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INTEGRATED USE OF ORTHOPHOTOS AND GEO-THEMATIC KNOWLEDGE FOR SINKHOLE RISK MITIGATION IN QUATERNARY ALLUVIAL PLAINS.

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ABSTRACT: Sinkholes formation is a widespread reality in Italy, but it is often not as well known as other hazards, such as landslides and earthquakes. The study of these phenomena has led over time to a better understanding of sinkholes and their associated formation mechanisms. In this work, we focused on sinkholes that originate in alluvial contexts, mostly due to deep piping and suffosion phenomena. The objective was to verify the presence of common evidence by observing the sites of 29 sinkholes before and after the collapse phase through the study of historical and recent orthophotos. After producing an initial list of surface evidences common to several sinkholes, various areas in the Italian alluvial plains were examined that maintained the catalogued evidences in the orthophotos. On the basis of these evidences, the number and quality of previous geothematic knowledge and the ease of access, an area in southern Tuscany was selected, where photogrammetric surveys, geophysical surveys and analysis of rainfall data were carried out to verify possible connections with deep piping/suffosion phenomena potentially active in the area and the surface evidences found in the orthophotos.

Keywords: Sinkholes, alluvial plains, geophysics, orthophotos, photogrammetry.

1. INTRODUCTION

Natural sinkholes occurring in alluvial plains are generally related to deep piping and suffosion phenomena. Over time, these sinkholes have been studied and the processes of their formation described. A sinkhole due to deep piping is generated under precise geological conditions, which generally involve a karstic bedrock (or permeable) covered by soft deposits with variable grain size from sandy to silty-clayey (Nisio, 2008A). The presence of geological discontinuities, such as faults, favors these types of processes, providing a preferential route along which fluids rise. Suffosion sinkholes, on the other hand, originate through erosion phenomena from below with the formation of vertical and sub-horizontal conduits that, however, only affect the first few metres of the overburden (Nisio, 2008A). In both phenomena, the movement of water erodes the superficial layers of the land cover, even leading to the creation of cavities. When the erosion phenomena are very pronounced or the cavities reach a critical size, sinking to the surface occurs.

The recent collapse in the Vepe caldera in the Municipality of Latera, in the Province of Viterbo, suggests that deep piping and suffosion phenomena may also be active in volcanic contexts, leading to the formation of sinkholes (Puzzilli et al., 2024). This sinkhole was studied using a combined multidisciplinary approach. Multidisciplinary methodologies have also been applied with good results in the research of karstic cavities in Apulia, making it possible to study these structures in the area of the Gravaglione sinkhole (Romano et al., 2023).

After its formation, a sinkhole due to deep piping/suffosion can have several evolutions. One of the most frequent is drowning, in which groundwater pours into the depression forming a small lake, the level of which may fluctuate over time or remain constant. Another possible evolutionary path is extinction, in which the sinkhole dries out and fills up (also by human action) until it becomes extinct, although this does not exclude possible reactivation over time. If reactivation does not take place in the same position as the initial sinking, then we speak of migration, which may be due to the variation of the fluid's ascent paths, also as a result of seismic events or the remote repetition of similar phenomena. Based on this knowledge, it is possible to identify areas with geological features that favour these types of sinkholes. In addition to what has already been mentioned, for example, the presence of other sinkholes and small lakes, the disappearance/reappearance of springs, and the presence of confined aquifers are clues that make it possible to identify vast areas where sinkholes could occur.

The combined use of geotematic knowledge with historical and archaeological records has yielded good results in the past, especially in the area of anthropogenic sinkholes (Madonna et al., 2023). This knowledge could be supplemented by the use of historical and recent orthophotos of the territory, in order to study the evolution of the site of a fairly recent sinkhole over time, especially in its pre-sinkhole state, in search of other clues that would allow the identification of factors common to several sites, even spatially distant ones. Today, thanks to the presence of dedicated web portals and their dissemination, it is easy to access these tools, covering a time span potentially ranging from the 1940s to the present day, making a large number of images available.

The work presented in this article aims to initially identify these common characteristics by analyzing historical and recent orthophotos of various sinkholes (attributable to deep piping and suffosion) present in the Italian national territory. Based on insights gained from orthophoto analysis combined with prior geological knowledge, an area in southern Tuscany (Municipality of Grosseto) was identified, exhibiting features similar to those observed at other sinkhole sites before collapse.

In-depth investigations were conducted in this area using photogramme-tric surveys, surface seismic surveys and analysis of rainfall data, as well as retrieval of previous studies and investigations carried out in the area. The aim is to contribute to enhance current methods for identifying areas at risk and susceptible to sinkhole formation by utilizing information derived from orthophoto analysis.

2. MATERIALS AND METHODS

The methodology employed initially involved the study of bibliographic material relating to different parts of Italy where sinkholes have occurred due to piping and suffosion, for which aerial images and available orthophotos dating back to different time periods were retrieved in order to study the pre-collapse state and post-collapse evolution.

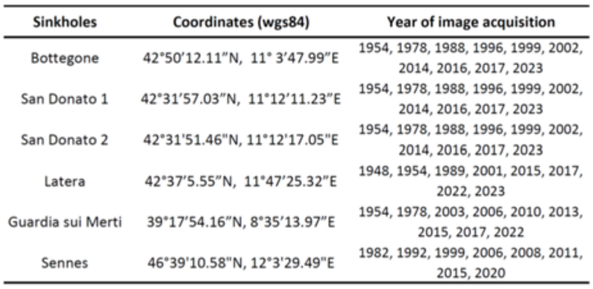
Based on the orthophoto analysis, several study areas were selected where the geological context was already known, and where features resembling pre-collapse sinkhole indicators were visible. Among these areas, a specific site in the Grosseto province was identified, where detailed field studies which included photogrammetric surveys, geophysical investigations and analysis of rainfall data were available.

The initial step was therefore a literature review in search of sinkholes formed in the last 70-80 years (Campobasso et al., 2004; Caramanna et al., 2008; Centamore et al., 2009; Del Prete et al., 2008; Nisio, 2008B; Nisio, 2008C; Nisio, 2008D; Nisio, 2008E; Nisio, 2008F; Nisio, 2008G; Nisio, 2008H; Nisio, 2008I; Nisio, 2008L) as a result of deep piping/suffosion phenomena and for which historical and recent orthophotos of the sites were available. Available orthophotos were collected for a period between 1940 and 2023, of the study sites occurring in the literature, national regional IGM and Google Earth map portals were examined as well as aerial photos from the 1940s.

The second step involved the construction of a GIS project, realised with the open-source software QGIS version 3.16 “Hannover” (QGIS Development Team, 2020). For each site, historical and recent orthophotos were collected in georeferenced format, ascertaining a complete and perfect overlap with the regional technical cartography elements. The aerial photographs and orthophotos with no spatial reference were georeferenced manually using the QGIS tool 'georeferencer', which requires the identification of 4 homologous points for the georeferencing process to take place. To facilitate this procedure, the vector formats of the hydrography and road graphs were obtained from the regional portals, so that the homologous points could be easily identified. The limits of the sinkholes were vectorized by drawing them on the georeferenced orthophotos.

For illustrative purposes and ease of discussion, based on the photographic availability, representativeness and classification of sinkholes, from initial 29 cases, five sinkholes were selected for this research. Figure 1 shows the sites of the examined sinkholes on the map and Table 1 shows the WGS84 geographical coordinates of each site. The images of these sites were taken from the National Geoportal (Geoportale Nazionale, 2024), the Tuscany Region portal (Geoscopio, 2024), the Lazio Region portal (Geoportale Regione Lazio, 2024), the Sardinia Region portal (Sardegna Geoportale, 2024) the Istituto Geografico Militare (IGM, 2024) and Google Earth (Google Earth, 2024). Information about the metadata and characteristics of the images can be consulted directly on the mentioned portals.

Fig. 1 - Outline of Italy with the location of the studied sinkhole areas.
1) Bottegone and selected area for field surveys, 2) San Donato 1 and 2, 3) Latera, 4) Guardia dei Merli, 5) Sennes.



Sinkholes	Coordinates (wgs84)	Year of image acquisition
Bottegone	42°50’12.11”N, 11° 3’47.99”E	1954, 1978, 1988, 1996, 1999, 2002, 2014, 2016, 2017, 2023
San Donato 1	42°31’57.03”N, 11°12’11.23”E	1954, 1978, 1988, 1996, 1999, 2002, 2014, 2016, 2017, 2023
San Donato 2	42°31'51.46"N, 11°12'17.05"E	1954, 1978, 1988, 1996, 1999, 2002, 2014, 2016, 2017, 2023
Latera	42°37’5.55”N, 11°47’25.32”E	1948, 1954, 1989, 2001, 2015, 2017, 2022, 2023
Guardia sui Merti	39°17’54.16”N, 8°35’13.97”E	1954, 1978, 2003, 2006, 2010, 2013, 2015, 2017, 2022
Sennes	46°39'10.58"N, 12°3'29.49"E	1982, 1992, 1999, 2006, 2008, 2011, 2015, 2020

Tab. 1 - Coordinates of the analysed sinkholes sites.

For Latera site only, a georeferenced UAV photogrammetric survey was carried out to obtain the sinkhole limits in a vector format. This step was indispensable to obtain an orthophoto of the sinkhole as it was not yet available. The use of UAVs for scientific purposes is now common practice and, with due support, reliable and accurate for obtaining accurate DTMs (Digital Terrain Models) and orthophotos (Gentili & Madonna, 2024; Pingel et al., 2021; Puzzilli et al., 2024). The latter survey was carried out using the DJI Mavic Pro UAV (unmanned aerial vehicle), supported by GPSs (ground control points) and CPs (control points) on the ground measured using a Leica GNSS (Global Navigation Satellite Systems) station consisting of a GS08 plus rover, CS10 controller and two-metre rod, connected to Lieca's Smartnet network. The flights were performed at an altitude of approximately 35m AGL (above ground level), at a speed of 3 m/s with an estimated photographic overlap of around 75-80%. The photogrammetric process was developed using Agisoft Metashape Professional software. In order to make more precise comparisons, the vectorized limits were projected onto the historical and recent orthophotos.

To assess the effectiveness of this integrated approach, several locations in Italy were selected that displayed specific indicators in the orthophotos (see Results) and a geological context favourable to deep piping and suffosion phenomena. On the basis of criteria such as the availability of orthophotos, the presence of in-depth stratigraphic studies, previous investigations in the area, ease of access and the possibility of carrying out photogrammetric flights in open conditions, an area in southern Tuscany in the municipality of Grosseto, located approximately 500 m north of the Bottegone sinkhole site (coordinates WGS84 42°50’28”N, 11°03’56”E), was selected among them. To enhance our understanding of the area and allow for comparisons with findings from previous survey campaigns, the following activities were carried out:

Photogrammetric survey. In order to identify localised depressions in correspondence with the study area, photogrammetric surveys were carried out using the same procedure illustrated above. Given the severe flight restrictions, due to the presence of the Grosseto military airport, which imposed an AGL altitude limit of 25m in the area in order to remain in open conditions (Regulations EU 2019/947 and ATM 09 Circular), the flight was carried out using a DJI Mavic Pro, at an altitude of approximately 24m, a speed of 2m/s and photographic overlap of around 70%. This survey was also georeferenced by Leica GNSS station.

Surface seismic tests. Two HVSR (Horizontal to Vertical Spectral Ratio - Nakamura 1989) tests were carried out in the Bottegone area and in the selected survey area. The HVSR method is based on the analysis of the spectral relationship between the horizontal and vertical components of the ground motion originating from environmental vibrations and recorded with a three-component single station. It is demonstrable (Ibs-Von Seht et al. 1999; Bonnefoy-Claudet et al. 2006; Lunedei et al. 2010) that the frequency corresponding to the maximum value of the HVSR function has a close correspondence with the local resonance frequency f0 of a site. The HVSR curve may have one or more peaks, caused by the presence of layers at depth both in terms of lithology and acoustic impedance. Although in an approximate manner, the peak frequency values of the HVSR can be correlated with the depth of the impedances (Albarello et al., 2010), thus providing an estimate of the thickness of the terrigenous deposits. The acquisitions were carried out using Sara Instruments' Gobox instrument with 4.5 Hz sensors, with a duration of 25 minutes and a frequency of 300 Hz, following (SESAME Team, 2004). The processing was carried out using the Geopsy software.

Rainfall data analysis. To determine the possible relations between the presence of certain signals in the orthophotos and rainwater, the data from the available rainwater stations were analysed. To this end, the data from the rain gauge stations made available by the Region of Tuscany (www.sir.toscana.it/consistenza-rete) were examined, in particular those of Braccagni, Stiacciole, Batignano, Caldana and Casotto dei Pescatori, due to their proximity to the study site. Rainfall data for August 2013, February 2015, August 2019, September 2019 and March 2023 were processed to make direct comparisons with the available orthophotos. The weighted distance method inversion (IDW, Goovaerts, 2012; Noori et al., 2014) was applied in a GIS environment to better analyse the rainfall data (Tab. 3). Due to the lack of data from the Bitignano station in the years 2013 and 2015, this method was only used for the years 2019 and 2023.

3. INVESTIGATED AREA

Various georeferenced orthophotos with projected sinkhole boundaries were exported from the GIS project. In the following part of the study, a brief description of each sinkhole site, geological context and photographic compositions obtained are reported.

Bottegone. This sinkhole formed in January 1999 near the plain north of Grosseto, in the vicinity of the Fattoria degli Acquisti. The geology consists of alluvial deposits with a silty-clay grain size resting on a carbonate substrate that can be located at a deep of around 200 m, with the presence of several direct faults (Del Greco et al., 2004). Initial studies hypothesised a formation due to the collapse of a karstic cavity in the substrate, which produced a subsidence path that caused surface subsidence. Subsequently, a hypothesis was put forward that sees deep piping as another possible cause, as it seems unlikely, due to the thickness of the overburden materials, that surface subsidence could occur. Impermeable or semi-permeable clay sediments may be able to absorb the deformations generated at depth (Nisio et al., 2004; Nisio, 2008A). As recent studies point out (Liang et al., 2018), karst sinkholes are generally found where sediment thickness is reduced. To date, the sinkhole is filled with water with a diameter of 170m and a depth of 17m. For example purposes, figure 2 shows the orthophotos of 1954 (A), 1978 (B), 2002 (C) and 2022 (D).

San Donato 1 and 2. The San Donato sinkholes are in the plain to the hydrographic right of the Albenga River near the settlement of the same name in the Ceppaie locality, in the Municipality of Orbetello. Although there are no mapped faults in the area, sandy-textured Pliocene formations are found. There are no precise data on the formation, but it is assumed to be around the 1950s. Figure 3 shows the photo collage of the site with orthophotos from 1954 (A),1978 (B), 1996 (C), 2013(D).

Latera. The collapse occurred between 30 and 31 January 2023 inside the Vepe caldera in the municipality of Latera. Since the 1st of February, photogrammetric

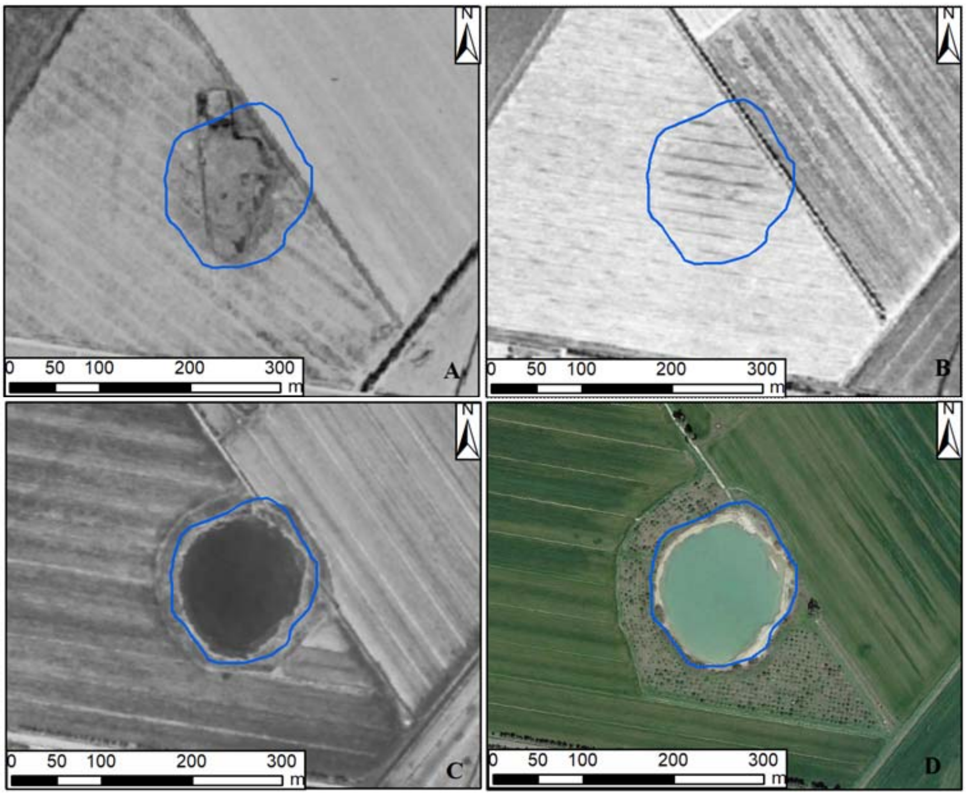


Fig. 2 - Orthophotos of the Bottegone area from 1954 (A),1978 (B), 2002 (C), 2023(D). Sinkhole limit in blue.

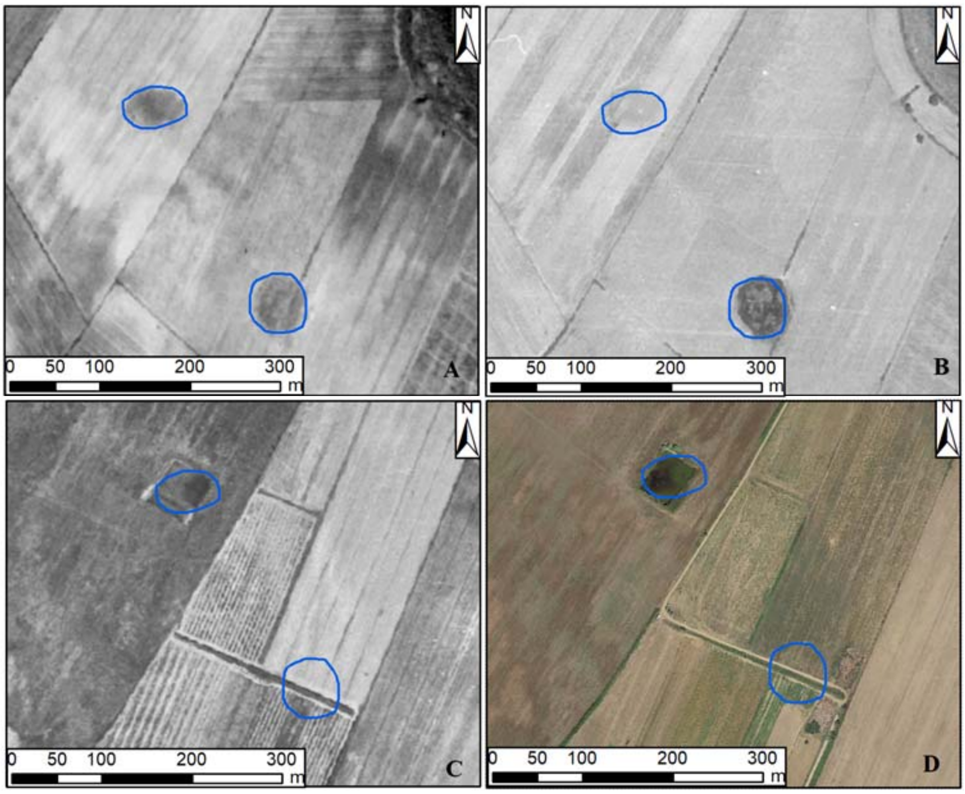


Fig. 3 - Orthophotos of the San Donato Plain area from 1954 (A),1978 (B), 1996 (C), 2013(D). Sinkholes limits in blue.

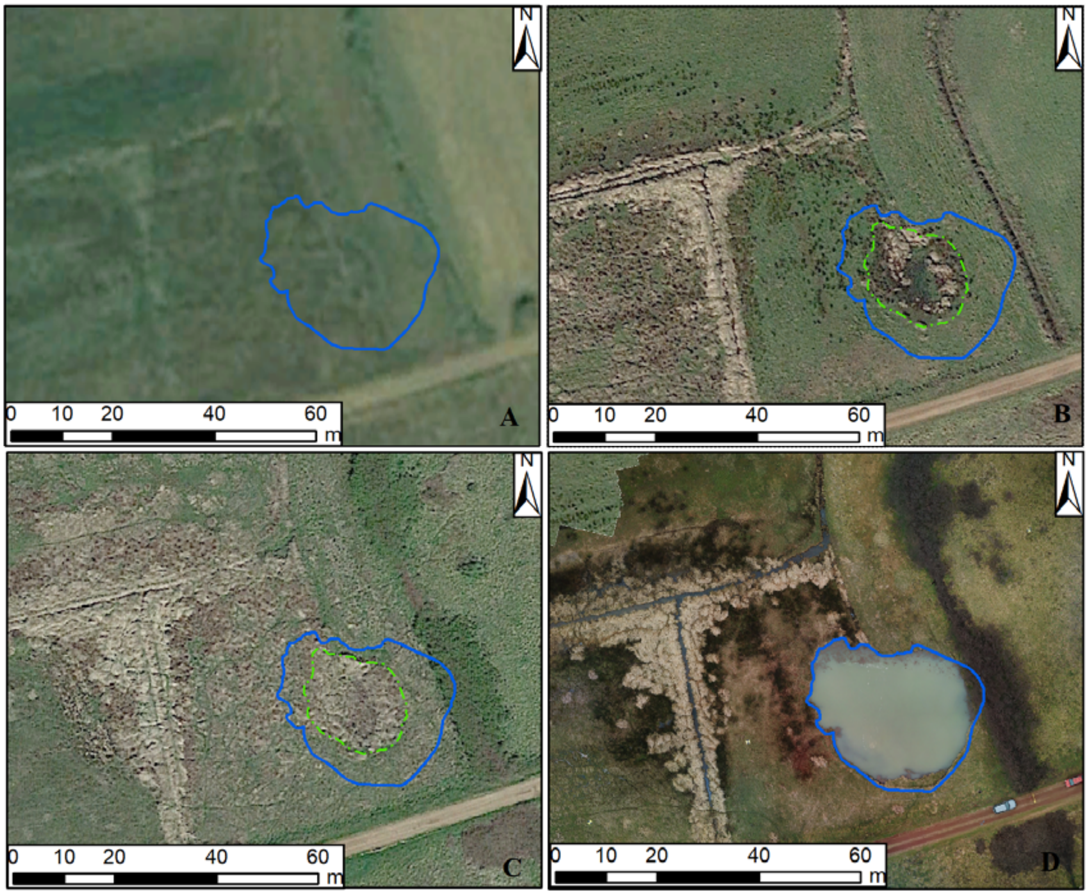


Fig. 4 - Orthophotos of the Latera site from 2001 (A), 2017 (B), 2022 (C), 2023(D). Sinkholes limits in blue. In green the limits of the vegetation supported by piping phenomena.

monitoring surveys have been carried out together with seismic, geoelectric and geochemical investigations to define the stratigraphic conditions and monitor the evolution of the phenomena over time. The sinkhole site is characterised by the presence of alluvial and eluvial-colluvial soils, resting on eruptive sequences put in place by local volcanic activity in the Pleistocene. As a result of geophysical and geochemical investigations and geomorphological considerations, a structural lineament was found just at east of the sinkhole, probably due to the last caldera collapse in the late Pleistocene. In particular, geochemical investigations have revealed the presence of rising fluids typical of these lineaments (Puzzilli et al., 2024). In figure 4 the photo collage of the site from 2001 (A), 2017 (B), 2022 (C), 2023(D).

Guardia sui Merti. Located in the Iglesiente area, this sinkhole originated in 1999. The geological context is characterised by the presence of gravelly-sandy alluvium in a clayey matrix on sandstones levels lying on a carbonate basement, located at a depth between 20 and 40 m (Nisio, 2008G). Approximately 900 metres to the south of the site there are more contemporary age sinkholes. In figure 5 the photo collage of the site form 1954 (A), 1978 (B), 2010 (C), 2022 (D).

4. RESULTS

A list of clues deduced from the orthophotos of sinkholes sites was prepared:

- Presence of slightly depressed areas with sub-circular or elliptical conformation
- Dark colouring in orthophotos, localised and sub-circular or elliptical shape
- Localised growth of herbaceous plants with sub-circular or elliptical shape
- Presence of marsh-type ecosystems, localised and detached from the landscape
- Presence of other sinkholes in the vicinity and small lakes, including artificial ones.

Selected area for field surveys. This area is located approximately 400 m north of the Bottegone sinkhole, where a favourable geological context for sinkhole formation has established (Nisio, 2008C; Del Greco et al., 2004). Coordinate WGS84 42°50'27"N, 11°03'52"E.

The plain is a graben, bounded by direct faults (figure 6) in the Triassic formations (Cavernous Limestone and Verrucano) with thick terrigenous deposits infilling the basin. The alluvial overburden deposits consist of silts and clays, and, subordinately, sands and gravels; the depositional environment varies from proxi-

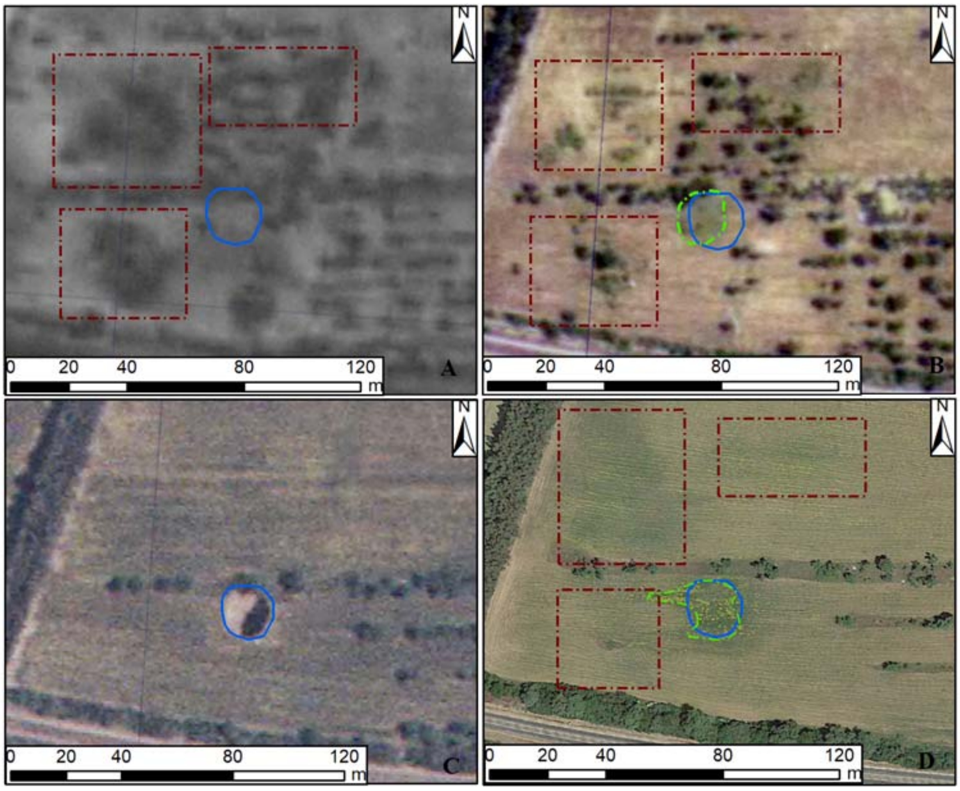


Fig. 5 - Ortophotos of the Guarda su Merti area dating 1954 (A), 1978 (B), 2010 (C), 2022 (D). Sinkhole limits in blue. In green, areas with pronounced plant growth/ herbaceous patches within and around the sinkhole. In brown rectangles areas outside the sinkhole showing dark colouring/pronounced plant growth.

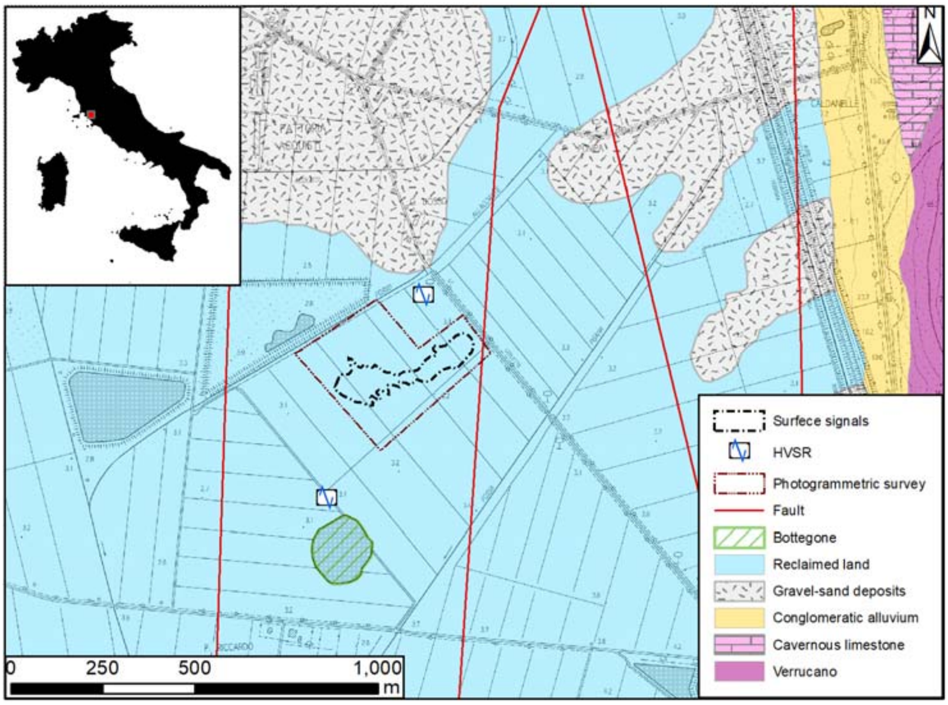


Fig. 6 - Geological and structural map (from Nisio, 2008C and Del Greco et al., 2004). The evidences found in orthophotos are reported with the investigations carried out.

Year	1954	1978	1988	2003	2013	2015	2019	2023
Surface (m^2)	8208	6727	7281	8573	7513	9112	7933	8126

Tab. 2 - Surface of the dark patch.

mal marine to marsh and fluvial (Nisio, 2008C). The thickness of these deposits vary from 110 to 190 m as inferred from surveys (Berti et al., 2002; Del Greco et al., 2004). Cavernous limestone and Verrucano formations constitute the bedrock of these deposits.

The aquifer is 90-100 m deep and there are several perched aquifer systems in the sandy-gravel horizons. The shallowest aquifers are found a few metres from the surface in the area of the Fattoria degli Acquisti (400 m North from the site). There are minor thermal springs located along the faults, under-saturated in anhydride and over-saturated in gypsum and calcite (Nisio, 2008C; Berti et al., 2002).

A photographic collage was also created for this site, displaying available orthophotos from 1954 to 2023 (figure 7). These images reveal dark patches consistently appearing in the same locations across various times of the year and different years.

The westernmost portion, which is markedly elliptical in shape, was subjected to surface measurements using the various georeferenced orthophotos. This portion was selected because it is more visible and can be detailed in a GIS environment. The results are in table 2.

Photogrammetric survey. The processing of the photographic images and points measured by GNSS led to the production of 3D reliefs. The errors, automatically calculated by the Metashape software as RMS, are 0.047 m for the Latera site and 0.084 m for the surface evidence study site, respectively. The orthophotos obtained from the survey (Fig. 8A, reported in a GIS environment on a CTR Toscana 1:10000 basis), made it possible to estimate a surface area of the westernmost dark patch of approximately 8612 m^2. The DTM (Fig. 8B) obtained from the point cloud of the survey was used to make measurements of the microtopography affecting the area.

HVSR. The microtremor acquisitions lasted 25 minutes each. Processing was carried out using Goepsy software, while the SESAME criteria were checked using the HV_Test tool. Figure 9 shows the results at Bottegone sinkhole site (Fig. 9A) and at the study area site (Fig. 9B).

A frequency of 0.75 Hz was measured at the study site, while a frequency of 0.74 Hz was measured at the Bottegone sinkhole.

Figure 10 shows the results of IDW interpolations

Fig. 7 - Orthophotos of the study site (in the red rectangle): 1954 (A), 1988 (B), March 2003 (C), August 2013 (D), February 2015 (E), August 2019 (F), September 2019 (G) and March 2023 (H). To the south is located the Bottegone sinkhole.

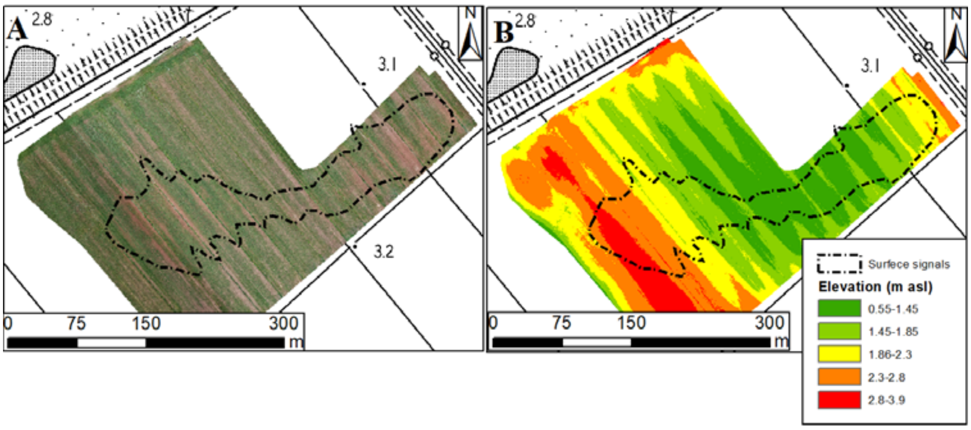


Fig. 8 - A) Orthophotos from a survey and B) DTM, rendered in a GIS environment on a map basis.

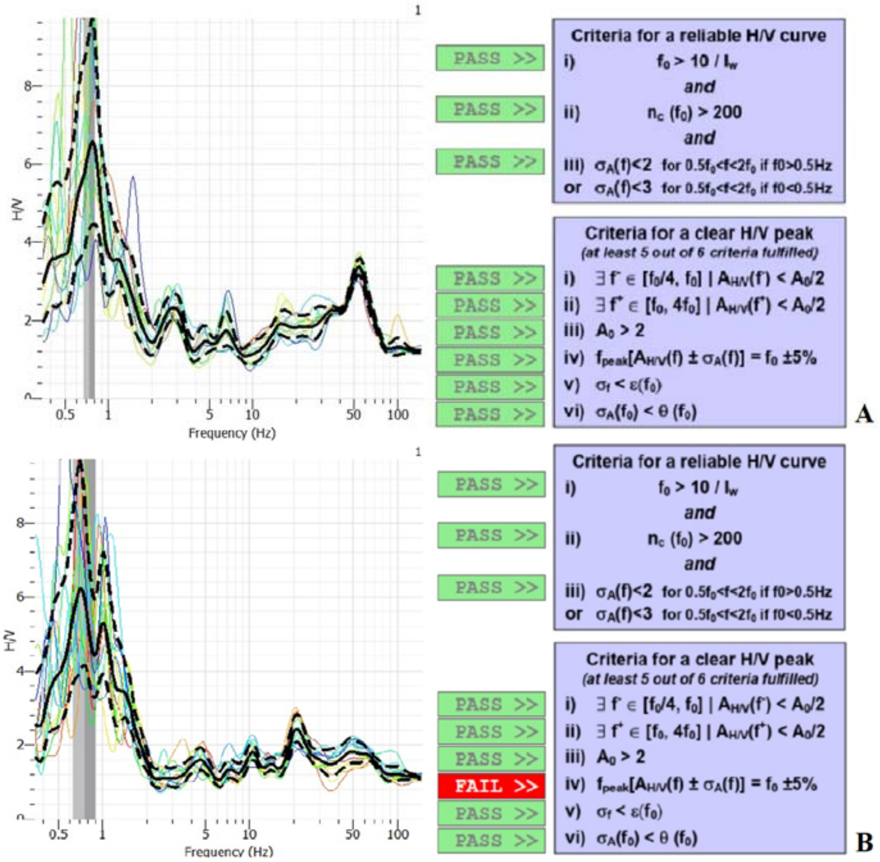


Fig. 9 - A) HVSR test in Bottegone site. B) HVSR test in the study site.

Pluviometer	aug-13	feb-15	aug-19	sept-19	mar-23	Lat/Long	Elevation
Braccagni	38,4 mm	98,4 mm	27,8 mm	109,6 mm	34,8 mm	42°55’51”/11°4’41”	40 m asl
Stiacciole	1,6 mm	101,2 mm	4,6 mm	98 mm	57 mm	42°47’19”/11°10’33”	53 m asl
Casotto P.	1 mm	117,4 mm	1,8 mm	32,4 mm	55,4 mm	42°46'04"/ 11°0'56"	2 m asl
Caldana	12,4 mm	168,6 mm	5 mm	77,8 mm	38,2 mm	42°53'34"/ 10°55' 37"	146 m asl
Bitignano	-	-	4 mm	95,6 mm	43,2 mm	42°52'01"/ 11°10'01"	140 m asl

Tab. 3 - Rainfall data. List of rainfall stations with coordinates, elevation above sea level (asl) and rainfall for the reference months.

4. DISCUSSION

The analysis of the results focused on the examination of the pre- and post-collapse state. Temporal evolutions were examined for each site:

Bottegone. At this site, clear signs of depressions existing prior to 1954 were identified, probably reshaped by anthropic intervention (Fig. 2A). The agricultural use of the area may have led to the complete levelling of the previous surface situation. The deep piping phenomenon, which may have contributed to the depression visible in 1954, is still active in 1978, where a darker furrow colouration, scarcely present outside the projected limits of the future sinkhole (Fig. 1B), is found. This colouration can be associated with increased plant growth due to the greater availability of water, or the presence of more moisture that darkens the normal surface colour levels. The increased water supply can be directly attributed to the contribution provided by the deep piping, or to a stagnation of rainwater flowing into a local depression that can be identified as a precursor of the future sinkhole.

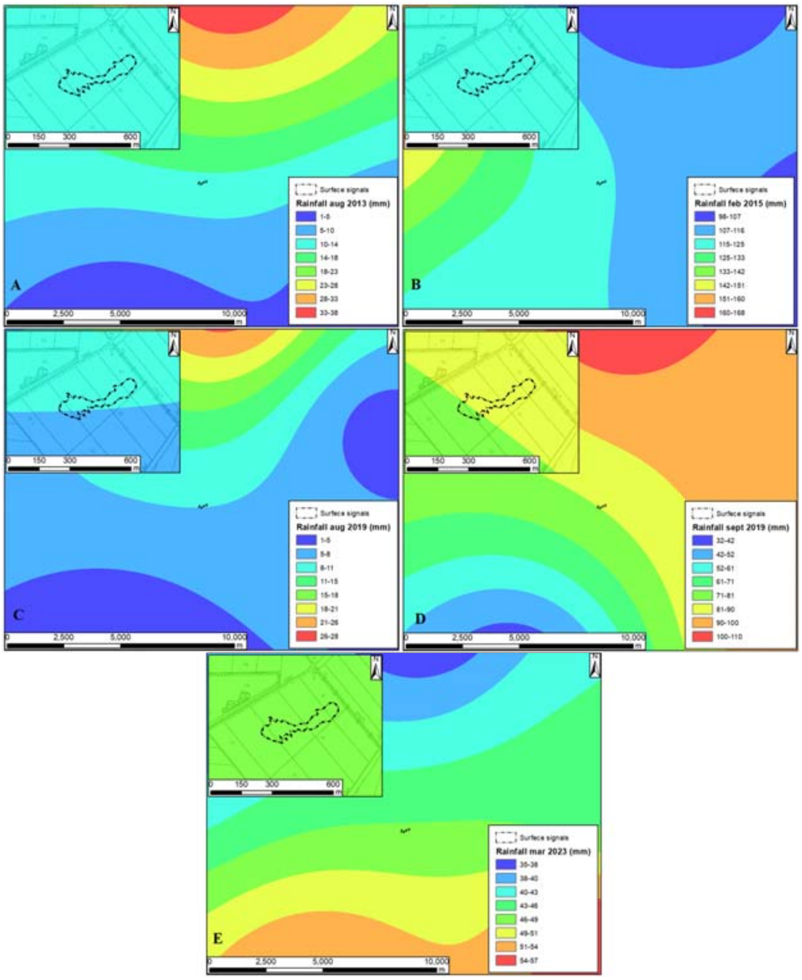


Fig. 10 - IDW elaborations of data from August 2013 (A), February 2015 (B), August 2019 (C), September 2019 (D) and March 2023 (E).

San Donato 1 and 2. In the San Donato area, there are two sinkholes whose formation is uncertain in time and is generally placed before the 1950^s. Again, between 1954 and 1978 the northernmost sinkhole, identifiable with darker colours than the immediate surroundings (figure 3A), was partially filled in for agricultural purposes. In Figure 3B, relative to the situation in 1978, despite the agricultural use, the edges of the depression can again be seen, probably due to ongoing deep piping activity. The visible evolution of this site is the anthropic transformation into an irrigation pond, which acquires an artificial quadrilateral shape (Fig. 3C-3D). This functional choice is probably due to the presence of water on the surface.

There is no particular evidence of evolution of the sinkhole to the south, apart from pronounced plant growth between 1954 and 1978 probably due to waterlogging. The lack of evidence, even in the most recent orthophotos, does not allow further hypotheses.

Latera. The Latera sinkhole area, developed in a volcanic geological context, has always been used as agricultural land. From the photos of the 1940s, this vocation is clearly evident and tends to persist throughout the 20th century until the early 2000^s (Fig. 4A). During this period, however, more vegetation growth is noted in the area of the T-shaped drainage ditches and the future sinkhole. Around 2015-2017, there is a partial abandonment of the fields and the appearance of a marsh ecosystems, characterised by distinctly hygrophilous plants. This punctual ecosystem develops around the T-shaped drainage channels and the depression (elliptical in shape) that is clearly evident in the centre of the future sinkhole, which at various times also manifests the presence of water (Fig.s 3B and 3C). The pronounced plant growth is undoubtedly supported by the increased amount of water, due to deep piping/dipping. The incoming volumes are such as to support a marsh-like, localised and well-defined plant ecosystem in the area of the sinkhole and channel.

The central depression, which can be interpreted as evidence of the deep piping/suffosion phenomena underway, appears to be the area most easily colonised by these plants, a sign of the massive presence of water probably also brought to the surface through a discontinuity system located to the east of the sinkhole (Puzzilli et al., 2024).

Guardia sui Merti. Studies of the oldest orthophotos of the area (Fig.s 5A and 5B) indicate areas of darker colour and sub-circular shape, widespread near the sinkhole site. Such evidence is always attributable to pronounced plant growth or the presence of surface moisture that darkens the natural soil colour. Projecting the boundaries of the sinkhole onto the 1978 orthophoto (Fig. 4B), a corresponding herbaceous patch of green color can be seen. In addition to this, there are obvious herbaceous patches to the east and north of the future sinkhole, which can also be seen on the 1954 orthophoto. This localised herbaceous growth can only be sustained by local water inputs. In this area, a sinkhole occurred in 1999, which was probably filled, also with anthropogenic input, up to the exemption (Fig. 4D)

Today, darker coloured patches due to increased herbaceous growth are still visible, overlapping with those of 1954. This growth appears to be accentuated at the sinkhole site, probable evidence of the resumption of piping/suffosion phenomena or of a localised depression in which rainwater tends to stagnate.

Bottegone and the study site

By analyzing a well-established geological context favorable to sinkhole formation, we were able to directly assess the practical value of insights gained from studying orthophotos in the field. To achieve this, we initially selected the area north of the Bottegone sinkhole, where the orthophotos consistently indicated signs of water in the ground.

The aerial images show two distinct patches that appear unified in some orthophotos. The stain further to the west is more visible than the one further to the east. The surface is stable over time, although in some photos a reduction is evident. The study of the geology of the area and the presence of other sinkhole phenomena of considerable dimensions immediately suggested that the context was favourable to the formation of sinkholes. The search for localised depressions, which could be identified as precursors of a sinkhole, involved the use of drone photogrammetry.

The analysis of the DTM processed and reported in the GIS environment (Fig. 8B) made it possible to understand the detailed topography of the dark patches in the orthophotos. The westernmost part appears to be located on a relative high, with maximum altitudes within 3.9 m asl. Eastwards, a real depression begins, which appears to be within 1.1 m elevation and then rises to elevation values of 2.1 m at the eastern limit of the relief and 1.8 m at the southern limit of the relief. The easternmost spot visible in the orthophotos is positioned in this area.

The HVSR tests indicate very similar frequencies to each other, and the low values suggest deep impedances of more than 100 m (Albarello et al., 2009), in agreement with the seismic tests conducted by Del Greco et al. (2004).

Therefore, in the study area, the same stratigraphic conditions found at Bottegone can be hypothesized, locating the two sites on the same graben. The slight difference between the frequency value of the study area (0.75 Hz) and that of Bottegone (0.74 Hz) suggests a declining trend of the carbonate bedrock in the NE-SE direction. This hypothesis is in agreement with seismic tests and drill cores carried out in the Bottegone area in 2004 (Del Greco et al., 2004; Nisio, 2008C), which indicate a bedrook depth between 170 and 200 m, and a buried profile with a NW-SE direction (Fig. 11).

Examining the precipitation data using the IDW method, it is not possible to find a direct correlation between rainfall and surface spots. This is easily verifiable by comparing the photos from August and September 2019 with the respective rainfall data. In fact, despite the scarcity of rain in August and the heavy rainfall in September (Tab. 3), the spots remain always visible and with a stable surface over time.

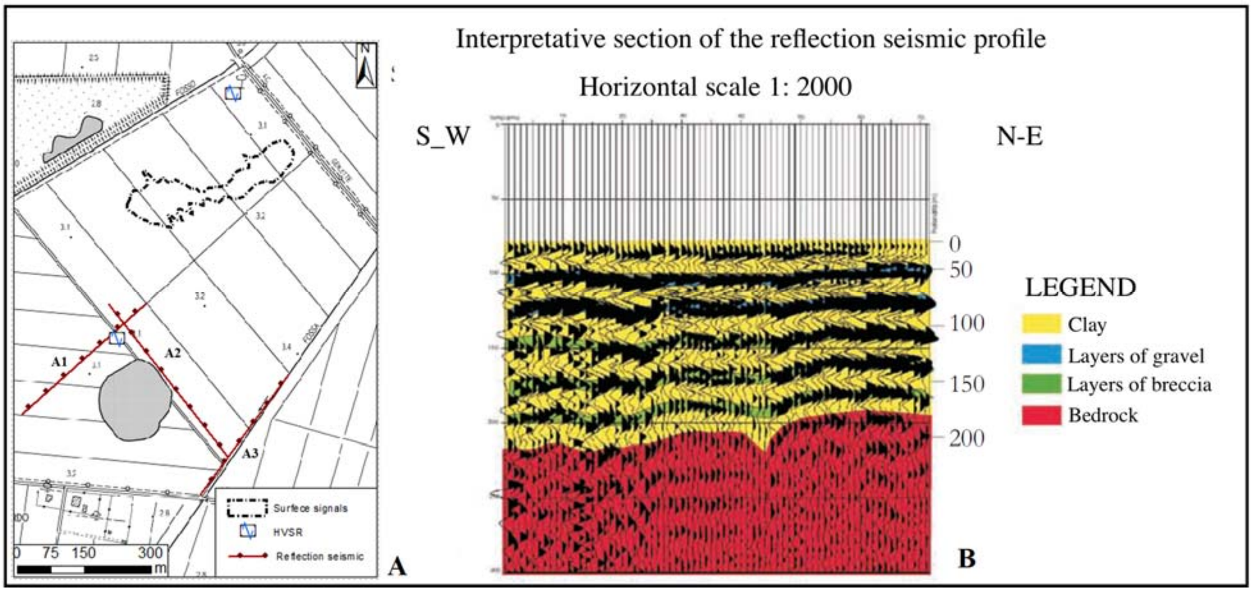
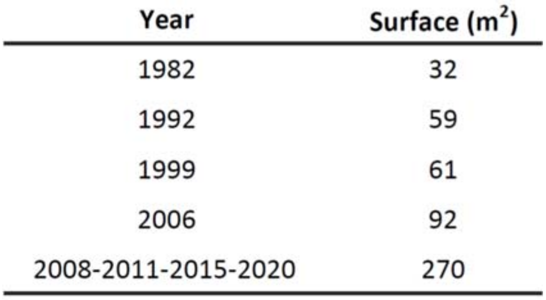


Fig. 11 - A) Reconstructed map of HVSR surveys conducted and reflection seismic arrays by Del Greco et al. (2004). B) Processing of the reflection test A3 by Del Greco et al. (2004) (from Nisio, 2008C). Horizontal scale 1:2000. On the right the NE end of the array and on the left the SW end. In red the carbonate bedrock, in yellow the clay deposits, in light blue the gravelly levels and in green the breccia.



Year	Surface (m^2)
1982	32
1992	59
1999	61
2006	92
2008-2011-2015-2020	270

Tab. 4 - Sinkhole surface.

Moreover, the particular topography of the westernmost spot does not allow for stable and lasting water stagnation over time. Additionally, the evidence is hardly linked to particular soil chroma as that land has been subjected to agricultural work for over 100 years and in the last 50 years also with heavy agricultural machinery. Agricultural work would have led to the dispersion of soil with particular chromatic characteristics, leading over time to a uniform color. The spots, however, remain well-defined and with a constant surface, especially in the last 20 years.

Given the existence of a favorable geological context, the presence of other sinkholes in the area, a well-defined depression, and the absence of a direct correlation with precipitation, it is possible to suppose that these surface spots are due to the rise of groundwater, probably through deep piping phenomena, an evidence that was clearly visible in the orthophotos of 1954 and 1978 at the site of the current Bottegone sinkhole. It was not possible to carry out more in-depth studies to assess the presence of any stratigraphic anomalies attributable to cavities in formation.

Identifying precursor signals of sinkhole formation in alluvial plains through orthophoto analysis.

By combining the information obtained from a simple comparison of orthophotos and documents relating to sinkholes in a alluvial plain context, it was possible to identify common elements that could be defined as precursor signals of sinkhole formation or, at least, of the potential occurrence of sinkholes. The extent of these signs of activity does not appear to be continuous over the years, being more evident in certain years and at certain times of the year, nor is it homogenous and easily distinguishable in all the cases examined. Evidence of the presence of water in the most superficial layers of the covers, if any possibility of surface contributions is eliminated (which can be verified by comparing the period of the photo with the rainfall series at that time), can be traced back to underground activity only, and, if the presence of a favourable geological context is ascertained, can be attributed to deep piping and suffosion phenomena, which are mainly responsible for the formation of sinkholes in alluvial contexts. This approach could also be used to search for old sinkholes, the location of which is unknown, that could undergo reactivation. Another application can be found in the monitoring of sinkholes that have been extinguished or filled by anthropogenic interventions, where signs of the pres-

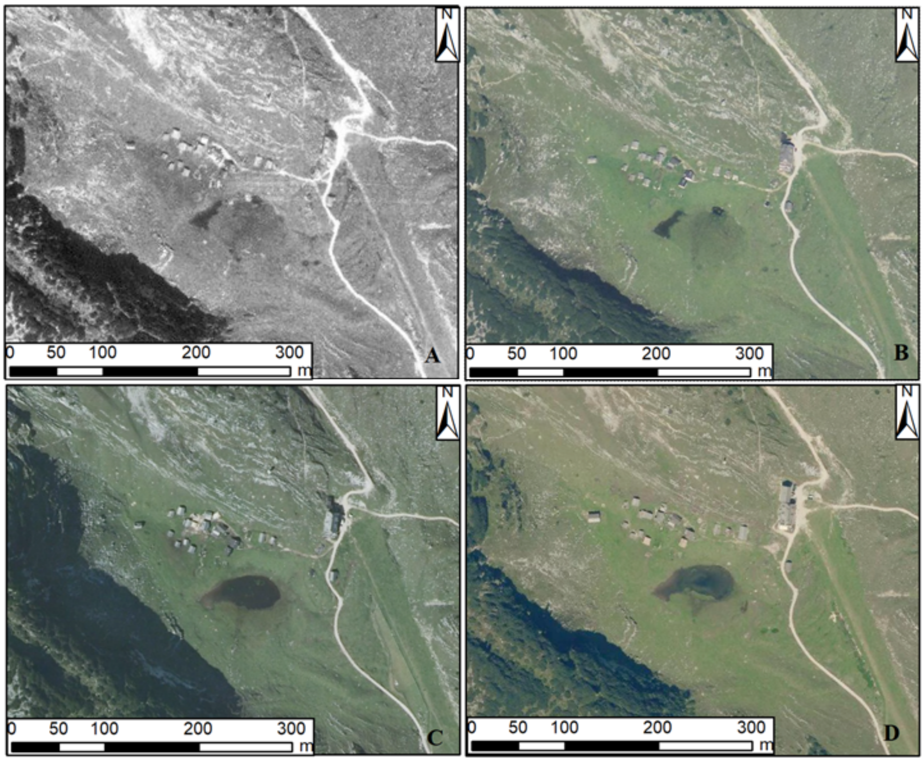


Fig. 12 - Orthophoto of the sinkhole site at the Sennes refuge in the Autonomous Province of Bolzano from 1992(A), 2006(B), 2008(C), 2022(D). Images from the Bolzano autonomous province (Geoportale Alto Adige 2024) and Google Earth.

ence of water could indicate the resumption of triggering phenomena.

The observation of orthophotos, in combination with the use of historical documents (Madonna et al., 2023), cartographies and the most up-to-date geological records together with data from In-SAR technology (Costantini et al., 2009; Raspini et al., 2022), could therefore be used to identify areas, more or less vast, characterised by a predisposition to sinkholes formation. The low cost of application and the large number of orthophotos produced, especially in the last 15-20 years, makes this approach easily replicable and also usable to delineate what could be defined as areas with predisposing factors for sinkholes formation in alluvial plains. Any proposed interventions in these areas should be further investigated.

For illustrative purposes only, this method was also applied to a karstic sinkhole located in the Bolzano Autonomous Province, near the Sennes Refuge, (WGS84 46°39'10.58"N, 12°3'29.49"E). Since 1982, clear signs of the presence of a natural cavity near the refuge's structures emerged, which underwent a further collapse between 2006 and 2008, giving rise to an alpine lake. As a first adaptation of this approach to karst sinkholes, the surface area of the forementioned sinkhole was measured to monitor the evolution in each of the available orthophotos (1982, 1992, 1999, 2006, 2008, 2011, 2015, 2020, Fig. 12 shows some of these) in a GIS environment (Tab. 4).

Despite the low quality of the 1982 photos, an increase in size can be detected between 1982 and 1992. The slight increase in surface area and diameter between 1992 and 1999 could be attributed to a measurement error related to the limited resolution of the available photos. Between 1999 and 2006 there was another increase in surface area and the clear filling of the cavity with water. Between 2008 (when the collapse had already occurred) and 2020, fluctuations in the lake level were recorded. In particular, in the orthophotos of 2015 and 2020, interpreting the darker colours as water with a greater depth, it is possible to estimate the surface area affected by the last collapse at approximately 270 m^2.

5. CONCLUSIONS

In this article, we examined the issue of sinkholes caused by piping and suffosion, which are commonly found in recent floodplains, such as those dating back to the Quaternary period. A defining characteristic of these phenomena is the rapid onset of sinkholes, which significantly heightens the associated hazards and risks, especially in areas with anthropogenic activities.

With this work we introduced the application of both historical and recent orthophotos to identify clues related to the pre-collapse conditions of several sinkholes across Italy. This effort has resulted in an initial list of evidence that is common to several sites, mostly related to the effects of large volumes of water being pushed near the surface by piping and suffosion processes. The use of historical and recent orthophotos in combination with geotematics knowledge of the area can provide the tools to identify vast areas with a certain level of predisposition to sinkholes. Although it is not possible to attribute a real susceptibility level with orthophotos alone, it is possible, through the use of photogrammetry, geochemistry, geophysical surveys (as geoelectric and surface seismic arrays), In-SAR technology and analysis of available meteorological data, to intervene in these specific areas to assess the actual level of susceptibility and identify more localized areas with an evaluable hazard level. This approach could, at least theoretically, also be applicable to sinkholes in karst environments.

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