Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

PHOTOGRAMMETRY AND SATELLITE EARTH OBSERVATION TECHNIQUES FOR SINKHOLE MONITORING: APPLICATION IN THE VEPE PLAIN (LATERA - ITALY)

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EXTENDED ABSTRACT

I sinkhole, sono fenomeni geologici causati dal collasso di cavità sotterranee, che portano alla formazione improvvisa di un cratere sulla superficie terrestre. Questi fenomeni possono essere naturali o antropogenici e sono studiati e classificati in base al meccanismo di formazione. In Italia, sono stati catalogati numerosi sinkhole, spesso situati vicino a centri abitati e attività umane; tali fenomeni frequentemente costituiscono preoccupazioni in relazione al rischio e all'impatto che possono avere sulla sicurezza e sull'economia. Il rischio associato ai sinkhole dipende da vari fattori, tra cui la dimensione e la velocità di sviluppo della cavità e la densità della popolazione nelle vicinanze. In questo contesto, l'approccio multidisciplinare è fondamentale per affrontare e studiare questi fenomeni. Recenti ricerche si sono concentrate sul monitoraggio e sulla localizzazione delle cavità sotterranee, utilizzando una combinazione di tecniche storiche, geofisiche e topografiche, con l'aiuto di strumenti GIS (Sistema Informativo Geografico). Il sinkhole oggetto di studio si è formato nella caldera di Vepe (Latera, VT) ha un diametro di circa 36 metri e un volume stimato di 2000 m³. La storia geologica di questa zona è complessa, con tre fasi principali di attività vulcanica che hanno visto la formazione di flussi di lava, depositi piroclastici. I depositi lacustri e alluvionali presenti all'interno della caldera sono legati a periodi di occupazione lacustre, che potrebbero influire sulla formazione di sinkhole nella zona. Al fine di studiare e analizzare la formazione del sinkhole di Vepe, è stato seguito un approccio multidisciplinare mediante l'utilizzo di diverse metodologie. Per l'analisi del contesto geologico e geografico è stato sviluppato un progetto GIS con il software open source QGIS in cui sono confluiti dati geologici, immagini storiche e recenti dell'area che hanno permesso di analizzare e confrontare uno scenario, dettagliato dello stato pre-collasso. In particolare, sono state utilizzate le fotografie satellitari di Google Earth e i dati di osservazione satellitare, ottenuti tramite il programma Copernicus: questi hanno contribuito a monitorare l'evoluzione del fenomeno, analizzando parametri come la vegetazione (NDVI), la presenza di acqua (NDWI) e le variazioni ambientali nel tempo. Inoltre, sono stati effettuati rilievi fotogrammetrici tramite droni, utilizzando fotocamere ad alta risoluzione per acquisire immagini ogni 30-45 giorni, al fine di documentare i cambiamenti nel tempo e monitorare l'andamento del livello dell'acqua nel sinkhole. I rilievi sono stati georiferiti tramite stazioni GNSS, garantendo alta precisione nella localizzazione dei punti di controllo. L'analisi delle osservazioni satellitari ha evidenziato che l'indice NDVI ha mostrato un aumento della vegetazione nelle vicinanze del sinkhole, mentre l'NDWI ha rivelato le variazioni del livello dell'acqua nel corso del tempo. Le tecniche di interferometria satellitare (InSAR) non sono state utilizzabili nell'area, in quanto non vi sono riflettori naturali o antropogenici sufficienti per monitorare il movimento del terreno con precisione. Tuttavia, l'analisi dei microtremori (metodo HVSR) ha fornito informazioni utili sulla direzionalità dei segnali sismici. Inoltre, è stato eseguito uno studio delle condizioni meteorologiche, consultando i dati pluviometrici, le temperature e l'evapotraspirazione per correlare eventuali variazioni nei livelli di acqua del sinkhole con le condizioni climatiche. I dati sono stati raccolti presso la stazione meteorologica di Latera Centro Florovivaistico, e la loro analisi ha permesso di comprendere meglio l'effetto delle precipitazioni sul fenomeno. In sintesi, il monitoraggio del sinkhole nella pianura di Vepe ha richiesto un approccio integrato, che ha combinato tecniche geofisiche, fotogrammetriche e satellitari, contribuendo alla comprensione dei meccanismi di formazione e alla creazione di una metodologia di monitoraggio che può essere utile anche per la gestione del rischio in futuro. I risultati ottenuti hanno permesso di elaborare una metodica di monitoraggio di questi fenomeni nel lungo periodo, specialmente tramite l'impiego della fotogrammetria da UAV.

IJEGE, 1 (2025): 9-19, DOI: 10.4408/IJEGE.2025-01.O-03
E-ISSN 2035-5688 | ISSN 1825-6635 / ©Author(s)

ABSTRACT

Sinkholes pose a serious risk to human activities, so it is essential to study their formation and behaviour. This study presents the results of a two-year monitoring conducted on a sinkhole in the Vepe plain (Latera, Italy). Monitoring began approximately 48 hours after the formation of the sinkhole, using UAV photogrammetry and satellite observation of the Earth, with reference to the ecosystem peculiarities of the area. Various HVSR tests were performed, focusing on the analysis of the directionality detected and dependent on the natural context. Finally, the water levels in the sinkhole were compared with rainfall data to investigate the relationship with the variation in water levels. The aim was to obtain more information on deep piping, a probable phenomenon behind sinkhole formation, and to develop monitoring protocols adaptable to different contexts.

Keywords: *sinkhole, photogrammetry, earth observation, HVSR, deep piping, pluviometry*

INTRODUCTION

Sinkholes are geological phenomena caused by the collapse of an underground cavity, leading to the sudden appearance of a sinkhole on the earth's surface. The term sinkhole was first introduced by Fairbridge in 1968 (Fairbridge, 1968). Sinkholes can be classified into natural and anthropogenic sinkholes, as well as according to their formation mechanisms (https://www.isprambiente.gov.it/it/attivita/suolo-e-territorio/sinkholes-e-cavita-sotterranee/classificazione-dei-sinkholes, Nisio 2008A). The most common sinkholes are those in karstic environments, such as slumps and subsidence, which occur in areas with carbonate rocks. However, there are also other types, such as those in floodplains caused by deep conduits and suffusions, where water creates vertical and horizontal conduits that lead to surface collapse (Nisio, 2008A). Some sinkholes occur in volcanic areas due to the collapse of lava tunnels or the dissolution of ignimbritic cover. Anthropogenic sinkholes result from the collapse of man-made cavities, which can form sinkholes near the surface. To study these phenomena, geophysical techniques such as geoelectrical tomography or gravimetry are used to understand the causes of collapse. Sinkholes have been catalogued throughout Italy (Nisio *et alii*, 2007, Nisio, 2008B, Nisio, 2008C, Nisio, 2008D, Nisio 2008E, Caramanna *et alii*, 2008, Del Prete *et alii*, 2008), identifying formation mechanisms and proposing risk mitigation strategies. These initial investigations revealed the presence of many sinkholes near human settlements, highlighting the associated risks, which depend on factors such as size, speed of development and population density. Sinkholes in densely populated areas or near infrastructure can have a significant economic and social impact, especially with regard to safety. Therefore, addressing these issues requires a multidisciplinary approach. Recent studies (Madonna *et alii*, 2023, Romano *et alii*, 2023; Gentili & Madonna, 2024; Madonna *et alii*, 2024) have focused on locating cavities to mitigate sinkhole risk. These studies utilise a combination of disciplines, including historical archaeological research, geophysics, topography and 3D surveying, often using GIS (Geographic Information System) as a central tool. This paper reports on the results of the multidisciplinary monitoring of the Latera sinkhole, which originated at the end of January 2023 in the extreme vicinity of provincial road 118. Deep piping was also identified as one of the possible causes (Puzzilli *et alii*, 2024). Monitoring began on 1 February 2023 and continued until 1 February 2025, initially using photogrammetric techniques from UAVs and satellite Earth Observation, supplemented, in the course of studies, by HVSR seismic surveys and the analysis of rainfall data.

The formation of the Vepe caldera, part of the Latera volcanic complex (central Italy), has been the subject of numerous studies describing its geological and volcanological evolution. The literature highlights three main phases in the evolution of Vepe volcanism. The first phase comprises volcanic activity characterised by effusive and explosive eruptions, with the formation of lava flows and pyroclastic deposits, which formed the pre-caldera volcanic edifice, with basalt and trachyte as initial magmatic products (Vezzoli *et alii*, 1987). The second phase saw the formation of the Vepe caldera, linked to high-magnitude explosive eruptions that led to the collapse of the surface structure, with a process of incremental caldera growth (Nappi *et alii*, 1991; Nappi & Renzulli, 1990). These eruptions generated large volumes of tuffs and ignimbrites, such as the Pitigliano ignimbrite, characterising the explosive phase (Turberville, 1992). After the collapse, volcanic activity continued with more modest eruptions, leading to the formation of lava domes and lava flows along the margins of the caldera. This phase, characterised by a more differentiated magmatic composition, includes the presence of trachytes and phonolites (Capoccini *et alii*, 1987), with the typical element of Monte Spinaio lavas (Fig. 1). The presence of lacustrine deposits and fine sediments within the caldera could be associated with lacustrine occupation phases.

MATERIALS AND METHODS

The methodologies applied included the use of UAVs with the aid of GNSS stations, the use of browsers for the application of earth observation, passive acquisition of environmental noise and analysis of rainfall data. The obtained data were examined using spreadsheets and reported in a GIS environment for better processing. It should also be noted that the first months of photogrammetric surveys with the first rainfall data processing, from February 2023 to September 2023, are common with the work of Puzzilli *et alii*, 2024.

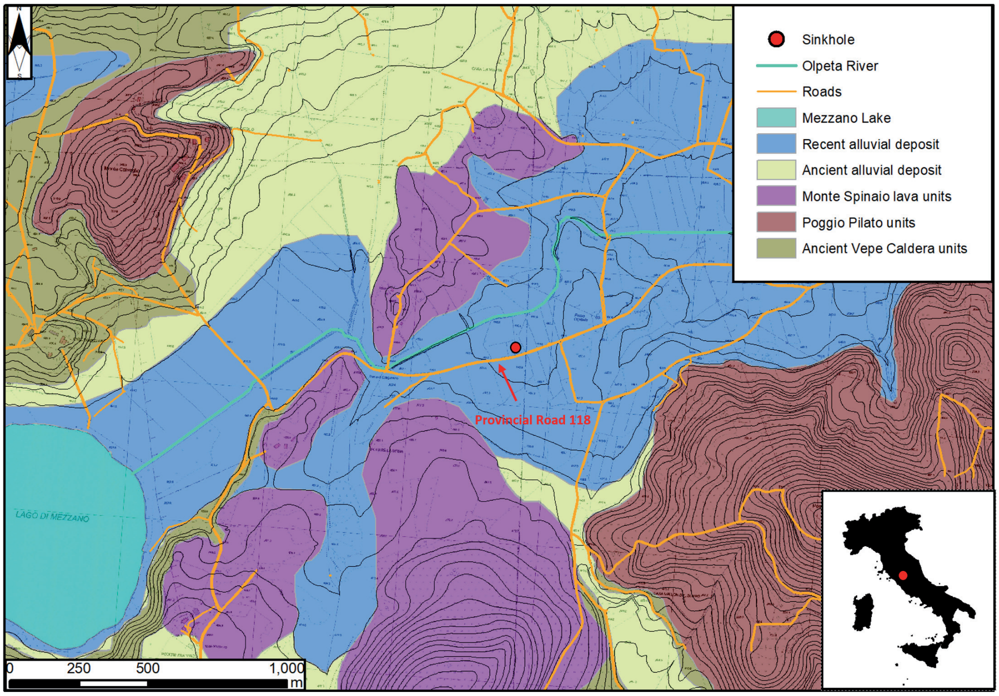

Fig. 1 - Geological map of portion of the Vepe caldera with proposed geological formations in Puzzilli et alii,2024

GIS project

The construction of a GIS project was the first step of this work. The opensource software QGIS version 3.16 'Hannover' (Development Team, 2020) was used. In this project, the collected orthophotos of the study area (from 1948 to the present), the photogrammetric surveys with all exportable products, and what was obtained from the Earth Observation sites were included. This application was very useful for studying the pre-collapse state of the sinkhole (Gentili & Rossi, 2024).

Photogrammetric surveys

The photogrammetric surveys were carried out using methods established in the literature (Colomina & Molina, 2014), approximately every 30-45 days, and involved two types of UAVs: the Italdron evo 4hse equipped with a Sony Alpha 7r Mark 2 camera and the DJI Mavic Pro with an integrated camera. The flight specifications varied according to the type of UAV used. For the Italdron evo 4hse, the flight altitude was 50 m agl (above ground level), with a speed of 6 m/s, photo overlap of 75-80% and GSD of 0.6 cm/pixel. For the Mavic Pro, the flight altitude was 25 m agl, with a speed of 3 m/s, photographic overlap of 75-80% and GSD of 0.8 cm/pixel. Both surveys were scaled and geo-referenced using the Leica GNSS station, consisting of a GS08 plus rover, CS10 controller and 2m rod, to measure the centre of special markers divided into GCPs (Ground Control Points) and CPs (Control Points) to estimate the accuracy of the surveys. Some markers were fixed to the ground to measure any subsidence directly from the GNSS station. The measured geographical coordinates were processed through the IGM GK2 grid, using the geoidal model ITALGEO 2005, to obtain the results in plane coordinates MM Italy I (EPSG 3003) and elevations expressed in metres above sea level. The photogrammetric process, carried out with Agisoft Metashape ver. 1.6.3 software (Agisoft LLC., 2020), led to the production of point clouds, DEMs, orthophotos and DTMs, the latter obtained from the cloud points classified as terrain points.

Earth Observation

Earth observation, is a scientific and technological field that uses satellites, airborne and ground-based sensors to monitor and analyse the Earth's environment. For many years, this technique has been used in various scientific fields, showing good applicability (Drusch *et alii*, 2012, Rousta *et alii*, 2020) Google Earth (Goolge Erath version 7.3.6.10.201) and Copernicus Browser (EUROPEAN UNION Copernicus Programme, 2024) were consulted for this work, the first to obtain images with good resolution and the second to verify the environmental conditions during the time evolution of the sinkhole. Copernicus Broweser reports images collected by the Sentinel 1 satellite (which mounts a radar sensor) and Sentinel 2 (which mounts a multispectral sensor). Several indices were consulted on Copernisuc Browser, which are obtained from the different combination of several bands. In particular, the following indices were examined, also using the timelapses function:

- NDVI: The Normalized Difference Vegetation Index (NDVI) is a straightforward yet powerful tool for assessing green vegetation. It evaluates the health of vegetation by analyzing how plants reflect light at specific wavelengths. NDVI values range from -1 to 1. Values near -1 typically indicate water, while values close to zero (-0.1 to 0.1) often represent barren landscapes such as rock, sand, or snow. Moderate positive values (around 0.2 to 0.4) suggest areas covered by shrubs or grasslands, and higher values (approaching 1) signify dense vegetation like temperate or tropical rainforest. Use frequency bands (B8-B4) (B8+B4).
- NDWI: The normalized difference water index is most appropriate for water body mapping. Values of water bodies are larger than 0.5. Vegetation has smaller values. Built-up features have positive values between zero and 0.2. The NDWI is used to monitor changes related to water content in water bodies. Use frequency bands (B3-B8) (B3+B8).
- Satellite interferometry for the sinkhole site was also checked. Several previous studies have used this tool for the study of sinkholes and other subsidence phenomena (Costantini *et alii*, 2009, Raspini *et alii,* 2022) For this work, the European Ground Motion Service (European Ground Motion Service 2024) was consulted as the interferometer data viewer.

Microtremor recording (HVSR)

HVSR monitoring was used to analyse the directionality of the natural microtremors and their possible correlation with the geological and hydrogeological context. Five microtremor acquisitions were carried out around the sinkhole, using Sara Electronic Instruments' Geobox 3-channel seismograph, with 4.5 Hz geophones, oriented north and correctly levelled, with a sampling frequency of 300Hz and a duration of 25 minutes (Fig. 2). Acquisitions took place at three-month intervals, starting in July 2023. The data were processed using the HVSR method (Nakamura, 1989). The main objective was to study the directionality of the signal, not to look for stratigraphic peaks, for which we refer to Puzzilli *et alii*, 2024. Acquisitions were performed in the absence of anthropic noise and the limited vehicular traffic was removed during processing. To evaluate the reliability of the H/V curves, the Geopsy software version 3.3.2 and the SESAME criteria (SESAME Team 2024) were used.

Meteorological data

For the study of rainfall, temperature, and potential evapotranspiration data, the SIARL - Integrated Agrometeorological Service of the Lazio Region (https://www.siarl-lazio.it/index.asp) was consulted. For the municipality of Latera, the station named

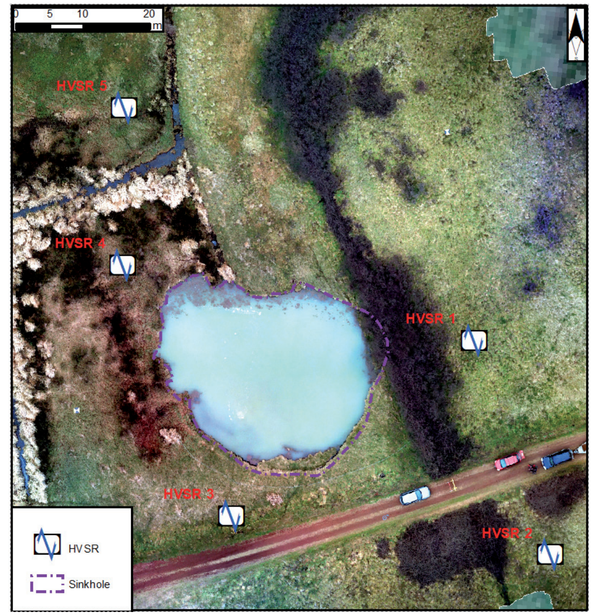

Fig. 2 - Location of HVSR tests

"Latera Centro Florovivaistico" was identified, and monthly historical data from January 2023 to February 1, 2025, were reviewed. The collected data were compared with the water levels in the Latera sinkhole.

RESULTS

GIS project and reconstruction of the pre-collapse state

The GIS project, as well as allowing the superimposition of different information, has enabled a more detailed study of the pre-collapse state of the sinkhole, using historical and recent orthophotos of the area. The precursor shapes and ecosystem details reported in the most recent publications are clearly evident (Puzzilli *et alii*, 2024, Gentili & Rossi, 2024) Using Google Earth's Street View tool, photos of the area dating back to November 2011 were retrieved (Fig. 3).

Photogrammetric surveys

A total of 19 photogrammetric surveys were conducted, some of which are shown in Fig. 4. Table 1 shows the average errors associated with the surveys carried out with different UAVs, both on GCP (Ground Control Points) and CP (Check Points). Measurements of fixed markers using a GNSS station do not indicate significant variations over a two-year period, recording minor fluctuations comparable to the estimated error of the station itself (approximately 1.8-2.5 cm). Water levels, measured through photogrammetry, field surveys, and satellite data, are reported in Fig. 4L.

UAV	Average error on GCP	Average error on CP
Evo 4hse	1.8 cm	2.3 cm
DJI Mavic Pro	2.7 cm	4.2 cm

Tab. 1 - Average error associated with surveys

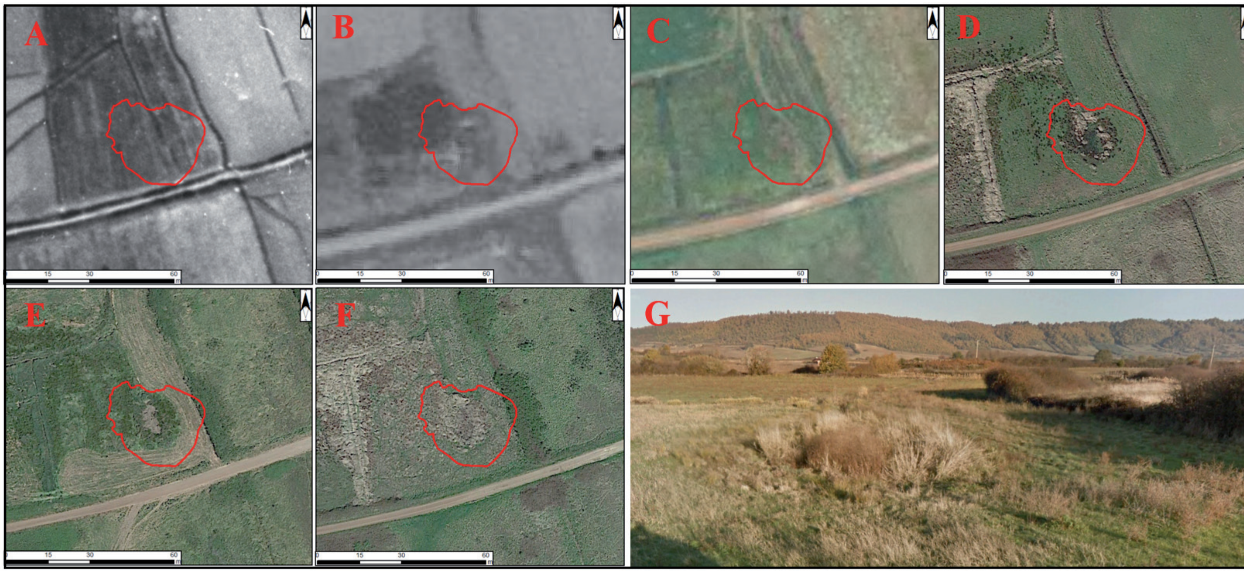

Fig. 3 - Orthophotos dated, 1948 (A), 1988 (B), 2005 (C), March 2017 (D), July 2019 (E), April 2022 (F), and November 2011 (G), with the sinkhole boundaries highlighted in red. The shapes described in PUZZILLI *et alii, 2024 and the growth of the unique ecosystem highlighted in* GENTILI *&* ROSSI*, 2024 are clearly visible*

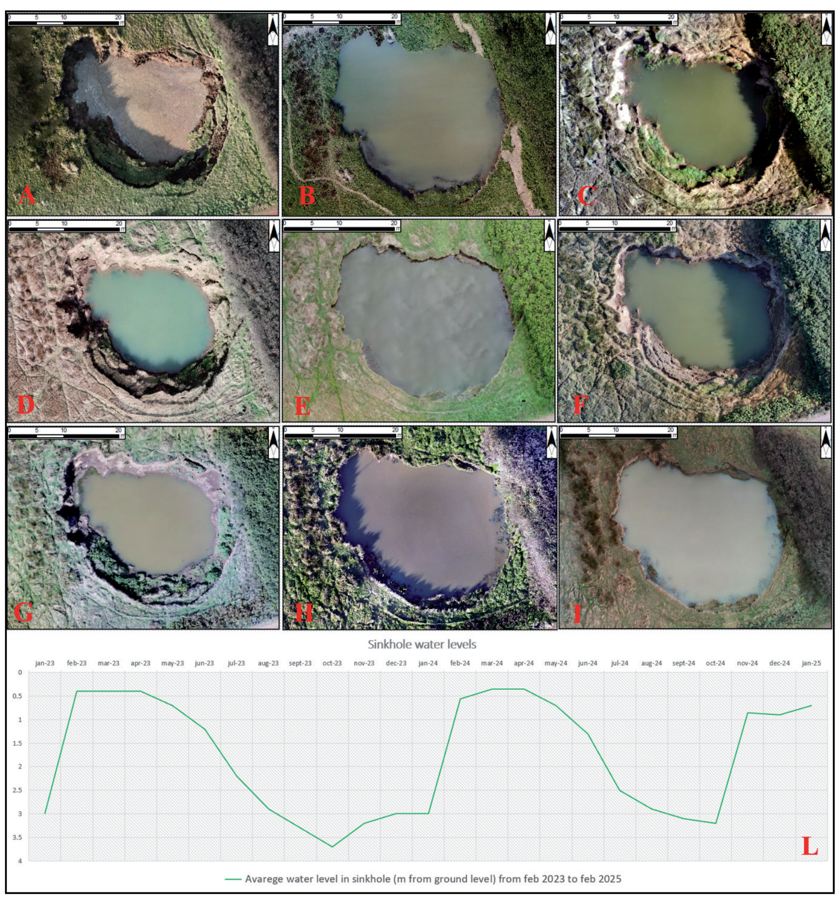

Fig. 4 - Orthophotos from UAV survey of February 2023 (A), April 2023 (B), August 2023 (C), February 2024 (D), April 2024 (E), July 2024 (F), September 2024 (G), November 2024 (H), February 2025 (I). Monthly average water levels in the sinkhole (L)

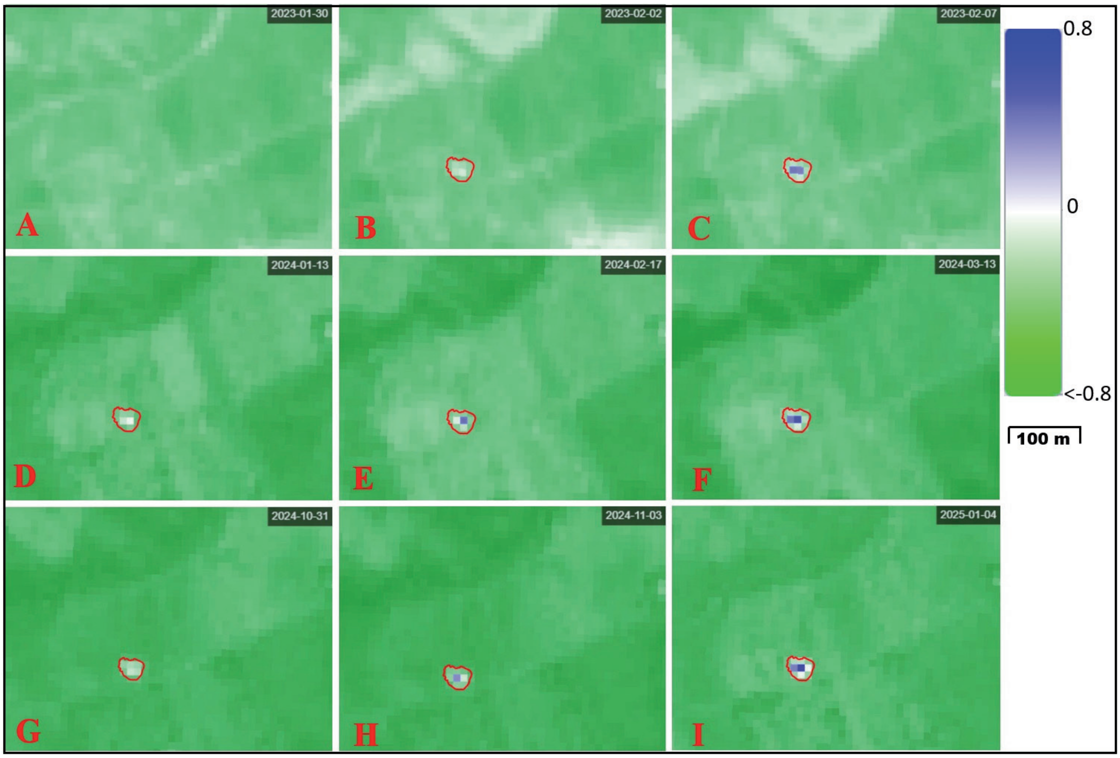

Fig. 5 - NDWI images from Copernicus Browser of the Sinkhole area dated 30 January 2023 a few hours before the formation (A), 2 February 2023 (B), 7 February 2023 (C), 13 January 2024 (D), 17 February 2024 (E), 13 March 2024 (F), 31 October 2024 (G), 3 November 2024 (H), 4 January 2025 (I). In red are the boundaries of the sinkhole, which are not visible in Figure 5A as they had not yet formed at the time of satellite acquisition

Earth Observation

The The NDVI index shows the presence of more lush vegetation around the sinkhole, which is also evident from the orthophoto. The NDWI index proved to be very useful, as it makes much more explicit the variation of the water level in the sinkhole (Fig. 5). The absence of natural or anthropogenic reflectors did not allow the use of In-Sar techniques. In the sinkhole area and most of the Vepe plain, there is a complete absence of these data.

HVSR

All of the HVSR analyses show peaks between 0.51 Hz and 0.62 Hz. As can be seen in Fig. 6, accentuated directionality is evident in the H/V ratio and frequency values detected by the analysis. This figure illustrates the H/V curves with peaks for each HVSR trial, the SESAME criteria that an HVSR trial must meet to be considered reliable, and the directionality analysis. Since the study focuses on directionality, only the first three are to be considered, those inherent in the H/V curve, which is found to be statistically reliable in all tests. The third image represents the directionality analysis, in which the main source direction of seismic noise is expressed as a function of frequency. The graduated scale below the frequency axis represents the H/V ratio, which can also be read on the ordinate, again as a function of frequencies, in the graph of the H/V curve. These findings are reported for each test performed during the monitoring phases. It is again emphasised that these peaks do not have stratigraphic significance as the analysis was carried out to understand whether or not there was a predominant direction of the natural microtremors. The location of the surveys is shown in Fig. 2. Table 2 shows the frequency values for each individual HVSR.

	HVSR 1	HVSR 2	HVSR 3	HVSR 4	HVSR 5
Frequency (Hz)	0.51	0.52	0.55	0.52	0.62

Tab. 2 - HVSRs frequency peaks

Meteorological data analysis

The meteorological data were processed for monthly averages and compared with the water levels in the sinkhole. Rainfall, potential evapotranspiration (PET) and temperature for the reference period between January 2023 and 1 February 2025 were processed. Figure 7 shows graphs comparing these data with the fluctuation of water levels in the sinkhole. PET data for the first 20 days of July 2023 are not present. To remedy this problem, an average of the available July data between 2004, the year the station was commissioned, and 2024 was made.

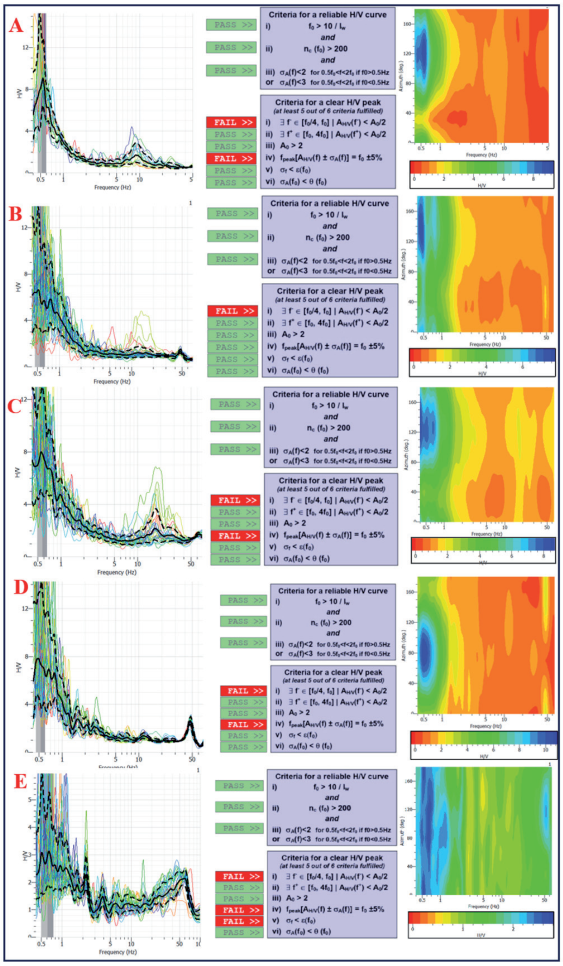

Fig. 6 - *Frequency peak, SESAME criteria and directionality HVSR 1 (A), HVSR 2 (B), HVSR 3 (C), HVSR 4 (D), HVSR 5 (E)*

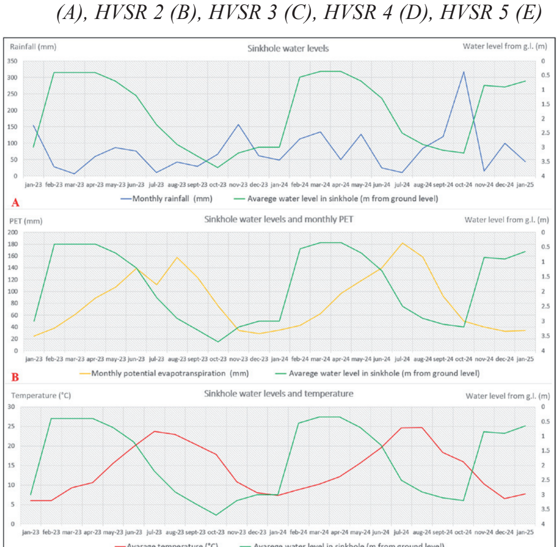

Fig. 7 - *Comparison of water levels in the sinkhole with rainfall data (A), PET (B) and temperature (C)*

DISCUSSION

The results obtained from the study of the pre-collapse state show evidence of some forms that approximate those of the future sinkhole, as indicated in Puzzilli *et alii*, 2024 and Gentili & Rossi, 2024. In particular, as reported in the latter work, when the land was no longer used for agricultural purposes, there was a complete replacement of local and cultivated plants with typically marsh species, identified mainly as common rush (Juncus effusus L.) and conglomerate rush (Juncus conglomeratus L.), shown in Fig. 8C and 8D and observed in the sinkhole area. Applying Earth observation in a GIS environment, the Vepe caldera has been carefully studied over time in order to better understand the changes that have taken place from the 1940s to the present day. Throughout the caldera, the only area where a similar ecosystem is present is located near Lake Mezzano, where the Olpeta River originates, also known in this stretch as 'Fosso delle Volpi' (Fig. 8). The presence of this ecosystem can be easily explained by a marshy area connected to the reclamation of a portion of Lake Mezzano that began at the end of the 17th century (Giraudi, 2004), which led to the formation of the 'Fosso delle Volpi' and numerous canals that still serve a drainage function today. Given the absence of constant rainfall in the sinkhole area, the volumes of water necessary to support these plant species can only come from groundwater rising to the surface, which can be reasonably explained by deep piping, as a geological context favourable to this phenomenon has been established. The volumes of water brought to the surface in this way promote highly accentuated soil moisture conditions, concentrated only in the area where piping is active. These humid conditions favour the growth of plant species and, as in this case, markedly hygrophilous ones. This further highlights the value of using orthophotos and satellite images to monitor these and other warning signs over time, such as the appearance/disappearance of springs and sub-circular or elliptical depressions, identifying areas prone to sinkhole formation where a favourable geological context exists. The photogrammetric surveys did not show any changes in the size of the sinkhole or any subsidence or ground uplift, as confirmed by measurements taken with a GNSS station. The interventions made it possible to collect reliable measurements of the water level and to calculate the volumes entering and leaving the doline on a monthly basis.

The lack of some data, due to the absence of UAV flights, was mitigated through direct measurements and especially through the use of the NDWI index, derived from practical Earth observation applications. The frequency of passage of the Sentinel satellites made it possible to obtain information (albeit more qualitative) of water fluctuations approximately every 7-10 days, although due to cloud cover, images for several days were not usable. Other types of indices were not very useful, especially for the type of treatment, with the exception of the NDVI index, which indicates more luxuriant growth around the sinkhole. This index, when

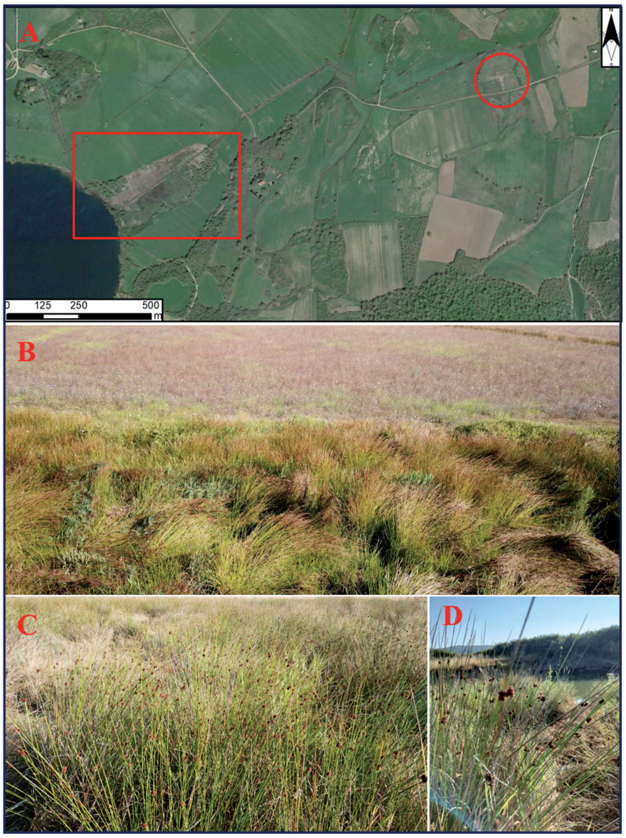

Fig. 8 - Orthophoto from 2022 of the Vepe caldera, in the red circle the sinkhole area and in the red square the reclaimed area (A), rushes in the Lake Mezzano area (B), rushes in the sinkhole area (C and D)

combined with colour orthophotos, can provide information on vegetation growth in a given area and, when used in conjunction with geological-stratigraphic and pluviometric information, can provide information on possible piping phenomena near the surface. Interferometric data were not available because reflectors were absent. A certain cyclicity emerges from the study of water levels. From what we have seen, the sinkhole begins to fill with water in late January early February, and then reaches full fill by mid-February, at least as seen in 2023 and 2024, as is evident from both the photogrammetric surveys and the NDWI index. Levels tend to remain stable and then begin to slowly decline in early May, reach a minimum in September-October and then rise again. This cycle is also partially evident from historical orthophotos. In particular, in the one from March 2017, the presence of water can be seen, which is not the case in July 2019 (Fig. 3D and 3E), in agreement with what was seen from the surveys. In early November 2024, filling occurred again with similar timing as in February 2023 and 2024. As of February 2025, the sinkhole is still filled with water. By comparing weather data with long-term water levels, a certain correspondence between rainy periods and increased water in the sinkhole might emerge. The same could be said of warm periods with more pronounced evapotranspiration. For this reason, although the problem has been simplified, the changes in water volume have been compared with the difference between rainfall and PET in the sinkhole (Fig. 9). It is clear from the graph that the fluctuations in level depend only minimally on rainfall and PET, thus being a function, by exclusion, of groundwater motion.

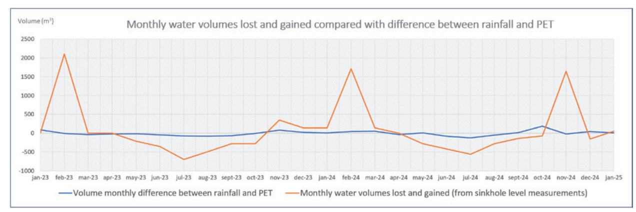

Fig. 9 - Variation of water volumes in the sinkhole compared with volumes lost or acquired through PET and rainfall

The rapid and cyclic groundwater movements, which led to the filling of the sinkhole in approximately 7-10 days, may have been responsible for its formation. Over time, the change in piezometric level, probably related to deep piping, would have eroded the alluvial sediments, weakening the surface layers and causing the sinkhole. The sinkhole was in fact formed between 30 and 31 January 2023, probably at the beginning of the rapid phase of piezometric level rise. The date of formation of the sinkhole was confirmed by satellite images, which show no morphological changes on 30 January. Water level fluctuations are active throughout the year, albeit with varying speeds and directions depending on the period. Similar sinkings, attributed to deep piping, are documented in the literature at the same time of year (Nisio, 2008C, Berti *et alii*, 2002, Del Prete *et alii*, 2008). The study of these cycles could be useful for assessing the propensity for sinkhole formation in floodplains, particularly in known geological contexts and in the presence of anthropogenic activities. Since water movements, especially the rapid ones that characterise filling phases, are localised in the ground and can be associated with a source of seismic noise, HVSR surveys were carried out to study the directionality of these noises and try to understand their origin. This method has already been applied in the past to sinkhole risk mitigation (Liang *et alii*, 2018) and also, albeit for other purposes, to the study of groundwater (Haefner *et alii*, 2011, Galone *et alii*, 2024) The recording positions show two substantial main directions of the seismic noise, one coming from 110°-140° and the other from 70°-100° (Fig. 10A), ideally indicating the discontinuities identified by Puzzilli *et alii*, 2024, as further confirmation of these structures. This directionality could therefore be related to the presence of such discontinuities, but also to the upward/downward movement of groundwater along vertical channels oriented parallel to these faults or be linked to the combined effects of these possible causes. A possible partial link between directionality and water movements is also suggested by HVSR No. 5, whose directionality, although identifiable, is much more extensive than the other. The position of this recording, further north than the others, probably makes it less affected by microtremors from 70°-100°. The peak detected appears to have a higher frequency than the others (0.62 Hz outside the 0.5-0.55 Hz range), approaching the values found in the area and reported in Puzzilli *et alii*, 2024 (around 1-1.1 Hz). It is remarkable that the major axis of the sinkhole is oriented in the direction of the seismic noise, and the same can be said of the depression located immediately north of it (Fig. 10C). In particular, also in this area, water fluctuations in conjunction with those found in the sinkhole were detected by analysing the level changes in the T-shaped drainage channels. A final thought can be made about the discontinuities in the area. According to the stratigraphy, these involve the Monte Spianio lavas. These formations are generally associated with the final stages of volcanic activity at Vepe and thus put in place when the caldera was already formed. The presence of these discontinuities allows us to advance the hypothesis that these lavas were put in place during the final phases, but that the last settlements of the caldera also affected these.

From this monitoring it was possible to sketch the following method for monitoring sinkholes by means of photogrammetry, which can be described as follows:

- Place fixed markers detectable with a GNSS station, at least in a variable number depending on the size of the sinkhole, but in a minimum number of 4. The placement should take place around the sinkhole but also in the vicinity of any infrastructure (such as in

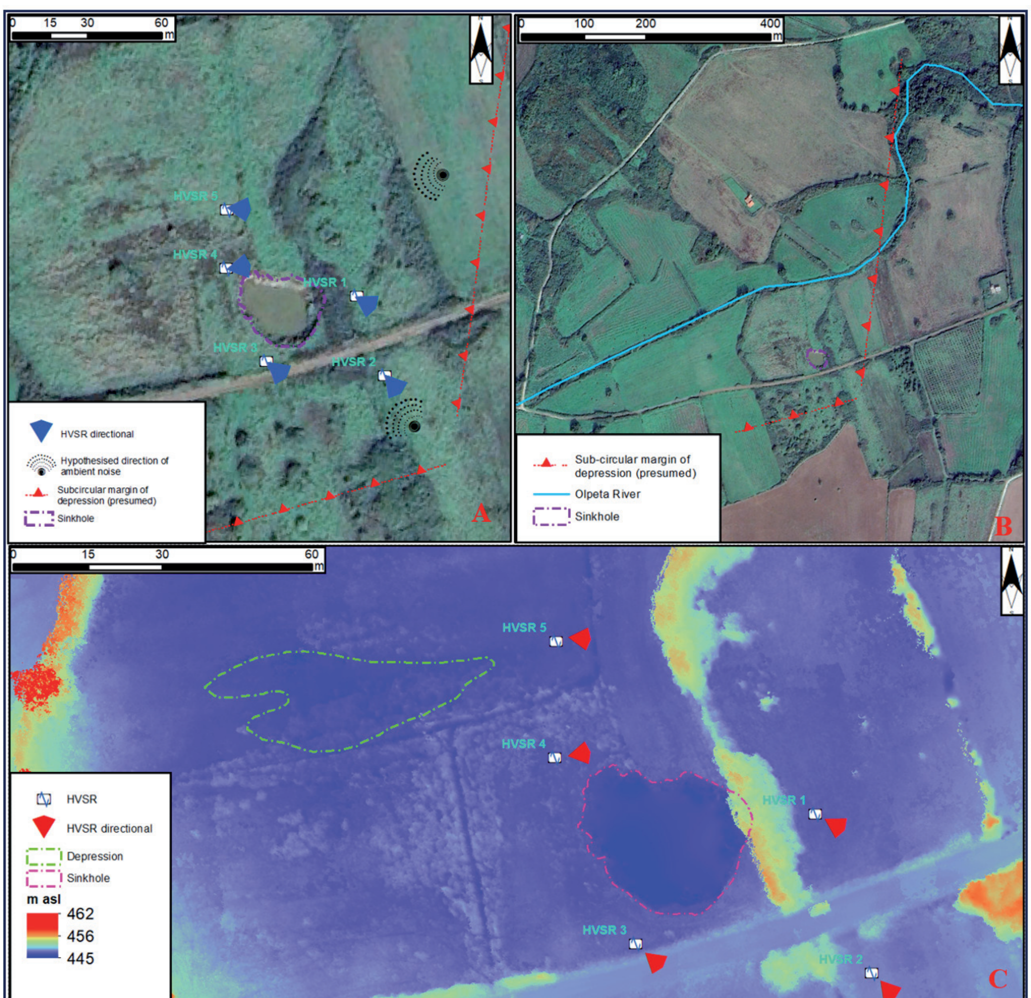

Fig. 10 - Directionality of the HVSR with seismic noise and discontinuity assumptions proposed by Puzzilli *et alii, 2024 (A), ideal alignment of the discontinuity with the course of the Olpeta River (B), DEM showing alignment of the major axis of the sinkhole and the depression north of the sinkhole with the seismic noise (C)*

this case the provincial road 118). If no other methods of scaling and georeferencing are used (such as UAVs with RTK-PPK GPS) then these markers must always be clearly visible in the orthophotos in order to be able to take direct point measurements.

- Use of mobile markers for surveying, to be divided into GCPs and CPs, also in variable numbers depending on the area to be surveyed, but a minimum of 7 GCPs and at least 5 CPs are recommended.
- Execution of flights with good photographic overlap, at least 70%, to be performed at altitudes and speeds that guarantee GSD between 1-1.5 cm/pixel.
- Produce orthophotos with a definition within 2cm/pixel, in order to have good detail and visually verify shape variations in the sinkhole between surveys.
- Carry out monthly/bimonthly surveys and supplement the time intervals with satellite images.

CONCLUSIONS

This study presents the results of a two-year monitoring of the sinkhole in the Vepe Plain, formed between 30 and 31 January 2023. The main results include a detailed reconstruction of the pre-collapse state, which revealed premonitory signs of the phenomenon and indirect effects of piping, such as localised ecosystems separated from the surrounding landscape. This opens up the possibility of looking for similar effects in other alluvial contexts to identify areas where deep piping is potentially active. The cause of sinkhole formation attributed to deep piping was confirmed to be an active phenomenon even in contexts without karstic carbonate rocks, expanding the locations where sinkholes can occur. A possible mechanism of action of deep piping has been identified, with cyclical variations related solely to groundwater levels, causing the deterioration of surface layers. The use of HVSR seismic testing was proposed to identify contexts favourable to deep piping for grounfwater movement. Finally, a monitoring protocol was developed based on photogrammetry, satellite observation and GNSS stations, applicable to different contexts.

ACKNOWLEDGMENTS

This research was partially funded by PNRR-European Union-NextGeneration EU-Mission 4 “Education and Research”-Component 2 “From Research to Business”-Investment 3.1 “Fund for the realization of an integrated system of research and innovation infrastructures”. CUP: I53C22000800006.

REFERENCES

AGISOFT LLC. (2020) - *Agisoft Metashape (Version 1.6.3) [Software].* available at: https://www.agisoft.com.

Berti G., Canuti P., Casagli N., Micheli L. & Pranzini G. (2002) - *Risultati preliminari sullo sprofondamento in località Bottegone (Grosseto).* In: *“Le voragini catastrofiche, un nuovo problema per la Toscana”.* Att. Conv. 31 Marzo 2000, Gr. Regione Toscana, 242-256.

Capaccioni B., Nappi G., Renzulli A. & Santi P. (1987) -*The eruptive history of Vepe Caldera (Latera Volcano), a model inferred from structural and geochemical data.* Periodico Di Mineralogia, **56**: 269-283.

Caramanna G., Ciotoli G. & Nisio S. (2008) - *A review of natural sinkhole phenomena in italian plain areas.* Natural Hazards, **45**: 145-172.

Colomina I. & Molina P. (2014) - *Unmanned aerial systems for photogrammetry and remote sensing: a review.* Isprs Journal of photogrammetry and remote sensing, **92**: 79-97. https://Doi.Org/10.1016/J.Isprsjprs.2014.02.013.

Costantini F., Fea M., Nisio S., Sarti F. (2009) - *Radar interferometry: preliminary study about sinkhole prone areas.* Atti Del 2° Workshop Internazionale: Gli sprofondamenti catastrofici nell’ambiente naturalizzato ed in quello antropico, Roma 3-4 Dicembre 2009, 967-971.

Del Prete S., Guarino P.M., Nisio S. & Santo A. (2008) - *The sinkholes in Campania region.* Mem. Descr. Carta Geol. D’it., **85**: 149-212.

DEVELOPMENT TEAM (2020) - *Qgis Geographic Information System. Version 3.16.* Open Source Geospatial Foundation Project. Accessed 2 February 2025. https://Qgis.Org.

Drusch M., Del Bello U., Carlier S., Colin O., Fernandez V., Gascon F. et al. (2012) - S*entinel-2: Esa’s optical high-resolution mission for Gmes operational services.* Remote Sensing of environment, **120**: 25-36. https://Doi.Org/10.1016/J.Rse.2011.11.026.

EUROPEAN GROUND MOTION SERVICE (2024) - *Ground motion data for Europe.* European Environment Agency. https://Land.Copernicus.Eu/En/Products/European-Ground-Motion-Service.

EUROPEAN UNION, Copernicus Programme - Copernicus Browser. Accessed On 2 February 2025. https://browser.dataspace.copernicus.eu/.

Fairbridge W. (1968) - *The encyclopedia of geomorphology.* Ed. Reinhold: New York, Ny, Usa, 1968; 1295P.

Galone L., Panzera F., Colica E., Fucks E., Carol E., Cellone F., Rivero L., Agius M.R. & D’amico S. (2024) - *A seismic monitoring tool for tidal-forced aquifer level changes in the Río De La Plata coastal plain, Argentina.* Sustainability 2024, **16**: 1432. https://Doi.Org/10.3390/Su16041432.

Gentili F., Madonna S. (2024) - *Photogrammetry from uav and low-cost Lidar for sinkhole hazard mitigation in urban areas: applications and evaluations.* Geographies, **4**: 343-362. https://Doi.Org/10.3390/Geographies4020020.

Gentili F. & Rossi F.G. (2024) - *Integrated use of orthophotos and geo-thematic knowledge for sinkhole risk mitigation* In Quaternary Alluvial Plains. Alpine and mediterranean Quaternary, **37**(2): 89-101. Https://Doi.Org/10.26382/Amq.2024.05

Giraudi C. (2004) - *Le oscillazioni di livello del lago di Mezzano (Valentano-Vt): variazioni climatiche e interventi antropici.* Alp. Mediterr Quat., **17**: 221-230.

GOOGLE EARTH Versione [7.3.6.10.201] Accessed On 2 February 2025, https://earth.google.com/.

Haefner R.J., Sheets R.A., & Andrews R.E. (2011) - *Evaluation of the horizontal-to-vertical spectral ratio (HVSR) seismic method to determine sediment thickness in the vicinity of the south well field, Franklin County, Oh. Ohio.* Journal of Science, **110**(4): 77-8.

https://www.isprambiente.gov.it/it/attivita/suolo-e-territorio/sinkholes-e-cavita-sotterranee/classificazione-dei-sinkholes.

Liang D., Gan F., Zhang W., Jia L. (2018) - *The Application of HVSR method in detecting sediment thickness in karst collapse area of Pearl River Delta, China.* Environmental Earth Sciences, **77**. doi: 10.1007/S12665-018-7439-X.

Madonna S., Nisio S., Gentili F., Vessella F., Scardozzi G., Romagnoli G., Di Nezza M., Di Filippo M., Pelorosso M. & Pagano G. (2023) - *The role of historical-archaeological sources integrated into the Gis environment with geological and geophysical data,* In: The mitigation of geological risks in some urban areas. Rend. Online Soc. Geol. It., **61**: 50-57, 4 Figs. https://Doi.Org/10.3301/Rol.2023.46.

Madonna S., Gentili F., Mattioli M., Scatolini A., Pendola V., Monaldi G.G. & Monaldi G. (2024) - *Survey techniques integrating smartphone Lidar and Uav photogrammetry: The example of the anthropic underground cavities of Montefiascone (Viterbo, Central Italy).* Rend. Online Soc. Geol. It., **64**: 26-34. https://doi.org/10.3301/Rol.2024.46.

Nakamura Y. (1989) - *A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface*. Railway Technical Research Institute, Quarterly Reports, **30**: 1

Nappi G. & Renzulli A. (1990) - *Genesi ed evoluzione della caldera Del Vepe (Complesso vulcanico di Latera).* Memorie Descrittive della Carta Geologica D'Italia, **38**: 129-144.

Nappi G., Renzulli A. & Santi P. (1991) - *Evidence of incremental growth in the vulsinian calderas (Central Italy).* J. Volcanol. Geotherm. Res., **47**: 13-31.

Nisio S. (2008A) - *The Sinkholes: terminological problmes, genetic mechanism, classification.* Mem. Descr. Carta Geol. D'it., **85**: 17-32.

Nisio S. (2008B) - *The Sinkholes in the Lazio Region*. Mem. Descr. Carta Geol. D'it., **85**: 33-148.

Nisio S. (2008C) - *The Sinkholes in the Tuscany Region.* Mem. Descr. Carta Geol. D'it., **85**: 213-268.

Nisio S. (2008D) - *The Sinkholes in the Sardinia Region.* Mem. Descr. Carta Geol. D'it., **85**: 387-398.

Nisio S. (2008E) - The Sinkholes In The Padana Plain. Mem. Descr. Carta Geol. D'it., **85**: 409-418.

Nisio S. (2008) - *The sinkholes: terminological problems, genetic mechanism, classification.* Mem. Descr. Carta Geol. It., **85**: 17-32.

Puzzilli L. M., Ruscito V., Madonna S., Gentili F., Ruggiero L., Ciotoli G. & Nisio S. (2024) - *Natural sinkhole monitoring and characterization: The case of Latera sinkhole (Latium, Central Italy).* Geosciences, **14**: 18. https://doi.org/10.3390/Geosciences14010018.

Romano G., Capozzoli L., Abate N., De Girolamo M., Liso Is., Patella D. & Parise M. (2023) - *An integrated geophysical and unmanned aerial systems surveys for multi-sensory, multi-scale and multi-resolution cave detection: The Gravaglione site (Canale di Pirro Polje, Apulia).* Remote Sensing, **15**(15): 382.

Raspini F., Caleca F., Del Soldato M., Festa D., Confuorto P., Bianchini S. (2022) - *Review of satellite radar interferometry for subsidence analysis.* Earth-Science Reviews, **235**: 7-46.

SESAME TEAM (2004) - *Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measurements, processing and interpretation.* (Deliverable No. D23.12), Wp12. Sesame European Research Project.

Rousta I., Olafsson H., Moniruzzaman M., Zhang H., Liou Y.-A., Mushore T.D., Gupta A. (2020) - *Impacts of drought on vegetation assessed by vegetation indices and meteorological factors in Afghanistan.* Remote Sens., **12**: 2433. https://doi.org/10.3390/Rs12152433.

Turbeville B.N. (1992) - *Tephra fountaining, rheomorphism and spatter flow during emplacement of the Pitigliano Tuffs, Latera caldera, Italy.* Journal of Volcanology and Geothermal Research, **53**: 309-327.

Vezzoli L., Conticelli S., Innocenti F., Landi P., Manetti P., Palladino D.M., Trigila R. (1987) - *Stratigraphy of the Latera volcanic complex: proposals for a new nomenclature.* Periodico Di Mineralogia, **56**: 89-110.

Received April 2025 - Accepted June 2025