. These activities included direct observation of surface landforms and, where accessible, underground cavities, supported by descriptive surveys and basic topographic documentation.

Advanced techniques such as remote sensing analyses, InSAR data, UAV surveys, and 3D modelling are part of the broader methodological framework of the PNRR Geosciences-IR project (Gentili et al., 2025a, b; Madonna & Nisio, 2020; Madonna et al., 2024), but are not the primary focus of this Short Note, which is centred on the updated inventory and selected representative examples.

All natural sinkholes were catalogued using standardised survey forms to ensure consistency in data acquisition, classification, and interpretation. The resulting database is conceived as an open and updatable tool to support civil protection activities, land-use planning, and hazard mitigation strategies.

To achieve a comprehensive assessment of sinkholes in volcanic settings, selected urban centres in Lazio and Campania (Italy) were also investigated. These areas, located within volcanic terrains, are affected by anthropogenic sinkholes related to the extensive excavation of pyroclastic deposits for construction materials and the development of long-standing underground networks.

## RESULTS

### Natural sinkhole in volcanic areas

The Italian Sinkhole Database (ISPRA), developed within the EC PNRR Geosciences-IR project (WP 3.2), documents the widespread occurrence of different types of sinkholes in volcanic terrains and provides separate inventories for natural and anthropogenic events (Fig. 1a–b). At present, 301 natural sinkholes are recorded in Italian volcanic areas (Fig. 1a). The database includes both documented historical subsidence events and subcircular depressions, sometimes hosting ponds or small lakes that, following targeted analyses, can be attributed to collapse-related processes (Nisio, 2008; Madonna & Nisio, 2020; Madonna et al., 2020).

Several natural sinkholes occur in volcanic areas of potential strategic relevance. Among the documented cases (301 natural sinkholes; Fig. 1a), selected examples are particularly significant not only for their morphological and genetic characteristics but also because they affect areas that potentially host high-risk installations.

A number of piping sinkhole cases developed within volcanic settings in the Lazio and Campania regions (central–southern Italy) have been investigated in detail. Figure 2 illustrates representative sites in Lazio, including Galliciano del Lazio (Metropolitan City of Rome), specifically the Passerano locality, where three sinkholes formed during historical times on a volcanic plateau and are currently artificially backfilled; the Capena area (Lago Puzzo); the Latera site (Province of Viterbo); and the

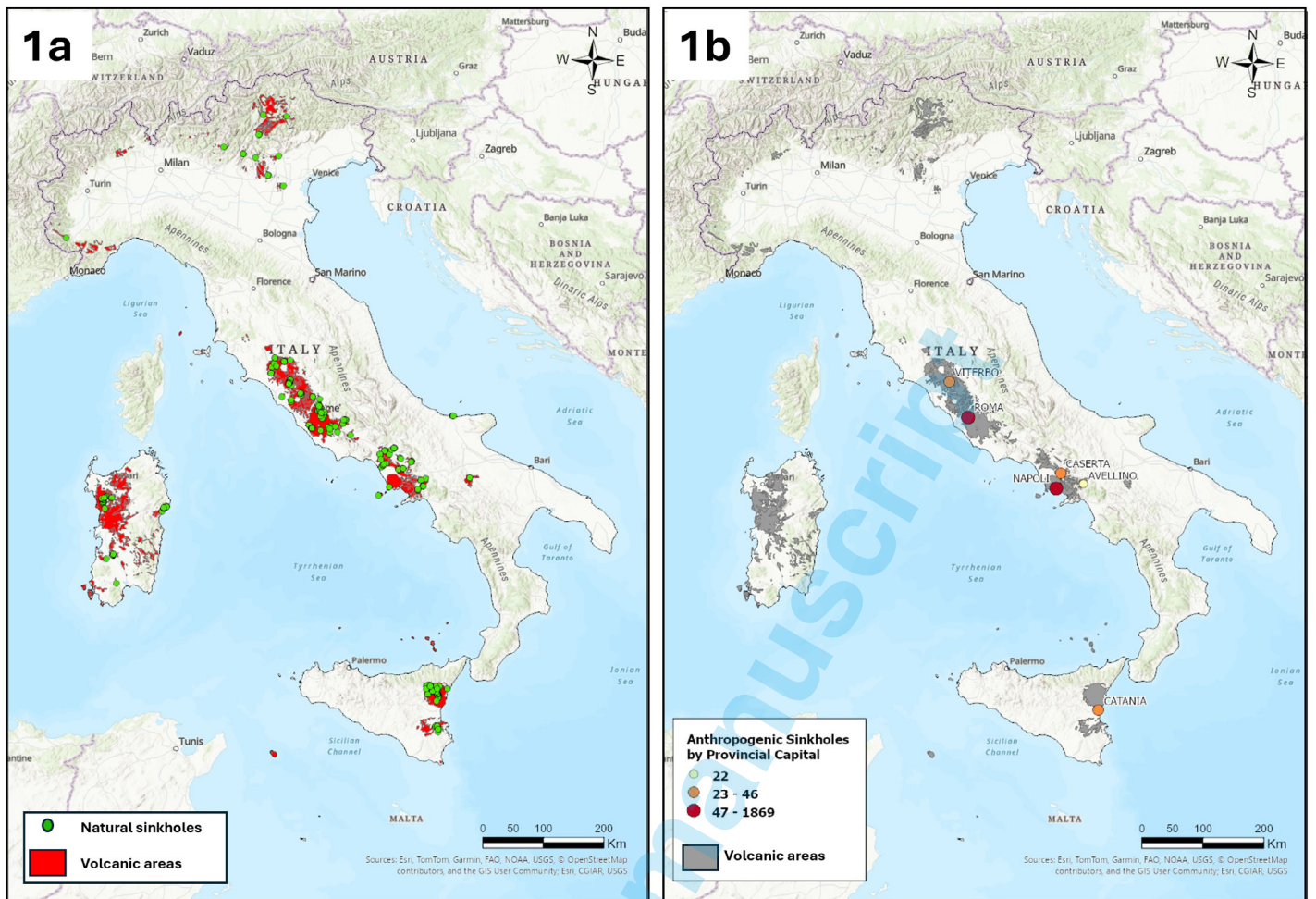


Fig. 1 - The main volcanic areas in Italy: a) related natural sinkholes; b) related anthropogenic sinkholes in the major urban area (provincial capitals).

Artena site (Metropolitan City of Rome), known as the Fossa della Puzzariga.

With regard to Campania, the analysed cases include Lago di Vairano, Lago di Falciano (Carinola), and Lago delle Corree in the Province of Caserta, as well as the Fossa di San Vito in the Province of Salerno.

The Latera sinkhole (Vepe–Latera caldera, Vulsini Volcanic Complex) represents a key example (Fig. 2c). The depression rapidly filled with groundwater within eight days (31 January–7 February 2023), highlighting strong hydraulic connectivity and emphasising the need for careful assessment of sinkhole genesis in areas considered for high-risk installations (Puzzilli et al., 2024). This event also suggests that sinkhole hazard should be evaluated not only at the location of critical facilities, but also along transport routes used for heavy and hazardous materials.

Additional *rock-collapse sinkholes* may develop as a result of lava-tube collapse. These features are commonly observed on the flanks of Mount Etna, where a comprehensive inventory of lava caves has been compiled based on bibliographic (Miceli, 1933; Poli, 1959; Brunelli and Scammacca, 1975; Bella et al., 1982; Barone et al., 1994; Bonaccorso and Maugeri, 1999) and cartographic data, complemented by photointerpretation analyses of rock-collapse events that have occurred over the past two decades (Fig. 3).

### Anthropogenic sinkholes in volcanic areas

More than 3500 anthropogenic sinkholes have been identified in urban areas located within volcanic settings (Fig. 1b). In pyroclastic rocks, the probability of large natural cavities is generally low, whereas artificial cavities are extremely widespread. Anthropogenic sinkholes are particularly common in large cities such as Rome, Naples, Viterbo, Caserta, Avellino, and Catania (Table 2), as well as in smaller towns and historical centres.

These phenomena are closely related to extensive underground networks excavated over more than two millennia for multiple

Table 2 - Distribution of recorded sinkholes by province and lithological setting (1960–March 2026 inventory).

City	Lithology	Number of Sinkholes
Rome	Effusive and alluvial–clastic	2449
Naples	Effusive	954
Viterbo	Effusive	56
Caserta	Effusive and alluvial–clastic	58
Avellino	Effusive and alluvial–clastic	24
Catania	Effusive and alluvial–clastic	39
<b>Total</b>	—	<b>3580</b>



Fig. 2 - Representative piping sinkhole sites in volcanic terrains of Lazio and Campania (central–southern Italy): (a) Galliciano del Lazio (Passerano); (b) Capena (Lago Puzzo); (c) Latera; (d) Artena (Fossa della Puzzariga); (e) Lago di Vairano; (f) Lago di Falciano (Carinola); (g) Lago delle Corree (Caserta); (h) Fossa di San Vito (Salerno).

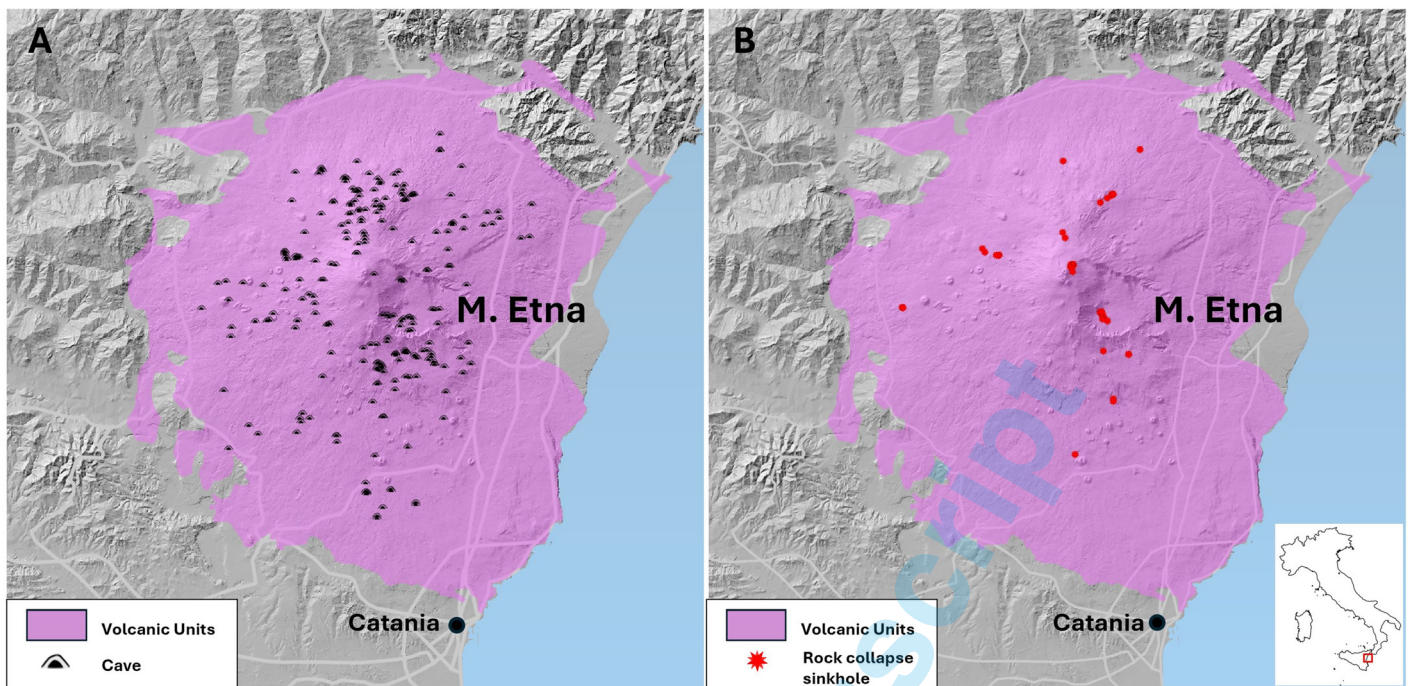


Fig. 3 - (a) Examples of cavities developed within lava flows of Mount Etna (Sicily); (b) rock-collapse sinkhole formed by the collapse of a lava tube.

purposes, including hydraulic systems, quarries, catacombs, and tunnels. Excavation phases range from Etruscan and Roman times to the Medieval period, with some reuse during World War II as shelters (Madonna et al., 2023). Surface collapses typically manifest as metre-scale depressions and are commonly associated with the combined effects of cavity instability and subsurface hydraulic dysfunction, such as leakage and erosion of loose volcanic deposits.

Additional triggering factors include water leakage into the subsurface and malfunctioning of buried hydraulic systems, which enhance erosion processes and reduce the stability of overlying materials. Database updates and susceptibility studies carried out in recent decades (e.g., Ciotoli et al., 2015; Meloni & Nisio, 2015; Meloni et al., 2013; Nisio et al., 2017) have significantly improved the identification of anthropogenic sinkhole-prone areas in major urban centres, supporting hazard mitigation and urban planning. However, while underground cavities in urban areas are often locally known, extra-urban anthropogenic networks remain largely unmapped.

## DISCUSSION

Natural sinkholes documented in volcanic terrains of Lazio and Campania predominantly occur within volcanic plateaus bordering tectonically subsiding carbonate reliefs, where thick Quaternary epiclastic volcanoclastic, fluvial–lacustrine, and other continental deposits fill structural depressions and locally interbed with volcanic successions. These deposits are often strongly modified by land use and long-term anthropogenic activity, which tend to obscure fault-controlled discontinuities and secondary volcanic features. Such structures may act as preferential pathways for gas

and fluid upwelling and may coincide with extensive or interlayered carbonate deposits (travertines), which are highly karstifiable and can significantly contribute to the development of natural sinkholes.

In volcanic settings, the inventory and classification of sinkholes are further complicated by morphological convergence. The similarity between sinkholes and maars represents a paradigmatic example of how morphologically analogous landforms may originate from fundamentally different genetic processes. As shown in Fig. 4, small lakes developed within maar-type volcanic depressions differ markedly from piping sinkholes, particularly due to the presence of raised rims formed by eruptive deposits, which indicate an ejective origin rather than a collapse mechanism.

These observations confirm that morphology alone is insufficient for reliable genetic interpretation. A robust classification requires a multidisciplinary approach integrating geological, lithological, morphometric, and geochemical evidence. In this context, a progressive-exclusion approach based on independent parameters—such as crater morphology, wall lithology, stratigraphy, the presence or absence of raised rims, and geochemical signatures—represents a reliable framework for distinguishing between volcanic and collapse-related landforms.

Historical interpretations further highlight this issue. For instance, the Fosse Falerne were initially described as “gaseous” volcanic features (Scherillo et al., 1965, 1966, 1968; Gasparini, 1965, 1966), whereas subsequent studies, supported by stratigraphic and historical evidence, favour a collapse or piping sinkhole origin (Del Prete et al., 2004; Nisio, 2003, 2008). Similar reinterpretations have been proposed for several depressions in Campania, where features that cut the Campanian Ignimbrite (~39 ka) and locally involve Holocene fluvio-lacustrine deposits lack diagnostic eruptive structures. The absence of raised rims and pyroclastic ejecta supports a non-volcanic origin and suggests

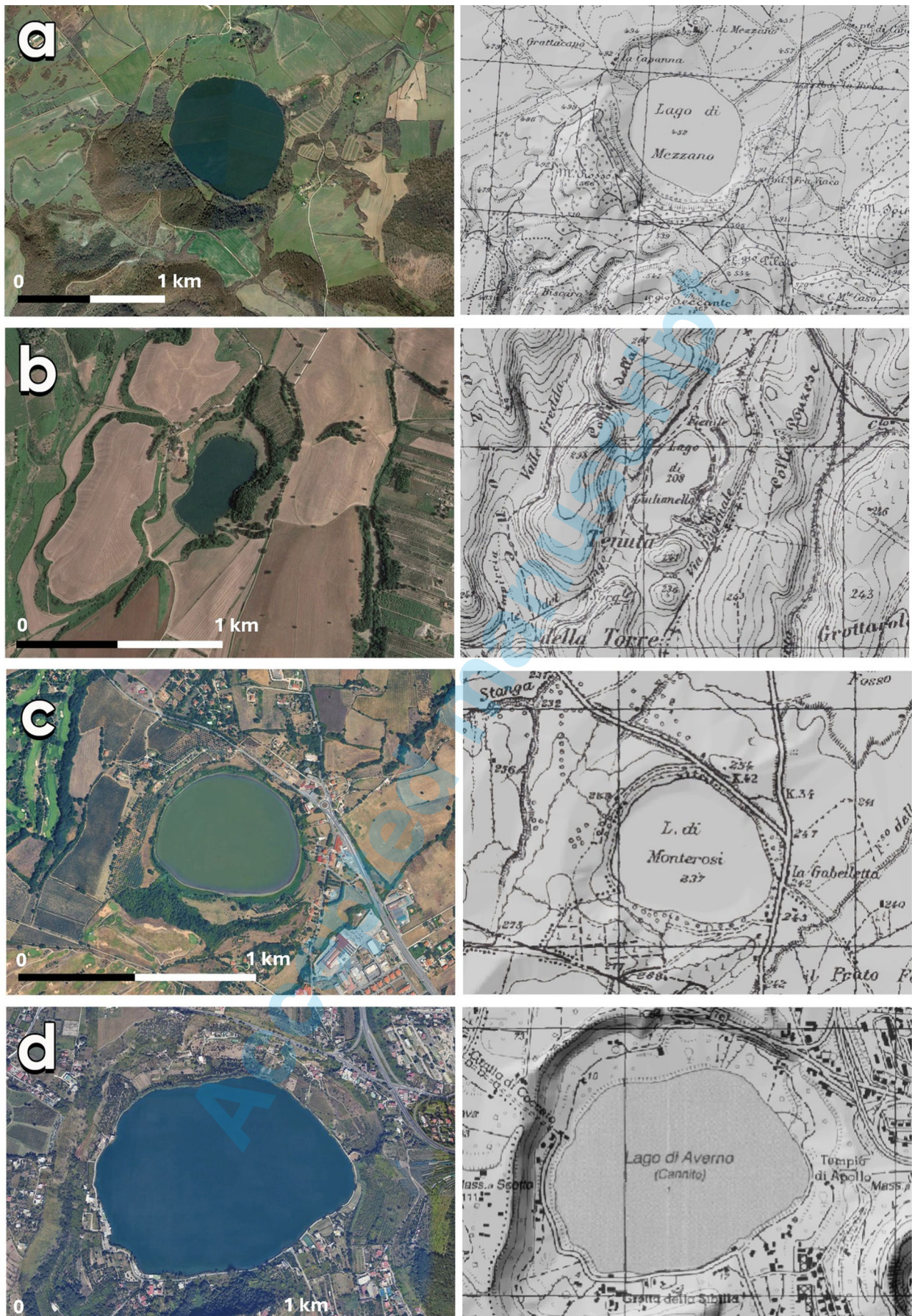


Fig. 4 - Examples of maars in Lazio and Campania (central-southern Italy): (a) Mezzano Lake maar (Viterbo, Lazio Region); (b) Giulianello Lake maar (Rome, Lazio Region); (c) Monterosi Lake maar (Viterbo, Lazio Region); (d) Averno Lake maar (Naples, Campania Region). For each site, the left panel shows a satellite base image, whereas the right panel shows the 1:25,000-scale topographic map of Italy produced by the Istituto Geografico Militare (IGM).

formation after the cessation of Roccamonfina volcanic activity (~53 ka), consistent with historical documentation indicating Roman to post-medieval ages (Gussone & Tenore, 1835; Scacchi, 1885; Nisio, 2003, 2008).

From a hazard perspective, the results demonstrate that sinkhole susceptibility in volcanic terrains is systematically underestimated. This is particularly critical in rural areas, where events often remain undocumented, and in densely urbanised and industrialised settings, such as Rome and Naples, where anthropogenic cavities and complex subsurface networks significantly increase collapse potential. The widespread presence of underground cavities, combined with hydrogeological perturbations (e.g., leakage, groundwater fluctuations, intense rainfall events), represents a key predisposing and triggering factor for anthropogenic sinkholes.

## CONCLUSIONS

Circular depressions of uncertain origin have long been recognised in volcanic areas, and their interpretation has evolved significantly over time. While many of these features were historically attributed to volcanic processes, increasing evidence indicates that a substantial proportion are more appropriately interpreted as piping or collapse sinkholes rather than volcanic landforms such as maars. This reinterpretation highlights the key role of subsurface erosion and collapse mechanisms in volcanic terrains.

The frequent morphological similarity between sinkholes and volcanic structures demonstrates that morphology alone is insufficient for genetic interpretation. Reliable classification requires a multidisciplinary approach that integrates geological, stratigraphic, hydrogeological, and geochemical evidence to avoid misinterpretation and ensure accurate hazard assessment.

The updated inventory of the Italian Sinkhole Database (ISPRA) documents 301 natural sinkholes in volcanic areas, while more than 3500 anthropogenic sinkholes have been identified in urban centres developed on volcanic terrains (Fig. 1a–b; Table 2). These data clearly indicate that sinkhole occurrence in volcanic settings is widespread and significantly underestimated.

Anthropogenic factors play a major role in increasing sinkhole hazard, both indirectly, through modifications to hydraulic and hydrogeological regimes, and directly, through excavation activities, underground infrastructure, and alterations to subsurface water flow. In addition, the increasing frequency of short-duration, high-intensity rainfall events (“cloudbursts”) may further enhance the occurrence of collapse phenomena, amplifying risks for populations, infrastructure, and subsurface networks.

The potential collapse of natural cavities within volcanic and related deposits remains poorly constrained and insufficiently investigated. This includes both karstifiable lithologies, such as travertine interbedded within volcanic successions, and volcanic rocks themselves (e.g., lava flows), which have been documented only in limited areas where they are not buried by pyroclastic covers (Fig. 3).

Overall, sinkhole development in volcanic terrains results from the interaction of multiple factors, including groundwater dynamics,

structural discontinuities, seismicity, gas–fluid circulation, and the presence of natural and anthropogenic cavities. These findings demonstrate that volcanic areas cannot be considered intrinsically low-risk with respect to sinkhole processes.

Effective mitigation, therefore, requires the integration of detailed geological investigations, systematic mapping of underground cavities, and targeted land-use planning strategies. Increased awareness of sinkhole hazard in volcanic environments is essential, particularly in areas hosting strategic infrastructure, where sinkhole susceptibility should be explicitly incorporated into planning and risk assessment frameworks.

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