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ENGINEERING-GEOLOGICAL INSIGHTS INTO THE GYPSUM-BEARING DEPOSITS OF PUNTA DELLE PIETRE NERE (PUGLIA REGION, ITALY)

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EXTENDED ABSTRACT

Nei pressi di Punta delle Pietre Nere, a NW del Lago di Lesina (Puglia, Italia), affiorano depositi gessosi e calcari neri intervallati da marne bituminose e rocce magmatiche (Melidoro & Panaro, 2000 e relativi riferimenti). I gessi sono riconducibili a formazioni evaporitiche del Triassico superiore, che sono, in quest'area, comunemente presenti al di sotto di successioni dell'ordine dei 3000 m di spessore di rocce carbonatiche giurassico-mioceniche. La loro presenza in affioramento può essere spiegata facendo riferimento a tre diversi meccanismi: a) diapirismo, b) spinta verso l'alto dovuta alla compressione tettonica e c) diapirismo associato alla tettonica (Melidoro & Panaro, 2000; Fidelibus *et alii*, 2011; Cotecchia, 2014).

Tra il 1927 e il 1930, e per quasi un chilometro, questi gessi sono stati interessati da lavori che hanno portato alla modifica del tracciato del canale di Acquarotta, necessario per facilitare le condizioni di deflusso dal lago di Lesina verso il mare. Nel tempo, però, fenomeni legati alla dissoluzione delle rocce gessose (*i.e. sinkholes*) hanno interessato sia la porzione di territorio a ridosso del canale Acquarotta, che il vicino centro abitato di Lesina Marina (Melidoro & Panaro, 2000). Di conseguenza sono state condotte numerose indagini, grazie alle quali sono stati approfonditi diversi aspetti relativi all'instabilità dei depositi gessosi.

In questo studio sono presentati i risultati degli studi più recenti condotti nell'area a sud di Lesina Marina (indagini geognostiche, tomografie di resistività elettrica, caratterizzazione delle acque sotterranee ed interpretazione di dati satellitari mediante la tecnica dell'Interferometria satellitare differenziale), che hanno permesso di delineare la distribuzione dei gessi nel sottosuolo e di evidenziare le differenze tra questo assetto e quello che caratterizza la zona di Lesina Marina, interessata da *sinkholes*. In particolare, in quest'area, i gessi sono stati rinvenuti solo nei sondaggi 95_S2 e 95_S12 e non altrove, anche se diverse perforazioni sono state spinte a 50-55 m dal p.c. Una limitata massa gessosa è stata poi individuata dalla tomografia elettrica a più di 30 m dal p.c., compresa tra materiali limoso-argillosi.

Questi gessi si trovano, quindi, in condizioni assai diverse da quelli di Lesina Marina in quanto: *i*) sono coperti da 25-30 m di materiali coesivi (limo sabbioso compatto), in luogo di modesti spessori di terreni sabbiosi sciolti (questi ultimi, a differenza dei primi, in grado di rifluire in eventuali cavità soggiacenti); *ii*) tutti i campioni prelevati in questi terreni presentano percentuali gessose nulle o bassissime; *iii*) le acque sotterranee, anche in corrispondenza di terreni con gessi, hanno velocità di flusso circa 10 volte più basse di quelle registrate a Lesina Marina e caratteristiche chimiche che evidenziano una scarsa interazione con acque superficiali; in tal modo, le possibilità di formazione di cavità e di accelerazione del fenomeno dissolutivo risultano fortemente inibite.

In sintesi, dunque, i dati indicherebbero che, a sud, i gessi sono poco presenti nel sottosuolo e con caratteristiche assolutamente non confrontabili con la zona di Lesina Marina (cosa confortata dalla totale assenza, a sud, di *sinkholes*). I limitati spessori gessosi individuati dalle indagini geognostiche farebbero infatti pensare non tanto a un esteso radicamento in profondità, quanto piuttosto a masse imballate in depositi detritici (in genere fini) e legate ad antichi fenomeni erosivi.

La maggiore conoscenza acquisita sulla distribuzione dei gessi nel sottosuolo di quest'area presenta un'ulteriore valenza positiva se si considera che, nel passato, l'incertezza dei dati rappresentava un fattore fortemente limitante le locali possibilità di sviluppo insediativo.

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ABSTRACT

In a very limited area near Punta delle Pietre Nere (Puglia region, Italy), chalky deposits crop out along with black limestones interspersed with bituminous marls and igneous rocks. From 1927 to 1930 these gypsums were affected by some works that modified the path of the Acquarotta Canal to connect the close lagoon (Lesina Lake) to the sea and facilitate its flow conditions. Over time, the strip of land close to the Acquarotta Canal was affected by sinkhole phenomena related to the dissolution of the chalk. These phenomena also occurred in the nearby town of Lesina Marina. Since 1990, numerous investigations have been carried out in the area, including geological, hydrogeological and geomechanical surveys, geo-electrical and seismic surveys, and remote sensing analyses. In this study, we present the results of recent site-specific investigations, which enabled to better understand the buried limits of the chalky deposits, their depth, the geological characteristics of the covering soils and the groundwater flow conditions. In summary, the distribution of gypsum-bearing deposits in the subsoil of the area is now better defined than in the past, when the uncertainty of the data represented a factor strongly limiting the local possibilities of settlements' development.

KEYWORDS: *gypsum deposit, Lesina Lake, stratigraphic cross-section, physico-chemical groundwater characterization.*

INTRODUCTION

Lesina Lake is a lagoon on the north-western side of the carbonate Gargano Peninsula in Puglia Region (Southern Italy). About twenty small streams, which originate in the relief, feed the lake and contribute to the supply of its surface recharge (COTECCHIA & MAGRI, 1966). Between 1927 and 1930, new canals were excavated to connect Lesina Lake with the sea in areas less prone to winter silting (S.A.I.M., 1927). Among these works, the path of Acquarotta Canal was modified (Fig. 1). In the past, starting from the lake, it was NS-oriented and then with Acquarotta Stream along followed its course to the Adriatic Sea. The works carried out in 1927 changed the last section of the bed, increasing of 1.6-km and moving the mouth northward in correspondence of Punta delle Pietre Nere (FIDELIBUS *et alii*, 2011), where gypsum-bearing deposits are present (MELIDORO & PANARO, 2000 and references therein).

Immediately after the realization of the new path some instability issues arose due to the dissolution of chalky deposits. Since 1970, a new extensive touristic and residential area (named Lesina Marina) was built on the left bank of the canal, above the shallow chalk substrate. This has gradually led to the occurrence and opening of sinkholes, the study of which has given rise to an extensive literature that provides a solid understanding of the local geological-hydrogeological conditions of the gypsum-bearing rocks (MELIDORO & PANARO, 2000; CANORA *et alii*, 2010; FIDELIBUS *et alii*, 2011; REFICE *et alii*, 2011, 2016; CAPORALE *et alii*, 2013; COTECCHIA, 2014; D'ANGELLA *et alii*, 2015).

Outside the area of Lesina Marina, no other information on chalky deposits (*e.g.*, their distribution in the subsoil, characteristics of the water flow, etc.) can be found in the literature. Over the years, however, the territory south of Lesina Marina (*i.e.*, south of the left tributary stream of the Acquarotta Canal) has been the object of numerous geological investigations motivated by new settlement projects and consequent legal actions. In this work, we present the results of both previous and supplementary investigations, which included geological and hydrogeological surveys and samplings, geotechnical and geomechanical tests, geophysical and geoelectrical surveys, and remote sensing analyses as well. The investigations allowed to better define the distribution of chalky deposits in the subsoil of this area and to identify the differences between this area and that one of Lesina Marina.

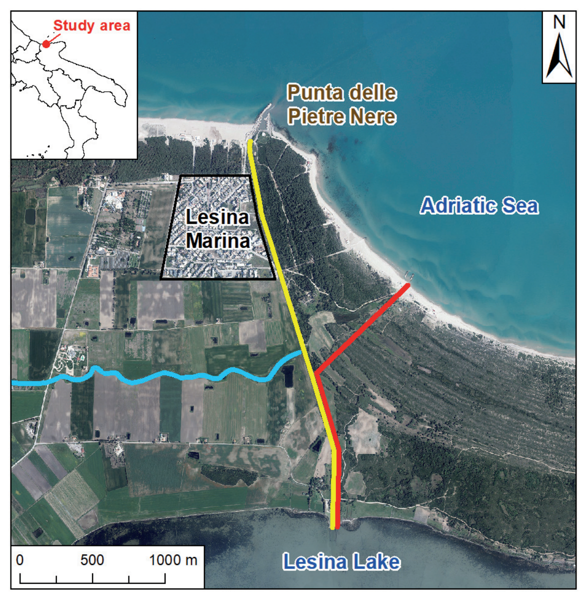

Fig. 1 - Location of the study area, the touristic area of Lesina Marina, the actual (yellow line) and pre-1927 (red line) Acquarotta Canal track and the left tributary stream of the Acquarotta Canal (light blue line). Basemap: 2019 aerial photo from https://www.sit.puglia.it/portal/portale_cartografie_tecniche_tematiche/WMS

GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF THE STUDY AREA

The chalky deposits cropping out in the Acquarotta Canal are traced back to evaporitic formations of the Upper Triassic, similar to those present below successions 3,000 m-thick of Jurassic-Miocene carbonate rocks (MARTINIS & PIERI, 1964; MELIDORO & PANARO, 2000 and references therein). They are interspersed with black limestones, bituminous marls and igneous rocks. Their presence at Punta delle Pietre Nere and along the Acquarotta Canal can be explained by referring to three different mechanisms (Melidoro & Panaro, 2000; Fidelibus *et alii*, 2011; Cotecchia, 2014): a) diapirism, b) thrust upwards due to tectonic compression, and c) diapirism associated with tectonics. Reverse faults favored the rising of the Triassic evaporitic and carbonate rocks, as well as of the igneous rocks (Bigazzi *et alii*, 1996; Posenato *et alii*, 1996; Melidoro & Panaro, 2000; Cotecchia, 2014).

Over the years, a large number of cover collapse and cover suffosion sinkholes due to gypsum dissolution have formed along the Acquarotta Canal and in the adjacent Lesina Marina residential area. Borehole logs show the presence of sandy deposits between 4 and 15-m thick covering a chalk bedrock, which presents a top irregular surface and is characterized by empty cavities and voids totally or partially filled with unconsolidated deposits (Fig. 2; Melidoro & Panaro, 2000; Fidelibus *et alii*, 2011). Gypsum dissolution is favored by high groundwater velocity and by NaCl concentration in groundwater. Groundwater velocity is rather high in proximity of the groundwater table (0.5–0.9 m/d), but tends to quickly decrease at a depth of 25 m below the groundwater table (Melidoro & Panaro, 2000; Canora *et alii*, 2010).

Several authors (Melidoro & Panaro, 2000; Canora *et alii*, 2010; Fidelibus *et alii*, 2011; Cotecchia, 2014) agreed that the northward excavation of the Acquarotta Canal within the chalky rocks has also modified the groundwater flow, which currently has its own final discharge point in the canal (Fig. 2). Total Dissolved Solids (TDSs) in surface waters range between 28.3 and 38.2 g/L, whereas TDSs in groundwater is much more variable, ranging between 0.3 and 36.6 g/L (Fidelibus *et alii*, 2011).

First records of damaging sinkhole occurrences in Lesina Marina date back to 1990. The area affected by subsidence and sinkhole phenomena has increased exponentially from 1999 to 2009, with an average rate of 1000 m²/year (Fidelibus *et alii*, 2011). Currently, most sinkholes are concentrated along two bands situated next to the Acquarotta Canal. The entire Lesina Marina area and a large area further south are also subject to uplift phenomena due to tectonic compression and/or diapirism (Refice *et alii*, 2011; Cotecchia, 2014; Refice *et alii*, 2016). An increase in volume of the chalky deposits due to residual hydration of the anhydrites still present is also hypothesized (Refice *et alii*, 2016).

Several direct and indirect surveys have been carried out in this area over the years (Fig. 3; Buccino, 1995, 2005, 2008; Convertini, 2010; Mocchiutti, 2012). These surveys enabled to improve the knowledge of the subsoil in the first 35-40 m from ground level. Only borehole n. 95_S2 (Fig. 4) found chalky deposits between 12 and 15 m b.g.l., whereas the other boreholes exclusively drilled the coarse-to-fine terrigenous deposits.

Chalky deposits have been identified in three Electrical Resistivity Tomographies (ERTs) at 17, 22 and 32 m b.g.l., respectively. Two deep boreholes were drilled down to 55 m (10_S11 and 95_S12; Fig. 4). Only the borehole 95_S12 found chalky deposits with voids interbedded with sand-silt deposits between 43 and 52 m b.g.l. Seismic surveys (Horizontal-to-Vertical Spectral Ratio - HVSR; Mocchiutti, 2012) seem to delineate a progressive lowering of the chalky deposits towards south reaching maximum depths of 66 m b.g.l.

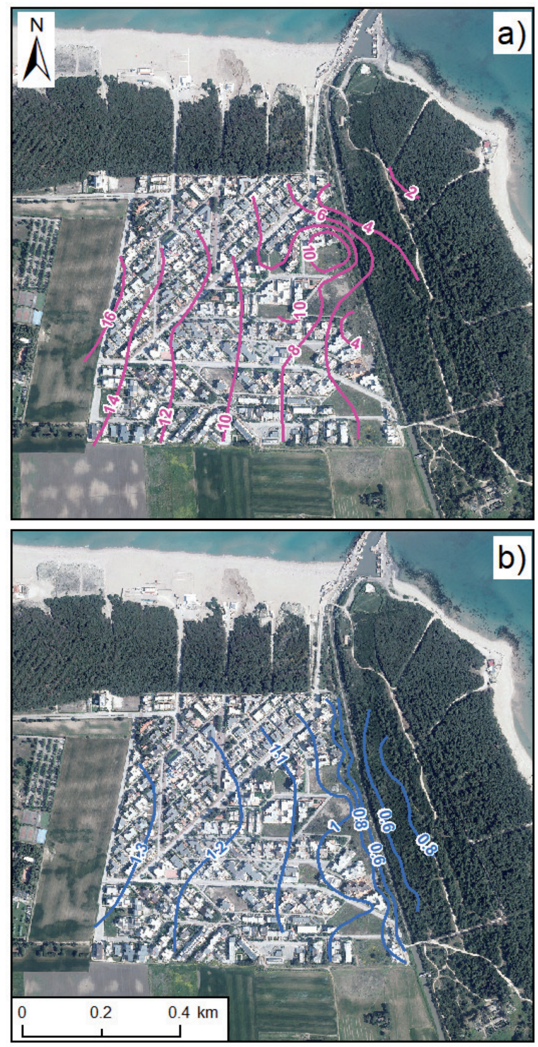

Fig. 2 - a) Thickness (in m) of the sandy soils covering the Lesina Marina chalky deposits (modified from FIDELIBUS et alii, 2011); b) groundwater level in m a.s.l. (modified from Caporale et alii, 2013). Basemap: 2019 aerial photo from https://www.sit.puglia.it/portal/portale_cartografie_tecniche_tematiche/WMS

DATA AND METHODS

The characterization of chalky deposits in the area of interest was carried out by means of several techniques. First of all, studies and technical reports were collected and analyzed; subsequently three mechanical boreholes (reported in Figure

3), an Electrical Resistivity Tomography (ERT; Fig. 3) and the groundwater characterization, were performed (Fig. 4).

To determine the gypsum content, if any, in the soils involved by boreholes, 11 samples were analyzed through X-ray diffractometry at the Department of Earth Sciences, Environment and Resources of the University of Naples Federico II. For qualitative assessment of the crystalline components, Panalitycal high Score Plus software, version 3.0.5, was used. It was coupled with ICSD FIZ Karlsruhe (2006) and PDF-2 (2004) databases, using a search/match procedure, for both interplanar distances (d) and relative intensities (l/l2) of the diffraction peaks of individual reflections satisfying Bragg's Law. Bruker TOPAS 5.0 software was considered for quantitative analysis.

The ERT was executed with IRIS Syscal Pro resistivity meter, by CNR_IRPI in Bari which has also determined the variation of groundwater physico-chemical parameters (temperature, electrical conductivity, pH, redox potential and dissolved oxygen), in boreholes S1, S2 and S3 (Figure 3 for position). Measurements of water filtration rate were also made by using the single-well tracer dilution technique.

As part of this study, surface deformation analyses were also conducted, using the Differential Interferometry SAR (DInSAR - Franceschetti *et alii*, 1992) technique. This technique allows for the detection of possible ground displacements with sub-centimeter accuracy. Analyses were carried out using two datasets, respectively: a) analysis of ground deformations obtained from the interpretation of ENVISAT satellite images from the European Space Agency (ESA) for the period 2002-2010, made available by the Ministry of the Environment as part of the Extraordinary Environmental Remote Sensing Plan (Costabile & Paci, 2010) and searchable on the National Geoportal of the Ministry of the Environment (www.pcn.minantembie.it) from which it is possible to view the interferometric products (mean displacement rate maps); b) COSMO-SkyMed images from the Italian Space Agency (ASI) processed for the period 2015-2018, obtained as part of the MapItaly Project (Sacco *et alii*, 2015).

RESULTS

The new borehole S1 (2.17 m a.s.l. and 55 m deep) found sands and silty sands down to 18 m b.g.l., then only silty clays, (groundwater level was found at 0.30 m a.s.l.). Conversely, S2 log (5.15 m a.s.l. and 50 m deep) crossed 21 m of sands and silts, then a deposit made of gravels, sands and silts, (groundwater level was found at 0.89 m a.s.l.).

The qualitative analysis of the crystalline components, performed on 5 samples from borehole S1 and 6 samples from borehole S2, shows the predominant presence of quartz and calcite with clay minerals, sometimes in association with feldspars and micas. Gypsum was detected in only 2 samples from S1: here the presence of gypsum was only a few units in percentages, values far from those attributed to chalky soils (>50 %; Asghari *et alii*, 2018; Schanz & Karim, 2018).

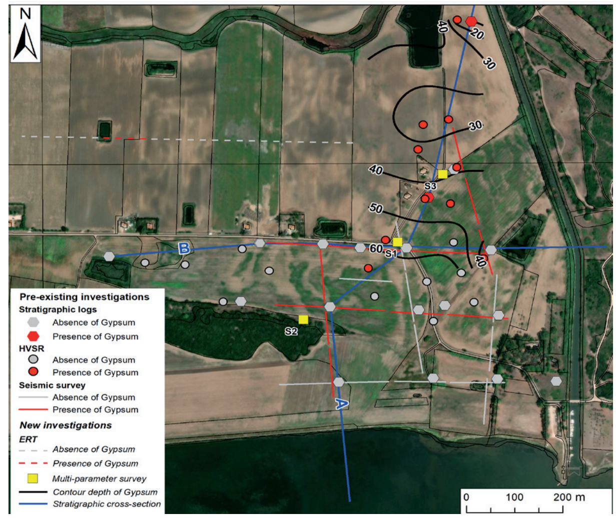

Fig. 3 - Map showing the location of surveys carried out in the study area (boreholes, HVSRs, ERT and multi-parametric surveys) with the indication of the presence/absence of gypsum. The pre-existing investigations are modified from Mocchiutti *(2012). Depth of the top of the gypsum is also shown (black lines). The traces of the two cross-sections reported in Fig. 4 are marked by the light blue lines. Basemap: 2019 aerial photo from https://www.sit.puglia.it/portal/portale_cartografie_tecniche_tematiche/WMS*

ERT allowed the investigation of a soil thickness up to about 80 m from the ground surface. As shown in Figure 5, the ERT identifies a mass characterized by high resistivity values in the western sector of the investigated area and between 30 and 60 m b.g.l, included between soils with lower resistivity values (probably silty-clayey materials). Moving southward, this mass appears depleted, as it was not present in any of the boreholes drilled. Based on the measured resistivity values, this mass can be associated to chalky deposits.

The multi-parameter probe surveys and groundwater velocity measurements carried out in S1, S2 and S3 (see Figure 3 for position), indicate:

1. S1: waters characterized by low salinity and significant oxygen content down to 5-6 m b.g.l, and more saline (30-40 mS/cm) and poorly oxygenated waters at greater depth with a very low water velocity (in the order of 0.01 m/days) in the first few meters from the ground surface and lower velocities (about 0.007 m/days; around 15 m b.g.l) to decrease dramatically at greater depths (down to 0.001 m/days);
2. S2: poor-saline waters until about 15 m b.g.l, gradually replaced by higher conductivities waters (20 mS/cm) with higher velocities (close to 0.02 m/days) in narrow levels (between 10 and 15 m b.g.l. and in the range 35-40 m b.g.l.);
3. S3: salinity and oxygenation very similar to those measured in S1, and velocities very low down to 20 m b.g.l. (generally less than 0.005 m/days), which subsequent increase.

Data from previous investigations and geomechanical surveys conducted in the study area allow to outline the geological and

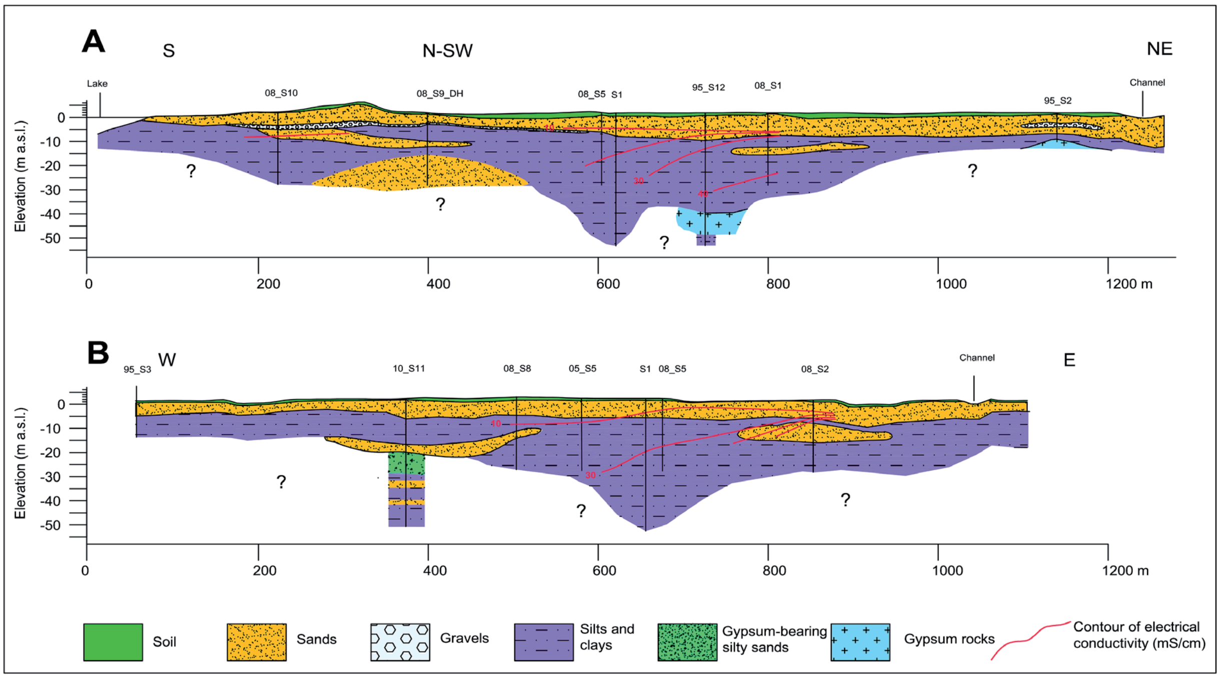

Fig. 4 - Stratigraphic cross-section derived from recent and previous surveys (see Figure 3 for position). Measurements of electrical conductivity are shown as contour lines (red lines)

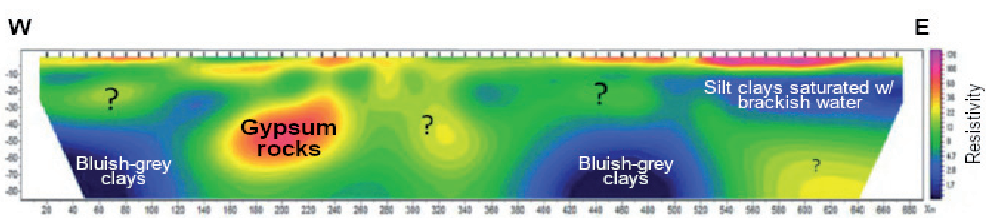

Fig. 5 - Electrical resistivity tomography (ERT) carried out in the study area. See Figure 3 for location

stratigraphic setting summarized in the cross-sections of Figure 4 (see Figure 3 for position). The cross-sections highlight, beneath a layer of top-soil approximately 1-2 m thick, a predominantly sandy layer (with occasional gravelly episodes) distributed throughout the area, with a thickness rarely exceeding 10 m. Moving downward, silty and clayey soils with sandy intercalations are present.

Gypsum rocks (with cavities) were present only in boreholes 95_S2 and 95_S12 (Fig. 4A). From these drillings, the top of the gypsum rocks appears to lower rather abruptly towards southwest, as the S1 borehole (depth: 55 m) did not found it anymore. Furthermore, borehole 95_S12, after passing through the chalky deposits, encounters for another 3 m silty and clayey soils, suggesting that the chalky deposits represent only masses embedded in such soils, also confirmed by the ERT (Fig. 5).

In some boreholes a shallow groundwater table was identified, likely connected to a single groundwater body, as also confirmed by the agreement of water levels in different deep drillings. Groundwater table is slightly elevated if compared to sea level and declines towards the canal. As already said, chemical characteristics and velocities of groundwater vary with depth; physico-chemical data indicate the presence of a lens constituted by oxygenated and low-salinity waters (conductivity < 10 mS/cm), whose thickness, varying from site to site, is generally around 10 m. This lens rests on more saline groundwater (very low in oxygen and redox potential), associated with seawater intrusion and poor in significant interactions with surface waters.

Finally, maps of the mean displacement rates recorded during 2002-2010 were obtained from the processing of ENVISAT images acquired in the two geometries, ascending and descending, respectively (Fig. 6a, c). As it can be seen, no natural reflectors could be found in the area of interest to highlight ground deformations. This is due to the low resolution of the ENVISAT images (20×4 m) but mainly to the fact that the area of interest is totally vegetated.

Regarding the second dataset, COSMO-SkyMed SAR images were processed, for the period 2015-2018, in ascending and descending, respectively (Fig. 6b, d). From the available images, 43 (in the period 17/08/2015 - 10/09/2018) and 41 (in the period 19/10/2015 - 09/09/2018), 132 interferograms were obtained for ascending images and 135 for descending images characterized by maximum spatial baseline of 300 m and maximum temporal baseline of 300 days. Mean displacement rate maps were estimated and even in this second period, the number of targets turned out to be rather small, for the same reason previously described for these points (*i.e.* no natural reflectors).

CONCLUSIONS

Data acquired and processed made it possible to delineate the distribution of chalky deposits in the area south of Lesina Marina and to highlight the differences between this setting and that characterizing the area of Lesina Marina affected by sinkholes.

In particular, in the area to the south, gypsum rocks were found only in boreholes 95_S2 and 95_S12 (Fig. 4A) but not elsewhere, even though several boreholes reached 50-55 m b.g.l.. Moreover, a limited chalky mass was detected by ERT more than 30 m b.g.l., included in silt-clay materials. These chalky deposits are, therefore, in a very different condition from those of Lesina Marina in that:

1. they are covered by 25-30 m of cohesive materials (dense sandy silts) in place of moderate thicknesses of loose sandy soils (the latter, unlike the former, capable of flowing back into any underlying cavities);
2. all samples taken in these soils have no or very low gypsum percentages;
3. groundwater, even in soils with gypsum, has flow velocities about 10 times lower than those recorded in Lesina Marina and chemical characteristics that show little interaction with surface water; thus, the possibilities of cavity formation and acceleration of the dissolving phenomenon are strongly inhibited.

In summary, data indicate that, in the investigated area, gypsum-bearing deposits are very little present in the subsoil and with characteristics that are absolutely not comparable with the Lesina Marina area (an evidence supported by the total absence, to the south, of sinkholes). In fact, the limited chalky deposit thicknesses identified by the surveys (Fig. 4) would suggest a shallow mass packed in detrital deposits (generally of fine grain size) and related to ancient erosional phenomena.

The increased knowledge gained about the distribution of gypsum in the subsoil of this area presents an additional positive value when one considers that, in the past, uncertainty of data was a strongly limiting factor for local settlement development possibilities.

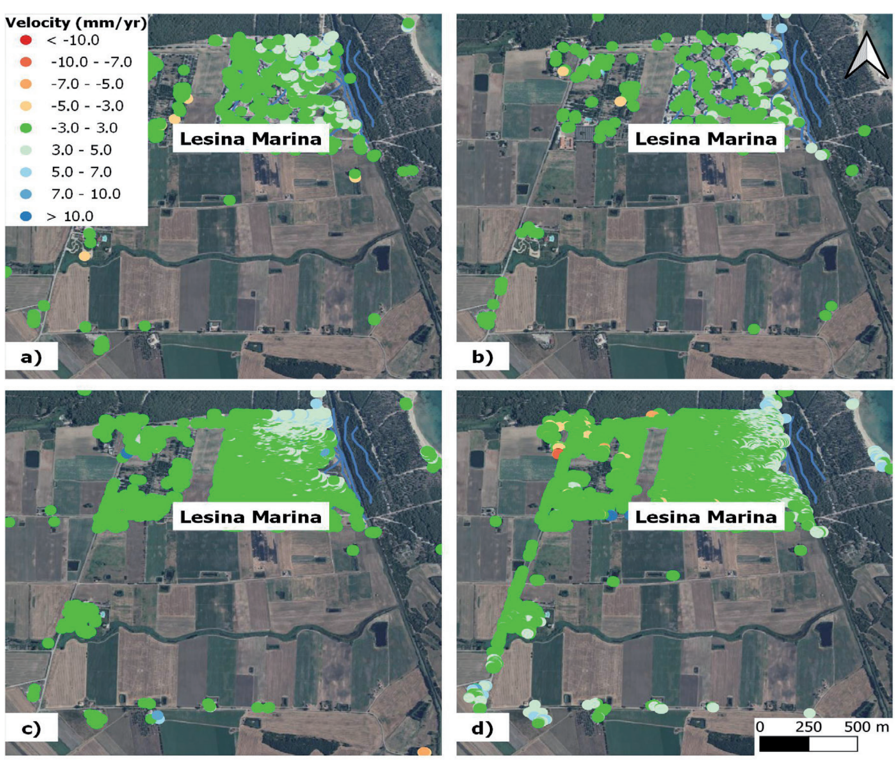

Fig. 6 - Maps of the average displacement rates recorded during 2002-2010 from the ENVISAT ascending (a) and descending (b) images, and COSMO-SkyMed SAR images for the period 2015-2018 in ascending (c) and descending (d)

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REFERENCES

Asghari S., Ghafoori M. & Sayed Salman Tabatabai S.S. (2018) - *Changes in chemical composition and engineering properties of gypseous soils through leaching: an example from Mashhad, Iran.* Bull Eng Geol Environ, **77**: 165-175. Doi: 10.1007/s10064-017-1076-6.

Bigazzi G., Laurenzi A., Principe C. & Brocchini D. (1996) - *New geochronological data on igneous rocks and evaporites of the Pietre Nere Point Gargano Peninsula, Southern Italy.* Boll. Soc. Geol. It., **CXV**: 439-448.

Buccino L. (1995) - *Piano di lottizzazione Zone C3 (Per. 143) - C4a (Per. 145) Lesina Marina*. Relazione geotecnica.

Buccino L. (2005) - P*iano di lottizzazione Zone C3 - C4a Lesina Marina*. Relazione geologica e geotecnica sulle indagini integrative.

Buccino L. (2008) - *Piano di lottizzazione Zone C3 - C4a Lesina Marina. Istanza di modifica della perimetrazione di area a pericolosità morfologica*. Studio di compatibilità geologica e geotecnica.

Canora F., Caporale F., Fidelibus M.D., Gutiérrez F., Leandro G. & Spilotro G. (2010) - *Variazioni idrogeologiche e riattivazione del carsismo nei gessi di Lesina Marina (Puglia)*. In: Nisio S. (Ed.), Proc. 2nd Int. Workshop "*I sinkholes. Gli sprofondamenti catastrofici nell'ambiente naturale ed in quello antropizzato*", Roma, 3-4 dicembre 2009: 435-452. ISPRA, ISBN 978-88-448-0400-8.

Caporale F., De Venuto G., Leandro G. & Spilotro G. (2013) – *Interventi di mitigazione del rischio da sinkholes nell'area di Lesina marina (Provincia di Foggia, Italia).* Mem. Descr. Carta Geologica d'Italia, **XCIII**: 121-142.

Convertini A. (2010) - *Piano di lottizzazione Zone C3 - C4a Lesina Marina*. Studio di compatibilità geologica e geotecnica.

Costabile S. & Paci M. (2010) - *The National Geoportal and the application of PSI data for the detection of high hydro-geomorphological risk areas (In Italian).* Geomedia, **14**(5): 26-30.

Cotecchia V. & Magri G. (1966) - *Idrogeologia del Gargano*. Geol. Appl. e Idrogeologia, **1**: 1-80.

Cotecchia V. (2014) - *Le acque sotterranee e l'intrusione marina in Puglia: dalla ricerca all'emergenza nella salvaguardia della risorsa.* Mem. Descr. Carta Geol. d'It., **XCII** (2): 15-66.

D'angella A., Canora F. & Spilotro G. (2015) - *Sinkholes Susceptibility Assessment in Urban Environment Using Heuristic, Statistical and Artificial Neural Network (ANN) Models in Evaporite Karst System: A Case Study from Lesina Marina (Southern Italy).* In: Lollino G., Manconi A., Guzzetti F., Culshaw M., Bobrowsky P., Luino F. (eds) Engineering Geology for Society and Territory - Volume 5. Springer, Cham; Doi: 10.1007/978-3-319-09048-1_79.

Fidelibus M.D., Gutièrrez F. & Spilotro G. (2011) – *Human induced hydrogeological changes and sinkholes in the coastal gypsum karst of Lesina Marina area (Foggia Province, Italy).* Engineering Geology, **118**(1): 1-19. Doi: 10.1016/j.enggeo.2010.12.003.

Franceschetti G., Migliaccio M., Riccio D., Schirinzi G. & Saras (1992) - *A synthetic aperture radar (SAR) raw signal simulator.* IEEE Trans. Geosci. Remote Sens., **30**: 110-123.

Martinis B. & Pieri M. (1964) - *Alcune notizie sulla formazione evaporitica del Triassico superiore nell'Italia centrale e meridionale.* Mem. Soc. Geol. It., **VI**: 666-678.

Melidoro G. & Panaro V. (2000) - *Sprofondamenti carsici nei gessi costieri di Marina di Lesina (Gargano) e mitigazione del rischio.* Geologia Tecnica e Ambientale, **3**: 13-24.

Mocchiutti A. (2012) - *Campagna di indagini geognostiche integrative finalizzate alla ri-perimetrazione di un'area a pericolosità geomorfologica* – Piano di lottizzazione C3 e C4 a Lesina Marina.

Posenato E., De Fino M., La Volpe G. & Piccarreta P. (1994) - *L'affioramento del Trias superiore delle Pietre Nere (calcari e gessi) e i prodotti del vulcanesimo basico paleogenico.* Geologia delle aree di Avampaese. 77° Congr. della Soc. Geol. It.; Guida all'Escursione pre-Congressuale.

Refice A., Bonvega F., Pasquariello G., Fidelibus M. & Spilotro G. (2011) – *Uplift at Lesina Marina (Southern Italy) revealed by PSI techniques.* Proc. FRINGE 2011 Workshop, ESA, Frascati (Italy).

Refice A., Pasquariello G., Bovenga F., Festa V., Acquafredda P. & Spilotro G. (2016) - *Investigating uplift in Lesina Marina (Southern Italy) with the aid of persistent scatterer SAR interferometry and in situ measurements.* Environ. Earth Sci., **75**: 243-256; Doi: 10.1007/s12665-015-4979-1

Sacco P., Battagliere M. L., Daraio M. G. & Coletta A. (2015) - *The COSMO-SkyMed constellation monitoring of the Italian territory: the Map Italy project.* In Proc. of 66th International Astronautical Congress (IAC 2015): 12-166.

S.A.I.M. - Sindacato Agricolo Industriale Meridionale (1927) - *Bonifica del Lago di Lesina.* Stab. Tipolitografico del Genio Civile, Roma.

Schanz T. & Karim H.H. (2018) - *Geotechnical characteristics of some Iraqi gypseous soils.* In: MATEC Web of Conferences, **162**: 1-9. Doi: 10.1051/matecconf/201816201005.

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