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INTEGRATED GEOMORPHOLOGICAL ANALYSIS OF A MEDITERRANEAN TEMPORARY POND PRIORITY HABITAT: THE LAGO DEL CAPRARO DOLINE (SALENTO PENINSULA, ITALY)

INTEGRIRANA GEOMORFOLOŠKA ANALIZA PREDNOSTNEGA HABITATA SREDOZEMSKEGA OBČASNEGA RIBNIKA: VRTAČA LAGO DEL CAPRARO (POLOTOK SALENTO, ITALIJA)

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Abstract UDC 551.435.82:551.579.4(450.7)

Francesco Gianfreda, Sergio Negri & Paolo Sansò: Integrated geomorphological analysis of a Mediterranean temporary pond priority habitat: the Lago del Capraro doline (Salento peninsula, Italy)

The Lago del Capraro doline (Salento peninsula, southern Italy), a valuable Mediterranean Temporary Pond (MTP), has been investigated aiming to define its geomorphological features and to collect data about the local hydraulic regime. At the bottom of the Lago del Capraro doline, in fact, a small temporary pond appears soon after major precipitation events as that one of autumn 2013. The morphological survey shows that this solution doline is placed on a karst plain surface stretching at about 70 m of altitude; the doline has an elliptical shape with the major axis 130 m long whereas the length of the minor axis is about 100 m. It shows a flat bottom, placed at about 65 m above m.s.l., due to the presence of a colluvial sandy clays filling, bordered by steep limestone slopes about 5 m high. Geophysical surveys and a cone dynamic penetrometer test allowed a detailed geological model to be realized. In particular, ERT and seismic refraction models revealed the geometry and the thickness of doline filling deposits as well as the preferential infiltration zones of surface waters. Interestingly, the cone penetrometer test reveals that resistance decreases downward in the filling lower part, most likely because of the active solution process at the doline bottom. The results of this study suggest an increase of surface water infiltration at doline bottom in the next future so that the development of a pond will be an increasingly rare event, partly compensated by the clustering of rainy periods during autumn months as expected in the future by climate models.

Keywords: solution doline, doline filling, Salento peninsula, Italy.

Izvleček UDK 551.435.82:551.579.4(450.7)

Francesco Gianfreda, Sergio Negri & Paolo Sansò: Integrirana geomorfološka analiza prednostnega habitata sredozemskega občasnega ribnika: vrtača Lago del Capraro (polotok Salento, Italija)

Cilj raziskovanja vrtače Lago del Capraro (polotok Salento, južna Italija), dragocenega sredozemskega občasnega ribnika, je bil opredeliti njene geomorfološke značilnosti in zbrati podatke o lokalnem vodnem režimu. Na dnu vrtače Lago del Capraro kmalu po večjih padavinah, kot so bile jeseni 2013, nastane majhen začasni bazen. Iz morfološke raziskave je razvidno, da je ta vrtača na površini kraškega ravnika, ki se razteza na približno 70 m nadmorske višine, vrtača ima eliptično obliko, njena glavna os meri 130 m, krajša os pa meri približno 100 m. Ima ravno dno, ta je na približno 65 m nadmorske višine in ga tvori koluvialni nanos peščene gline, nad njim pa se vzpenjajo strma apnenčasta pobočja, visoka približno 5 m. Geofizikalne raziskave in preiskava z dinamičnim konusnim penetrometrom so omogočile izdelavo podrobnega geološkega modela. Natančneje, geoelektrična tomografija in seizmična refrakcija sta razkrili geometrijo in debelino sedimentov vrtače ter prednostna območja infiltracije površinskih voda. Zanimivo je, da preiskava s konusnim penetrometrom razkriva, da se mehanska odpornost v spodnjem delu nanosa zmanjšuje navzdol, najverjetneje zaradi aktivnega procesa raztapljanja na dnu vrtače. Rezultati te študije kažejo, da se bo v prihodnje povečala infiltracija površinskih voda na dnu vrtače, tako da bo pojav ujete vode vse redkejši dogodek, tega bo delno nadomestilo združevanje deževnih obdobij v jesenskih mesecih, kot se v prihodnosti pričakuje na podlagi podnebnih modelov.

Ključne besede: vrtača, zapolnitev vrtač, polotok Salento, Italija.

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1. INTRODUCTION

Mediterranean Temporary Ponds (MTPs) are shallow water bodies with annual inundated and dry phases of varying duration and timing; they are identified as priority habitat (Annex I code 3170*) in the EU Directive 92/43/EEC (Habitats' Directive) and subsequently to the effective protection status they have been studied intensively (Vasilatos et al., 2019).

The main ecological characteristic of this habitat is that the autumn-winter wet (aquatic) ecophase is followed by a spring-summer dry (terrestrial) ecophase. The typical species found in them are often dwarf, "amphibious" species adapted to this alternation of ecophases. Thus, these seasonal water bodies, regardless of their small size, operate as biodiversity hotspots maintaining gamma diversity since they host flora and fauna species that are often rare and endemic occurring uniquely in this habitat.

MTPs flora is mainly composed of Mediterranean therophytic and geophytic species belonging to the alliances *Isoëtion*, *Nanocyperion flavescentis*, *Preslion cervinae*, *Agrostion salmanticae*, *Heleochloion* and *Lythrion tribractea* (European Commission, 2013).

The Salento peninsula, placed at the southernmost part of Apulia region and stretching between the Adriatic and the Ionian Sea (Fig. 1), retains numerous MTPs. Some of them are placed along the coastal area and are generally back-dune ponds, some others are hosted on wide and shallow depressions on marine terraces surface (Margiotta & Parise, 2019; Margiotta et al., 2021) whereas a significant number of MPSs is represented by solution dolines (Alfonso et al., 2011) or by collapse dolines (Bruno et al., 2008; Basso et al., 2013).

Dolines, also known as sinkholes in North America and in the international literature dealing with

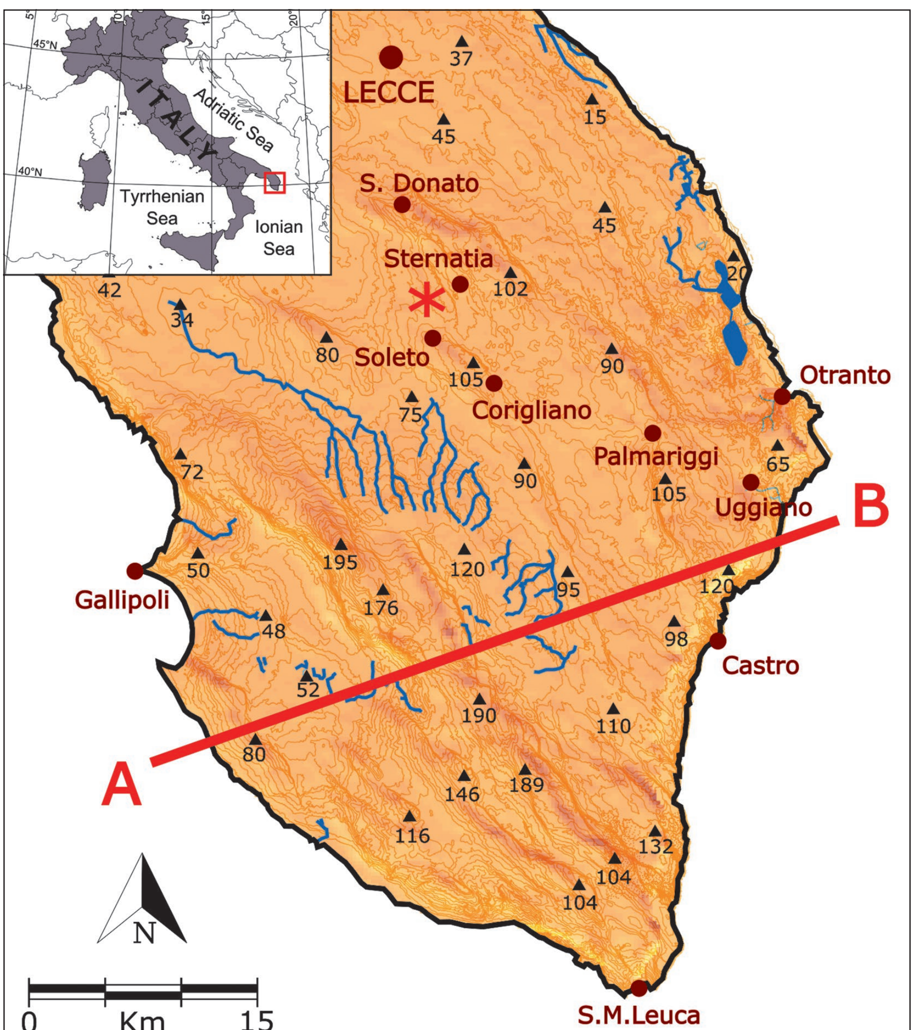

Figure 1: Geographical position of Lago del Capraro doline (Salento peninsula, southern Apulia). Some elevation points and main hydrographical network are also reported. AB red line is the position of the geomorphological section reported in Fig. 3.

engineering and environmental issues (Beck, 1988), are closed depressions with internal drainage, widely regarded as one of the main diagnostic landforms of karst (Ford & Williams, 2007). According to Gutiérrez et al. (2014) dolines can be classified in two main groups. One of them corresponds to solution sinkholes, generated by differential corrosional lowering of the ground surface where karst rocks are exposed at the surface or merely soil mantled (bare karst). The development of these dolines is governed by centripetal flow towards higher permeability zones in the epikarst and the consequent focused dissolution. The other group of dolines, which can be collectively designated as subsidence dolines, results from both subsurface dissolution and downward gravitational movement (internal erosion or deformation) of the undermined overlying material.

This study focuses on one of the most known MPS occurring at the bottom of a wide solution doline, the Lago del Capraro, which is placed in the middle area of Salento peninsula, between the Soleto and Sternatia municipalities (Fig. 1). This doline is placed at the top surface of Serra di San Donato limestone ridge, at an altitude of about 70 m a.s.l. The area in the surrounding of Lago del Capraro is occupied by olive trees which are dead because of the *Xylella* bacterial infection (Saponari et al., 2017); in the northeastern area deep land reworking works have been carried out and new olive trees have been planted. The doline is closed on all sides by minor roads bordered by low dry-stone walls. The doline bottom hosts a temporary pond after rainy periods with a pluriannual frequency. According to Ernandez and Marchiori (2012), the site bears the typical community characteristics of Mediterranean temporary ponds, including the phytosociological class of *Isoeto-Nanojuncetea*. In the centre of the pond, the dominant community is characterized by the rare water firn *Marsilea strigosa* Willd. and *Marsilea pulegium* L. in contact with *Eryngium barrelieri* Boiss., which flowers in late spring and summer and is included in the Regional Red List as VU. Higher areas of the pond are colonized by *Neoschischkinia pourretii* (Willd.) Valdés et H. Scholz, the margins by *Carex divisa* Huds. subsp. *chaetophylla* (Steud.) Nyman.

Notwithstanding its ecological relevance, the Lago del Capraro doline has not received particular attention by geomorphologists yet. Aiming to fill this gap, geomorphological research integrated by geophysics and geognostic surveys was carried out to define the geological and geomorphological features of Lago del Capraro doline and to collect new data useful for the description of the local hydrological regime.

2. GEOLOGICAL, GEOMORPHOLOGICAL AND CLIMATIC FEATURES OF SALENTO PENINSULA

The Salento peninsula is the southernmost emerged part of Adria Plate which constitutes the foreland of both Apenninic and Dinaric orogens. It comprises a Variscan basement covered by a 3-5 km thick Mesozoic carbonate sequence (the Calcari delle Murge unit) overlain by thin Tertiary and Quaternary deposits (Fig. 2). The most ancient cover rocks were produced by transgressions after the definitive emersion of the Apulian carbonate platform occurred between the end of the Cretaceous and the beginning of Paleogene periods; in some cases, bauxitic deposits can be found between Mesozoic limestones and Paleogene units (Doglioni et al., 1994).

Four sedimentary cycles have been recognized from Neogene to Lower Pleistocene periods (Giudici et al., 2012). The first cycle comprises the Pietra Leccese Formation and the overlying Calcarenite di Andrano Formation. The Miocene sedimentary cycle was interrupted because of the emersion of Salento which prevented the formation of Messinian evaporites. The total thickness of Miocene formations is greater than 150 m on the eastern side of the peninsula. The second cycle is represented by breccias and conglomerates of the Leuca Formation that were deposited during the Lower Pliocene, reaching a maximum thickness of 30 m. The third sedimentary cycle is represented by the Upper Pliocene Uggiano la Chiesa Formation, composed of well-stratified and fossiliferous biodetritical limestones and yellowish calcareous sands with a maximum thickness of about 80 m. The fourth sedimentary cycle promoted the deposition in the Lower Pleistocene of the Calcareniti del Salento Formation, a very fossiliferous biodetritical calcareous sediment marked by the occurrence of *Artica islandica* Linneo. Its maximum thickness is about 60 m. Finally, a number of Middle-Upper Pleistocene deposits related to eustatic sea level change mark the coastal landscape of Salento peninsula (Mastronuzzi et al., 2007).

Three main tectonic events affected the Salento Peninsula during the Eo-Oligocene, the Middle Pliocene, and the Middle Pleistocene periods. In particular, the most recent tectonic phase was responsible for the final uplift of the Apulia foreland which ended at Marine Isotope Stages (MIS) 9.3, about 330 ka BP (Mastronuzzi et al., 2007). Since then, maximum uplift rates have been recorded only in the Taranto area (0.25 m/ka according to Ferranti et al. 2006), whereas they decrease to zero in the southernmost part of the region. Finally, a slow subsidence has been recorded along the Salento peninsula coast during the last four millennia (Mastronuzzi & Sansò, 2014).

From the geomorphological point of view, the Salento peninsula shows a low-elevated landscape composed of several Pleistocene plains placed at different altitudes between 160 m of elevation and sea level (Fig. 3). They are bordered by degraded fault scarps, mostly elongated in NW-SE and NNW-SSE directions, by differential erosion scarps and relict cliffs (Pepe & Parise, 2014). The southern part of Salento peninsula is marked by NNW-SSE trending morphostructural limestone ridges, locally named "Serre". They generally show an asymmetrical transverse profile since one side is constituted by a steep fault scarp whereas the other one is a gentler slope, often marked by a sequence of marine terraces.

The landscape evolution of Salento peninsula is characterized by three phases of karstic landforms development that occurred during emersion periods of variable temporal length (Selleri, 2007; Gil et al., 2013). Small remnants of a Paleogene karstic landscape are preserved on the Serre top surfaces and in the area to the east of Uggiano La Chiesa - Castro alignment. The main karstic landforms of this landscape are wide and deep solution dolines shaped directly on Late Cretaceous limestone (Pepe & Parise, 2012), partly filled by bauxitic deposits as recognizable at Otranto, Montevergine (Palmariggi village) - Poggiardo and Corigliano ridges (Selleri et al., 2003).

A second karstic landscape developed at end of Lower Pleistocene; it is marked by a wide arrangement of epigeic and ipogeic karstic landforms and was most likely promoted by a low sea level stand associated to a tectonic phase with NE-SW oriented extension linked to the end of Apennine orogenesis. This landscape was partly fossilized during the Middle Pleistocene by a wide marine transgression and subsequent sedimentation of a siliciclastic marine cover (Selleri, 2007).

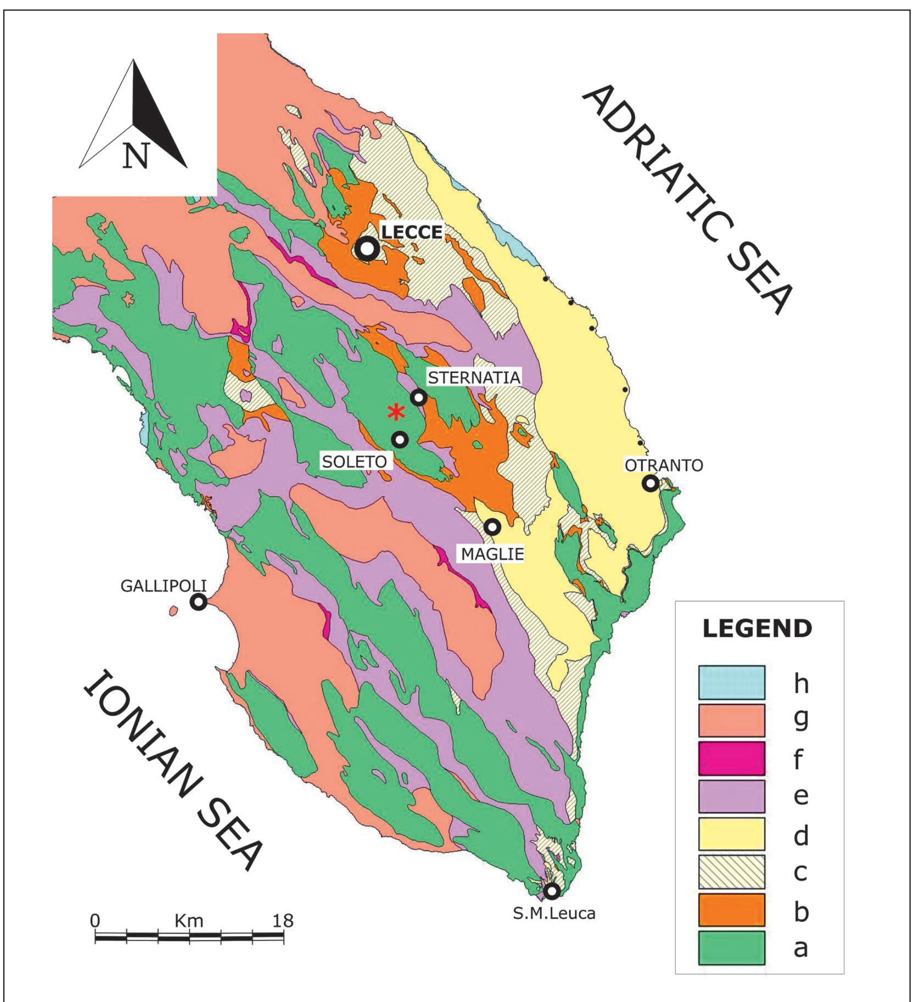

Figure 2: Geological map of Salento peninsula (southern Apulia). Legend: a - Calcari delle Murge unit (Upper Cretaceous); b - Pietra Leccese Formation (Miocene); c - Calcareniti di Andrano Formation (Upper Miocene); d - Uggiano La Chiesa Formation (Upper Pliocene); e - Calcareniti del Salento Formation (Lower Pleistocene); f - Argille subappennine Formation (Lower-Middle Pleistocene); g - Marine Terraced Deposits (Middle-Upper Pleistocene); h - Holocene deposits.

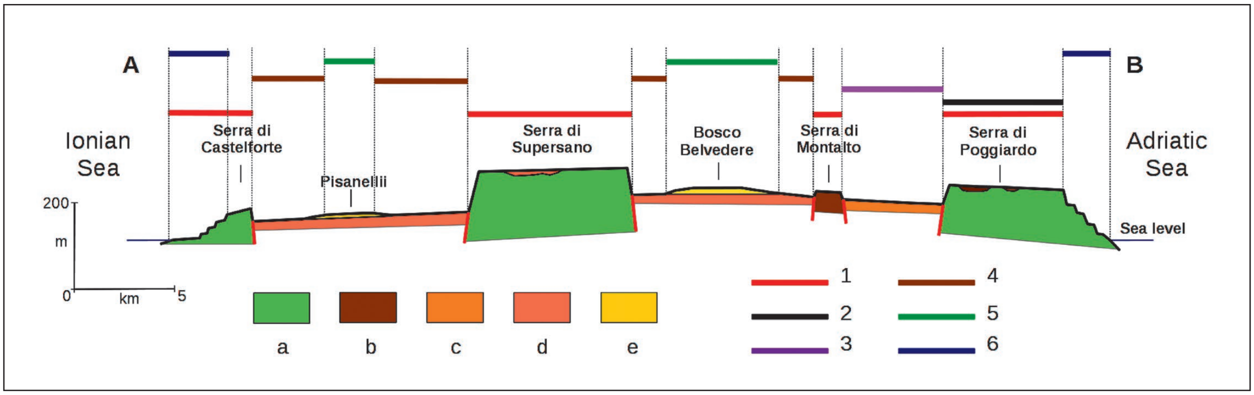

Figure 3: Geomorphological section of southern Salento. The position of the section is reported in Fig. 1. Legend: a - pre-Neogene units, b - Miocene units, c - Pliocene units, d - Lower Pleistocene units, e - Middle-Upper Pleistocene units, 1 - morphostructural ridge, 2 - Paleogene tropical karst surface, 3 - denudation surface shaped on Pliocene units, 4 - Lower Pleistocene karst surface, 5 - Middle-Upper Pleistocene sedimentary plain, 6 - Marine terraces (from Mastronuzzi & Sansò, 2017).

The last emersion of Salento peninsula has been accomplished by effective denudation processes with the development of a hydrographic network flowing toward northwest due to higher uplift of southeastern area. Denudation processes have been responsible for the re-exhumation of the Lower-Middle Pleistocene karstic landscape; moreover, the flow of a large amount of surficial waters in the karstified areas promoted the re-activation of karstic systems producing a typical example of contact karst (Selleri et al., 2002a). Where the karstic landscape is still covered by the Middle Pleistocene marine units the re-activation is scarce and linked mostly to the dynamics of perched groundwater.

Finally, a unique example of a hypogenic karst system occurred at Santa Cesarea Terme, along the eastern coast of the Salento peninsula. In this area, in fact, the rising of sulfidic thermal waters that mix with both recent fresh infiltration waters and coastal salt water has formed four active sulfuric acid speleogenesis caves (D'Angeli et al., 2021).

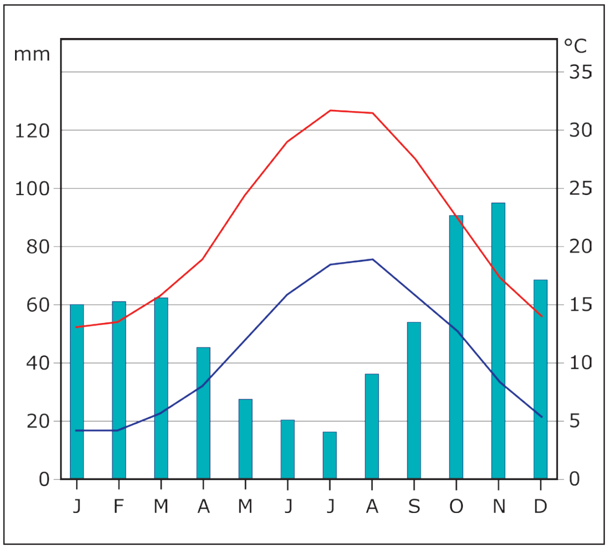

Figure 4: Monthly distribution of precipitation (blue columns), minimum (blue line) and maximum (red line) temperatures recorded at Galatina weather station in the period 1971- 2000.

Generally, the climate of the Salento peninsula can be defined according to the Köppen classification as "Mediterranean" characterized by cool, wet winters and hot, dry summers (Forte et al., 2005). In detail, the analysis of rainfall distribution allows two different areas to be identified in the Salento peninsula: the eastern area, marked by rainfall mean annual values of about 790 mm/year, and the western one where mean annual values of about 590 mm/year are recorded.

The weather station closest to the Lago del Capraro doline is 5 km northwestward far, at Galatina airport. Data recorded by this station from 1971 to 2000 (CMNCA, 2008) show that November is the rainiest month (95.1 mm of rainfall) whereas July is the driest (16.2 mm of rainfall). Maximum temperatures vary from 13.5 °C in January to 31.7 °C in July; minimum temperatures range from 4.2 °C in January and February to 19.9 °C in August (Fig. 4).

D'Oria et al. (2018) provides an up-to-date analysis of climate change over the Salento area using both historical data and multi-model projections of Regional Climate Models. The former indicates that on an annual scale, the minimum temperature in the Salento area has increased at a rate of 0.18 and 0.41 °C/decade in the period 1933–2012 and 1976–2012, respectively. The maximum temperature does not show significant variations in the period 1933–2012 but the monthly trends are always positive and often statistically significant in the period 1976–2012, with a higher gradient in summer and an annual increasing rate of 0.57 °C/decade. The monthly precipitation trends, in the period 1933–2012, are not significant except for September that presents an increasing gradient of 2.5 mm/decade; the total annual precipitation decreased at a rate of 2.4 mm/decade.

Regional Climate Models show that mean temperature will rise over this century with the highest increase in the warm season. The annual mean temperature could be more than 2–4 °C higher with respect to the 1986–2005 period at the end of this century. The total annual rainfall is not expected to significantly vary in the future although systematic changes are present in some months, i.e. a decrease in April and July and an increase in November.

3. MATERIALS AND METHODS

The study of Lago del Capraro doline has been carried out by integrating geological, geomorphological, geognostic and geophysical surveys.

The geological survey was conducted over an area of several square kilometers around the Lago del Capraro doline and in greater detail at the doline. In particular, the stratigraphic analysis and the identification of lithostratigraphic units cropping out in the area were integrated by a structural survey aiming to identify a likely structural control on doline formation and evolution.

The geomorphological analysis was carried out by field survey integrated by aerial photo interpretation; moreover, a detailed topographic survey realized by means of a Nikon DTM-A5 total station allowed the doline morphology to be defined. Field surveys after main rainy events in order to verify the occurrence of a pond at doline bottom have been scheduled since September 2022.

Moreover, a dynamic cone penetrometer test was performed at the doline bottom to obtain a direct measurement of filling thickness. For this purpose, an equipment characterized by a 30 kg hammer and 20 cm drop height was used; the graduated stems are 22 mm in diameter and 100 cm long whereas the cone is 3.56 cm in diameter, with 60° angle and 10 cm^2 surface. The number of strokes necessary to achieve a 10 cm advancement has been recorded.

The permeability of filling surficial layers occurring at the doline bottom was determined using a falling head permeability field test performed on a circular hand dug hole 15 cm in diameter (d) and 15 cm in height (h); permeability coefficient has been calculated according to an empirical formula (AGI, 1977), valid for circular holes in homogeneous and isotropic soil characterized by a permeability coefficient lower than 10^{-6} m/s.

3.1. GEOPHYSICAL SURVEYS

Geophysical surveys were carried out to identify the geometry of filling deposits as well as to detect main infiltration zones of surface water. Geophysical surveys are widely applied for these purposes using different survey methods depending on their efficacy (Negri et al., 2015; Margiotta et al., 2016; Barbolla et al., 2022). Their success depends strongly on the physical contrast between features such as fine sediments and the hosting rocks. Further factors influencing the outcomes of a geophysical survey are resolution, depth of investigation and availability of different methods since their integration helps interpretation of geophysical models. The choice of the most suitable method is influenced by several factors such as resolution and data processing; this last one can be sometimes highly challenging (Negri et al., 2015) because of difficult subsoil conditions, including heterogeneity of the medium. For these reasons, two geophysical methods were used in this research, the resistivity tomography (ERT), and the seismic refraction (RS). The former is a fast method which allows good depth investigation and resolution (Reynolds, 1997; Loke, 2021) whereas the latter is very sensitive to acoustical contrasts that generally occur at geological bodies boundaries due to variations in either the mass density or the seismic velocity, or both (Reynolds, 1997). For seismic refraction, velocities must increase with depth as it can be expected at Lago del Capraro doline. Although the two adopted methods have different resolution, their combination may substantially improve the information content provided from each method separately, since they are based on different physical parameters and, consequently, can provide useful independent data on the subsurface structure.

3.2. ERT METHODOLOGY

ERT is a non-destructive geophysical method which analyses electrical behaviour of subsoil layers detecting lateral and vertical resistivity changes in the subsoil with a high-resolution (Reynolds, 1997). ERT method uses numerous electrodes evenly spaced; distance between electrodes depends on planned resolution and depth of investigation. ERT survey can be carried out using different electrode arrays (dipole-dipole, Wenner, Schlumberger, etc.) by injecting electric current into the ground and measuring voltage signals. Taking into account the array configuration, apparent electrical resistivity can be calculated (Reynolds, 1997; Loke, 2021; Romano et al., 2023). Some authors consider Wenner array most sensitive to vertical resistivity change of the subsoil (Griffiths & Barker, 1993; Zhou et al., 2002); moreover, since this array has a small geometric factor, it leads to strong signals even in areas with electromagnetic background noise. On the other hand, the dipole-dipole array is very sensitive to changes in horizontal resistivity and relatively insensitive to vertical changes so that it is useful in the detection of vertical structures such as buried walls, cavities and contamination plumes.

At Lago del Capraro a geoelectric profile was performed roughly along the NW-SE long axis by means of a Syscal R1 Switch georesistivimeter adopting an interelectrode distance of 5 m and using 48 steel electrodes for a total length of 235 meters (green line in cross section 1, Fig. 7). Two arrays, a Wenner and a Dipole-Dipole, have been used; the adopted interelectrodes distance allowed the good resolution prospection of doline filling, which is about 10 meters thick as detected by the cone dynamic penetrometer test.

The true resistivity was calculated by means of a specific customized tool, derived from the TomoLab 2D inversion software and developed by Multi-Phase Technologies and Geostudi Astier, with a Finite Elements approach to model the subsoil. Throughout the inversion iterations, the effect of non-gaussian noise was appropriately managed through a robust data weighting algorithm (LaBrecque et al., 1996; Morelli & LaBrecque, 1996). In practice, the inversion is based on the robust algorithm formulation to Occam (Morelli & LaBrecque, 1996). The most important parameter in this case is X^2, a chi-square statistic with an expected value of ND, the number of independent data (apparent resistivity measurements). The reconstruction of the final actual resistivity model should not be done by seeking the solution with the smallest possible value of X^2, but that one that makes X^2 as close as possible to ND.

3.3. SEISMIC REFRACTION METHODOLOGY

The seismic refraction method is very sensitive to the acoustical contrasts in either the mass density and/or the seismic velocity occurring at the boundaries among geological layers (Reynolds, 1997). The seismic profile was carried out at flat doline bottom, partially covering the ERT profile (orange line in cross section 1, Fig. 7). The seismic survey was carried out by means of a DOREMI seismograph characterized by 24 channels and 24 4.5Hz vertical geophones spaced 3 meters so that the total length of the seismic profile was 69 m; the energy input came from an 8 kg hammer. The three energizing points were on the 1st geophone, 12th and 24th geophone. Acquired data were analysed according to the standard processing of seismic refraction (Burger, 1992) by means of Reflex software (Sandmeier, 2010).

4. THE LAGO DEL CAPRARO DOLINE

The area of Lago del Capraro doline is marked by the Serra di San Donato, a morphostructural ridge bordered to the north-east by a steep fault scarp, about 15 m high, which constituted the western flank of Sternatia depression; to the south-west the ridge's top surface gently dip from about 90 m down to 60 m of elevation (Fig. 5).

In the area three lithostratigraphic units crop out. The oldest unit is represented by the Calcari di

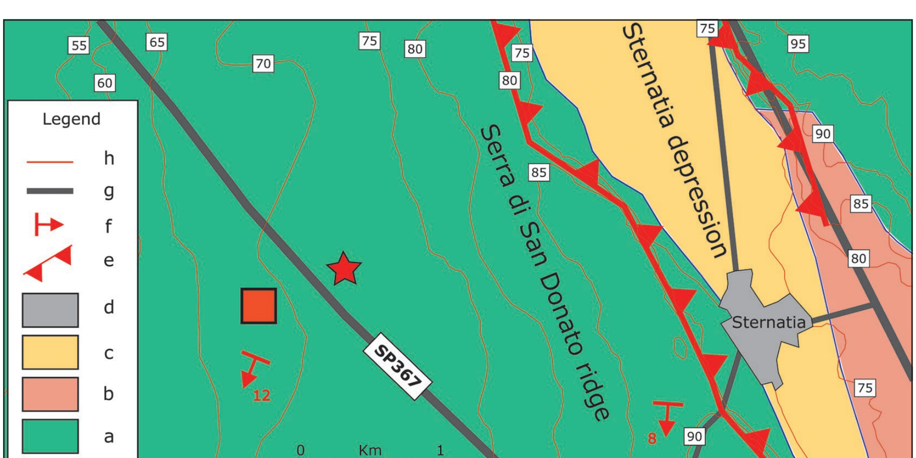

Figure 5: Geological map of Serra di San Donato ridge. Red star marks the Lago del Capraro doline position; the orange box marks the limestone quarry. Legend: a - Calcari di Altamura Formation (Late Cretaceous); b - Pietra Leccese Formation (Miocene); c - Uggiano La Chiesa Formation (Upper Pliocene); d - urbanized area; e - fault scarp; f - strata direction; g - main road; h - contour line.

Figure 6: Limestone strata cropping out along a quarry cliff in the surrounding of Lago del Capraro doline.

Altamura Formation, locally represented by alternating layers of variable thickness of compact limestones and dolomitic limestones of white and grey colour which have been referred to the Upper Cretaceous. This unit crops out in correspondence of Serra di San Donato ridge and was actively quarried in the area to produce material for road and building construction (Fig. 6). This unit, locally about 6 km thick, constitutes the main aquifer of the Salento peninsula; phreatic waters rest on saltwater intruding from the coastal area. The water table elevation reaches the maximum values of about 4 m a.s.l. in the middle area of Salento peninsula; no perched or surficial aquifers can be found at the Lago del Capraro area.

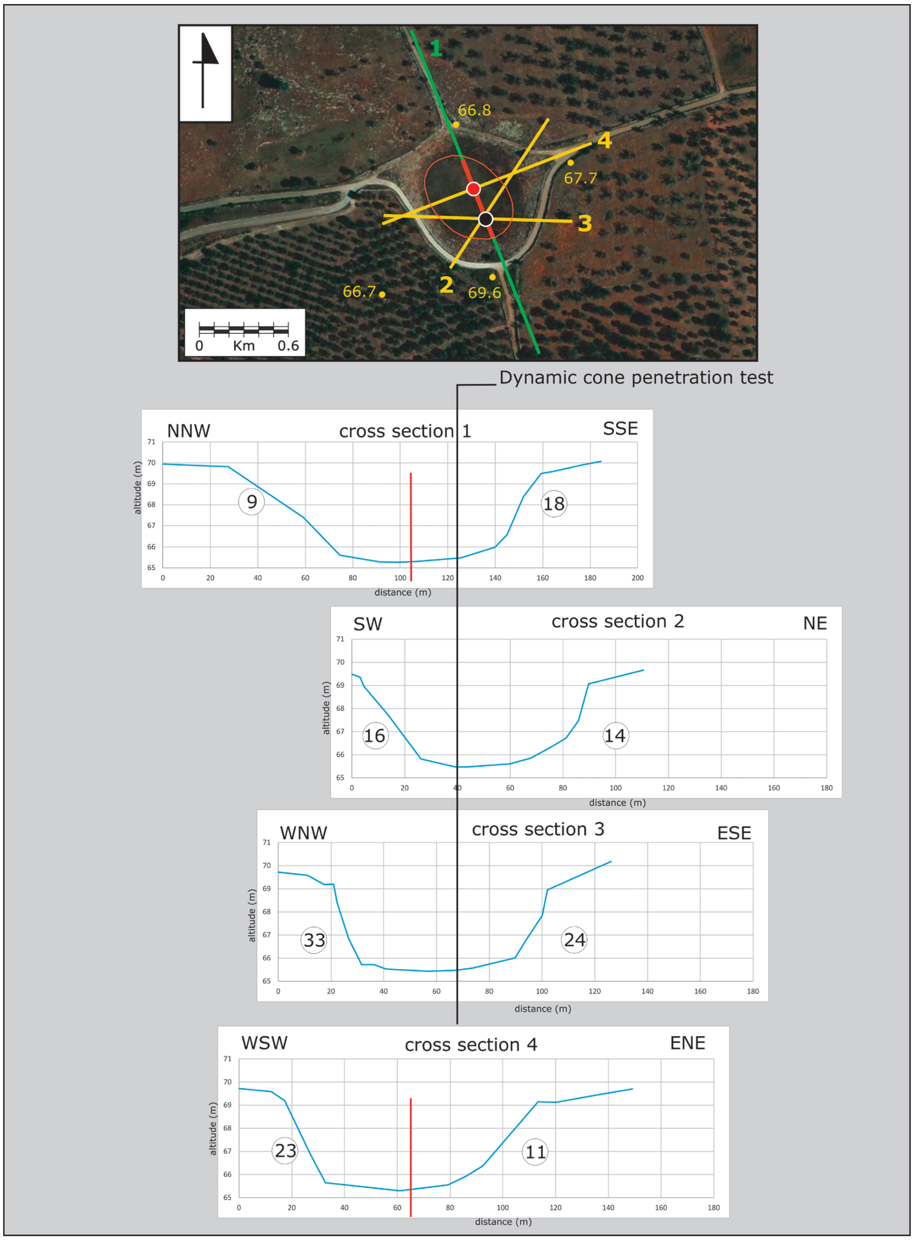

Figure 7: Cross profiles carried out at Lago del Capraro doline. Black point and line mark the dynamic cone penetrometer test position, red point and line is the geometrical centre of the doline bottom. Circled numbers are slope gradients (%). ERT survey (green line) and seismic survey (orange line) were carried out along profile 1.

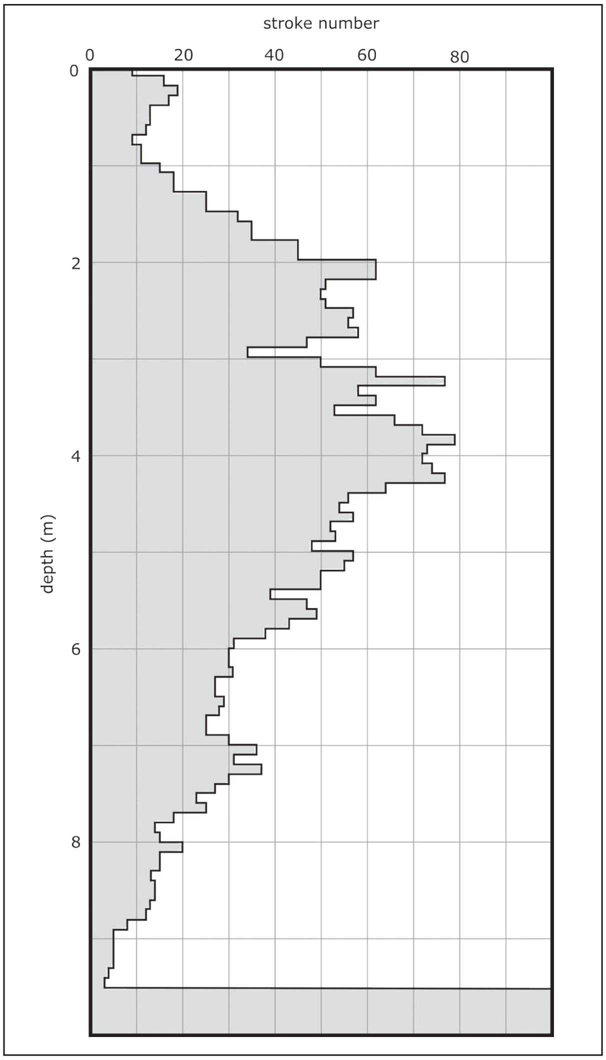

Figure 8: Dynamic cone penetrometer test carried out at the bottom of Lago del Capraro doline.

Two younger units can be recognized in the Sternatia morphostructural depression: the Pietra Leccese Formation and the Uggiano La Chiesa Formation referred to the Late Miocene and to the Upper Pliocene, respectively.

The Lago del Capraro doline shows a slightly elliptical planimetric shape since it is elongated in NNW-SSE direction, according to the main structural frame of Salento peninsula; the major axis is about 130 m long whereas the minor axis is about 100 m long. The bottom is flat, due to the occurrence of a thick colluvial sandy-clayey filling and placed at 65 m of altitude a.s.l.; the bottom major axis is about 65 m long whereas the minor axis is about 50 m long.

The reconstruction of four topographic cross profiles reveals a steeper slope in the southwestern sector, mostly due to rock debris dumping; slope values range from 18 to 33 % (Fig. 7). The northeastern sector still retains its natural profile marked by a 9 % slope shaped on bare rock.

A dynamic cone penetrometric (DCP) test was carried out into the colluvial filling at about 20 m from the SSE border of the flat bottom. DCP test is marked by an increasing resistance from the surface down to 4.2 m of depth followed by a gradual decrease. Layers placed just over the limestone bedrock, reached at 9.5 m of depth, are marked by very low resistance (Fig. 8).

A field permeability test was also carried out; it shows that upper levels of doline filling are marked by values of permeability coefficient (K) about 10^{-3} cm/s (Fig. 9), which define these deposits marked by mean/low permeability, typical of fine sands.

The monitoring of the Lago del Capraro doline after the main rainy periods occurred since September 2022 revealed that a small pond formed in the morning of 4th December 2022 (Fig. 10). Rain data collected by the

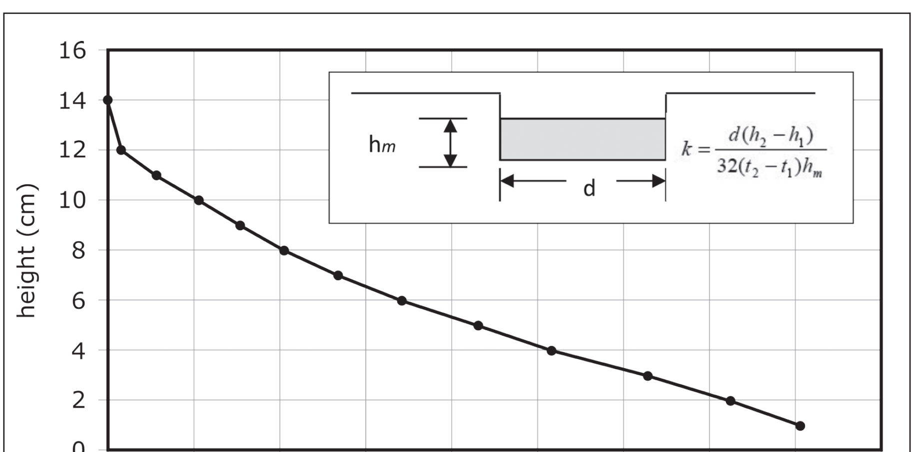

Figure 9: Field permeability test carried out at the Lago del Capraro bottom.

nearby Galatina airport weather station show that the pond formed after 5.5 hours of rain, with a total precipitation amount of 48.8 mm and a maximum intensity of 43.2 mm/hour (Fig. 11). The total precipitation amount since 15th September 2022 was 328.7 mm.

A major event of flooding has been recorded by a photo taken on 8th December 2013 (Fig. 10). The rain distribution recorded by Galatina weather station soon before this event was very similar to that of 2022 (Fig. 12) so that the greater flooding of doline bottom should be attributed to the contribution of the heavy rain event recorded on 7th October 2013. In this case the total precipitation amount since 15th September 2013 was 472.2 mm.

Interestingly, the distribution of daily precipitation

Figure 10: Ponds formed at Lago del Capraro bottom in December 2013 (left) and December 2022 (right).

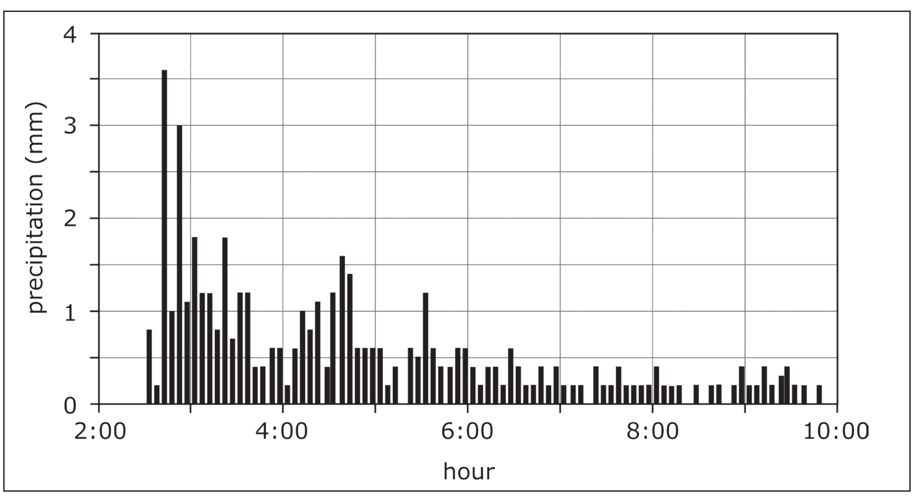

Figure 11: Precipitation data collected by Galatina weather station on 4th December 2022, when a small pond at the Lago del Capraro bottom formed (data from Servizio Meteorologico Aeronautica Militare).

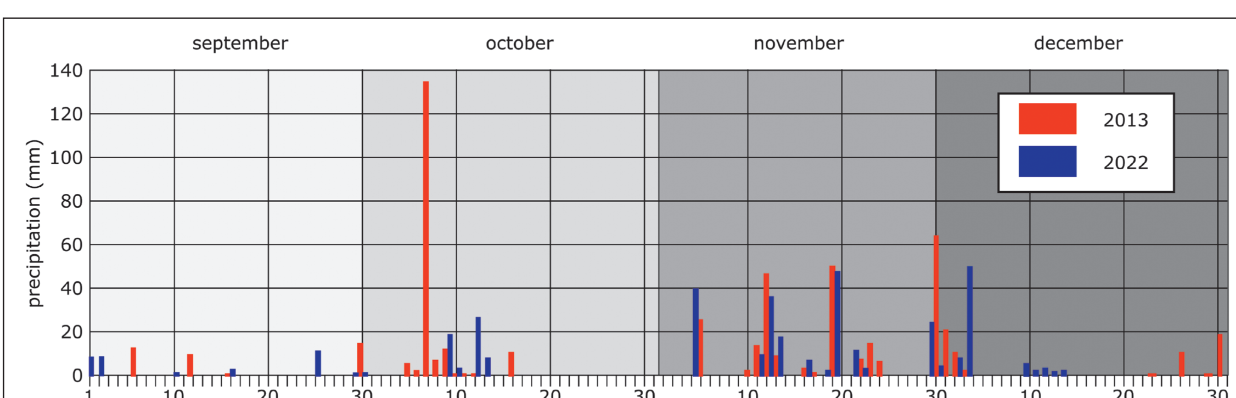

Figure 12: Comparison between precipitation distribution during autumn 2013 and autumn 2022, as recorded by Galatina weather station (data from Servizio Meteorologico Aeronautica Militare).

during the autumn 2022 would indicate 50 mm/day as threshold for doline bottom flooding; in fact, November 2022 precipitations, which have been lower than this value, did not produce any effect. However, monitoring over a longer period is necessary to better define this precipitation threshold value.

5. THE GEOPHYSICAL 2D MODELLING

5.1.. THE 2D RESISTIVITY MODELS

The 2D resistivity model of Lago del Capraro doline was based on data collected both from Wenner and dipole-dipole arrays. In our case, for the Wenner array the calculated value of X^2 is equal to the number of independent data, i.e. 360, whereas for the dipole-dipole array values of X^2 and ND are very close (492 and 467 respectively). A topographic correction was applied both to the Wenner and dipole-dipole resistivity section to take into account the influence of topography on resistivity values.

The dipole-dipole array did not reach the bottom of doline filling. A better data acquisition was obtained using the Wenner array, since its depth of investigation went far beyond the bottom of doline filling and therefore it detected the passage between colluvial deposits and limestone bedrock.

Both Wenner and Dipole-Dipole sections show a variation of resistivity values from about 12 ohm*m to about 10000 ohm*m (Figs. 13 & 14). In particular, a low resistivity zone (blue area) has been detected in the central part of the profile, corresponding to the doline bottom filling. Colluvial deposits occurring at doline bottom, in fact, are constituted by fine sediments which are marked by very low resistivity values, less than 60 ohm*m; the resistivity tomography does not show the differentiation inside filling deposits individuated by the cone penetrometer test so that it can be assumed that mechanical resistance does not influence electric properties of filling deposits. Limestone bedrock shows values of resistivity around 2000 ohm*m (green area) in correspondence of land surface for a thickness of about 5 m and at doline borders; these values mark out the most fractured limestone rock which allows surface waters infiltration. Values of resistivity greater than 5000 ohm*m are

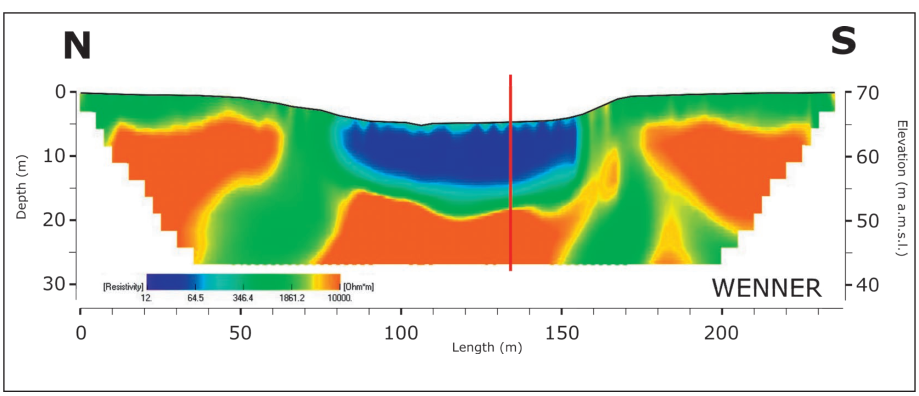

Figure 13: ERT profile carried out at Lago del Capraro doline along its long axis by means of Wenner array. The red line marks the position of the cone penetrometer test; the position of profile is reported in Fig. 7.

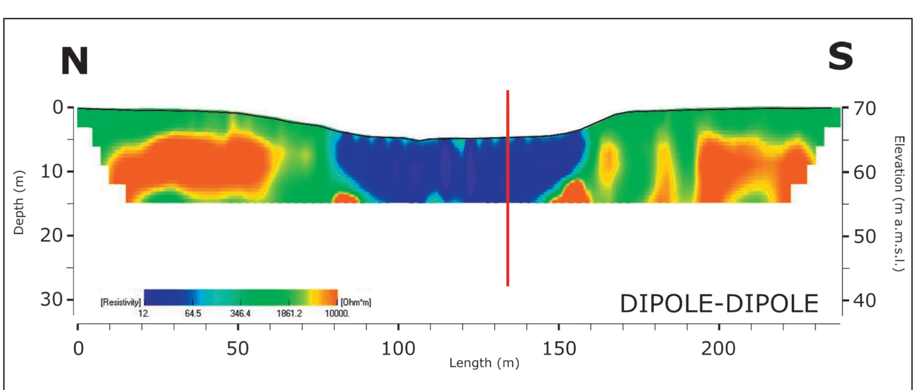

Figure 14: ERT profile carried out at Lago del Capraro doline along its long axis by means of Dipole-Dipole array. The red line marks the position of cone penetrometer test; position of profile is reported in Fig. 7.

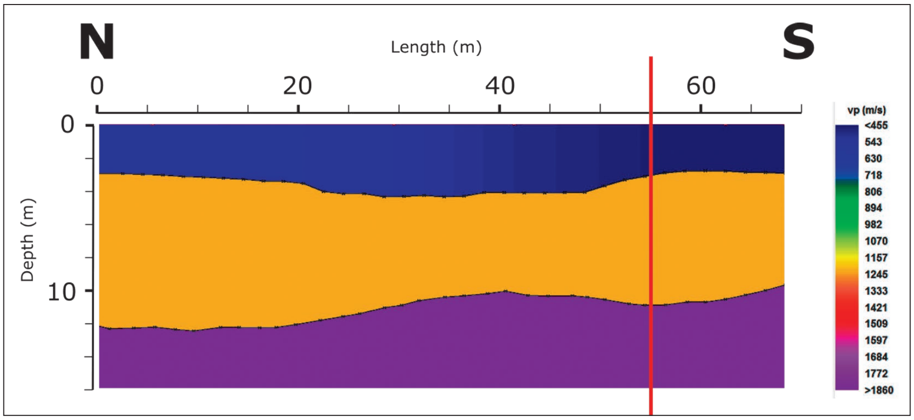

Figure 15: Seismic refraction model carried out at Lago del Capraro doline. The red line marks the position of the cone penetrometer test; the position of profile is reported in Fig. 7.

associated with low-fractured limestone rock mass (orange area).

Values of resistivity ranging between 3 and 100 ohm*m has been reported by Festa et al. (2012) for colluvial deposits occurring at the bottom of a re-actived doline near Lecce, placed about ten kilometers to the north-east of Lago del Capraro area. Also in this area, carbonate bedrock above the groundwater table is marked by resistivity values greater than 5000 ohm*m.

The Wenner section allows the morphology of the filling deposit/bedrock surface to be defined. This surface is marked by steep bordering slopes, the southern one steeper than the northern one, and a slight concave bottom; the thickness of colluvial deposits is quite uniform, ranging from 9 to 11 m.

5.2. THE 2D SEISMIC REFRACTION MODEL

The seismic survey carried out at the doline bottom and the following data processing (Fig. 15) pointed out the occurrence of three layers with different characteristics. The first layer, stretching from the surface down to about 3 m of depth, is marked by low values of velocity (Vp=450 m/s); this layer can be related to the surficial interval with increasing resistance identified by the cone penetrometric test. The second layer occurs between 3 and 9–11 m of depth and shows values of Vp about 1150 m/s; it could be related to the interval with decreasing resistance identified by the cone penetrometric test. Finally, limestone bedrock marked by values of Vp greater than 1800 m/s is detected below 9–11 m of depth.

6. DISCUSSION

In the Salento Peninsula, karst is the main morphogenetic process due to widespread outcrops of entirely carbonate successions. Karst has produced a number of surface landforms, mostly represented by dolines and depressions of variable size, and by several sinkholes which connect surface water circulation with the underground karst systems (Leins et al., 2023). The geographic distribution of main tectonic features and karst landforms in the Salento peninsula suggests a direct link between extensional tectonics and karst development in this region; the increase in permeability along faulted blocks would promote karst phenomena along bands sub-parallel to major faults (Festa et al., 2015).

Solution dolines develop because of focused dissolution in zones of higher permeability, resulting in the gradual and differential lowering of the ground surface (Dreybrodt, 2004; Ford & Williams, 2007). In general, this type of doline forms in areas with exposed or barely soil-covered soluble rocks (Gutierrez et al., 2014; De Waele, 2017; Parise, 2019, 2022; Zumpano et al., 2019). The main process involved in the genesis and evolution of a solution doline is dissolution or corrosion of the bedrock. The amount of a rock removed in solution depends on the concentration of the solute and on the volume of water draining through the doline bottom along main discontinuities (joints, faults, and bedding planes) (Kranjc, 2013). In areas with high fissure frequency, there are more and smaller dolines, whereas particularly large dolines develop in massive, less fissured rocks (Williams, 1983; 2004; 2008).

The bottom of a solution doline is commonly covered by fine-grained sediments, the non-soluble parts of the dissolved limestone, or derived from other fine materials in the surroundings, by local washout of soil or loose sediment, or wind deposits. It may be transformed into red karst soil, from *terra rossa* in humid and warm climates to carbonate brown soil on the karst in more temperate and cooler climates. This is the reason why commonly the bottoms of dolines can be cultivated over karst land.

In the Apulia region, the polygenetic origin of doline filling has been pointed out by a multi-method analysis carried out by Micheletti et al. (2023). The study of a *terra rossa* deposit occurring at the bottom of a Quaternary karst depression on Mesozoic limestones exposed in the Murge highplain, a karst area placed in the central part of Apulia region, shows that doline filling is produced by limestone alteration and chemical interaction with allochthonous siliciclastic material, as well.

Field survey of solutional dolines occurring in the Salento peninsula allows these to be divided in two distinct groups according to the lithological features and age of filling deposit at the doline bottom. The former group comprises dolines partly filled by bauxite deposits made of sub-spheroidal textural components (ooids) dispersed in a fine-grained matrix. Their mineralogy consists mainly of boehmite, iron oxyhydroxides (hematite and goethite), anatase and clay minerals; in particular, ooids are mainly formed of boehmite and generally show a thin rim of Al-hematite (Mongelli et al., 2015). Salento bauxitic deposits are the remains of a weathering mantle which developed under dry tropical climate during a middle Campanian emersion event of Apulian carbonate platform (Mongelli et al., 2015); they were eroded and subsequently deposited into wide karstic depressions developed during the Paleogenic emersion of the region. Afterwards, they were covered by a late Oligocene succession that formed in alternating freshwater, lagoonal and emergent environments (Esu & Girotti, 2010). Good examples of these wide solution dolines can be found at the top plain surface of Monte Vergine and Corigliano morphostructural ridges. Main outcrops of bauxite deposits cropping out in the Salento peninsula have been actively exploited in open pit quarries from 1966 to 1973 to produce alumina (aluminium oxide) (Margiotta & Sansò, 2017).

The second group is represented by dolines partly filled by red sandy clays which are most likely produced by the weathering of a Middle Pleistocene marine unit mainly composed of quartz and micas which crops out extensively in the central area of Salento peninsula. They cover a surface shaped on the Upper Cretaceous - Lower Pleistocene carbonatic bedrock which is marked by the diffuse presence of karstic landforms such as dolines, *kluftkarren*, etc.; this karstic surface was shaped between the end of the Lower Pleistocene and the beginning of the Middle Pleistocene (Selleri, 2007).

The analysis of a filled doline near Bagnolo del Salento locality, recently re-activated because of significative water discharge coming from the surplus of an important aqueduct tank, revealed that red sandy clays fill a small doline with truncated cone shape, about 4–25 m wide and 7 m deep (Selleri et al., 2002b). Another valuable example of this continental cover is also exposed at Masseria Forte di Morello, near Lecce, where the recent re-activation of sinking processes produced a steep slope into the filling deposits constituted by red sands and clayey sands, generally stratified, with a maximum thickness of about 5 m (Festa et al., 2012); a geophysical survey revealed that red sands fill a funnel-shaped depression.

The Lago del Capraro doline can be included in the second group of solution dolines. In fact, it shows a flat bottom due to the occurrence of a thick colluvial filling made of red sandy clays. The geophysical survey clearly indicates that the cross profile of doline filling is characterized by steep slopes, the southern one steeper than the northern one, and a broad concave bottom. The maximum thickness of filling deposits is about 10 meters, as also determined by means of dynamic cone penetrometer test. The distribution of resistivity values into the limestone bedrock would suggest preferential infiltration along both sides of doline filling.

The presence of filling into a doline bottom greatly influences karst processes producing positive feedback. Field measurements performed by Zambo et al. (1997) in a mantled doline at the Aggtelek National Park (Hungary) reveal that steeper slopes above the level of doline filling or in inter-doline terrain will tend to be self-sustaining because of their low potential dissolution. In contrast, there is exceptionally high potential for dissolution in the top 0.5–2.0 m of doline infill due to plant root respiration and aerobic bacteria so that if filling is maintained at a constant elevation in a doline, a corrosion bank or terrace can be expected to form around its perimeter.

The middle zone of doline fill tends to display lower porosity and permeability because of compaction and illuviation. This zone may become quite impermeable and conserve clasts from the side slopes; large, rounded limestone blocks often occur within them. Where these conditions extend to the doline floor the bedrock is protected from dissolution, and a pond may accumulate on the surface. On the contrary, the doline basal filling usually has greater porosity owing to dissolution of the underlying bedrock; the corrosion potential is high to maximal if flow at the soil-rock interface can be focused there.

The occurrence of these different levels inside a doline filling can explain the results obtained from the cone penetrometer test carried out at the bottom of Lago del Capraro doline. The upper levels, down to about 4 m of depth, show increasing resistance due to compaction and illuviation processes whereas lower levels rapidly decrease their resistance which tapers to zero at the bedrock contact. This last evidence suggests that active solution processes as well as infiltrated water flow are acting at the limestone base producing the slow sinking of filling basal levels. Karst processes at the doline bottom could be also promoted by present tectonics of Salento peninsula which would be affected by a radial extension due to the doming of the area (Di Bucci et al., 2011).

As a consequence of active karst processes, an easier flow of surface water occurs through the filling deposits and along rock/filling interface so that it is likely that increasing intense precipitation events will be needed in the future to generate a temporary pond.

7. CONCLUSIONS

The Lago del Capraro doline represents a valuable example of Mediterranean Temporary Pond (MTP) habitat. The geomorphological analysis integrated with geophysical prospection (ERT and seismic refraction methods) and a cone penetration test reveals that this solution doline is characterized by a sandy clayey filling, about 10 m thick, most likely coming from the weathering of a Middle-Pleistocene marine sands unit. Bottom bedrock is slightly concave whereas bordering rock slopes are subvertical; surface water infiltration into limestone basement occurs mainly along the borders of the doline filling.

The particular morphology of Lago del Capraro doline can be attributed to effective solutional processes promoted by the occurrence of filling deposits at doline bottom. Interestingly, the dynamic cone penetrometer test carried out at the doline bottom shows that filling basal levels are affected by a slow downward sinking most likely due to effective karst processes and hydraulic flow at filling/bedrock interface. This last process allows a more rapid infiltration of surface waters so that a major amount of precipitation will be required to form a temporary pond at the doline bottom. On the other hand, climatological models suggest for the next future an increase of precipitation during autumn months so that they could partly compensate major infiltration rates. As result of this hydrological change, more frequent flooding events of Lago del Capraro doline bottom during the late autumn can be expected even if increased infiltration rates will determine a shorter persistence of a pond. These new environmental conditions will surely represent a stress factor for the Lago del Capraro habitat and for its specialized flora and fauna.

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