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SINKHOLE OCCURRENCE AND EVOLUTION, AND SEAWATER INTRUSION IN A LOW-COASTAL SETTING OF APULIA

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EXTENDED ABSTRACT

Negli ultimi decenni, la comunità scientifica internazionale sta focalizzando la sua attenzione sulle aree costiere poiché altamente urbanizzate e popolate, nonché spesso siti di grande interesse turistico. Tali ambienti sono caratterizzati da elevata dinamicità essendo anche aree di transizione tra terra e mare, dove processi terrestri, marini, atmosferici e antropogenici agiscono sinergicamente. In particolar modo, le aree costiere carsiche mostrano una maggiore vulnerabilità ambientale, in termini di risorsa idrica sotterranea, e una maggiore propensione all'innesco di fenomeni di sprofondamento, i *sinkholes*. L'intrusione marina in acquiferi costieri determina la salinizzazione delle risorse idriche sotterranee, mentre la zona di mixing tra acque dolci e salate esercita una dissoluzione più aggressiva sulle rocce solubili accelerando la formazione di *sinkholes*.

In questo lavoro sarà presentato e descritto un settore costiero-carsico della Puglia, situato in una delle zone più turistiche della regione e compreso tra le province di Bari e Brindisi. Questa porzione costiera è localmente chiamata "Costa Merlata" poiché ricca di profonde insenature e baie che modellano la morfologia del paesaggio, ricordando i merli di un castello medievale. In particolare, il lavoro qui presentato descrive l'avanzamento dell'intrusione di acqua marina nella falda idrica costiera e l'evoluzione di *sinkholes* da collasso osservati nell'area selezionata.

La successione geologia mostra dal basso verso l'alto: il substrato roccioso calcareo del Cretaceo, calcareniti cenozoiche più recenti e, infine, depositi marini terrazzati del Quaternario. La topografia è controllata dalle discontinuità strutturali, orientate principalmente in direzione SW-NE; esse esercitano un forte controllo sullo sviluppo delle cavità carsiche e, di conseguenza, sul ruolo della coalescenza di *sinkholes* nella genesi di insenature. L'orientazione preferenziale delle baie, infatti, è in linea con quella tettonica regionale (SW-NE). L'evoluzione morfologica è caratterizzata da diverse fasi: genesi di un sinkhole singolo, formazione di altri *sinkholes*, coalescenza e formazione di baie ben sviluppate. Il caso di studio evidenzia la grande influenza che l'evoluzione per coalescenza di *sinkholes* da collasso può rivestire nel processo di evoluzione geomorfologica costiera, elemento essenziale nelle azioni di pianificazione territoriale.

Dal punto di vista idrogeologico, dell'area di studio presenta importanti sorgenti carsiche retro dunari con portate di centinaia di litri al secondo, e numerosissime sorgenti sottomarine diffuse, spesso con portata sconosciuta. Sebbene in alcuni settori le aliquote di flusso idrico verso mare siano consistenti, l'area costiera è interessata dal fenomeno di intrusione marina; la salinità delle acque sotterranee, infatti, raggiunge valori compresi tra 0,5 g/l e oltre 5 g/l. Il tratto costiero si estende per circa 25 km ed è soggetto alla fluttuazione dell'interfaccia Ghyben-Herzberg che si sposta nel tempo e nello spazio in funzione delle maree, dei trend stagionali dell'acquifero e della quantità di acqua emunta per scopi agricoli, domestici, industriali e turistici. Lo spostamento della zona di mixing acqua dolce/ acqua salata espone un'ampia porzione del sottosuolo all'azione fortemente aggressiva della soluzione salmastra, aumentando l'area del territorio ad elevata vulnerabilità da *sinkholes*.

In una zona così complessa, le grotte costiere possono essere considerate dei siti preferenziali di monitoraggio delle acque sotterranee, soprattutto in prossimità del mare, dove si incontrano acqua dolce e acqua marina. In collaborazione con altri gruppi di ricerca, nell'area descritta si stanno portando avanti tecniche innovative per il monitoraggio dei parametri ambientali. La stigofauna, ovvero le specie animali che vivono esclusivamente nelle acque sotterranee, può essere considerata un indicatore ambientale e tracciante naturale, poiché altamente sensibile alle variazioni delle condizioni chimico-fisiche dell'ambiente circostante; pertanto, lo studio degli ecosistemi delle acque sotterranee consentirà di caratterizzare la qualità delle acque sotterranee e tracciare i percorsi preferenziali delle acque dolci carsiche.

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ABSTRACT

In the last decades, the scientific community has paid an increasing attention on coastal karst areas, since these are highly urbanized and populated, and attract high number of tourists. This transition zone where anthropogenic, terrestrial, and marine processes simultaneously act, is intrinsically fragile, and its vulnerability to geological hazards is enhanced by the mixing between fresh and salt waters, causing a stronger dissolution on carbonate rocks.

In this paper, a case study located along the coastal karst of Apulia, between the provinces of Bari and Brindisi, in one of the most touristic areas of the Region is described. In detail, this manuscript deals with description sinkholes evolution at the coastal zone and seawater intrusion in coastal aquifer. The case study highlights the influence of sinkholes in the modification of coastal geomorphology, potentially leading to natural hazards in terms for communities, urbanized land, and infrastructures.

The geological setting presents the Cretaceous limestone bedrock overlain by more recent Cenozoic calcarenites and Quaternary marine terrace deposits. The topography is controlled by structural discontinuities, mainly oriented in SW-NE direction. This area is locally defined "Costa Merlata", which means "Merlon coast", as it resembles the merlons of a medieval castle. This is due to a strong control exerted by sinkholes in the genesis of bays and inlets. In fact, in this stretch of the Adriatic coastline, it is possible to observe important freshwater outflows, including the main spa of central Apulia (Torre Canne spa), and several evidence of sinkholes, including recent collapse at a few meters from the coastline. The morphologic evolution is characterized by different phases: individual openings of sinkholes, which evolve to small inlets showing the larger sinkhole inland, accompanied by minor openings toward the sea; the last phase is characterized by well-developed bays, deriving from coalescence of sinkholes, overall entering inland for some tens of meters, by means of progressive failures, also favored by sea-storms.

In addition to the sinkhole hazards, the area is affected by inland seawater intrusion. In fact, the hydrogeological setting of the coastal stretch, extending for about 25 km, shows evidence of groundwater salinization, with salinity values ranging from 0,5 g/l to more than 5 g/l. The springs with high discharge rate are in the sand dunes zone (Fiume Grande, Fiume Piccolo, and Fiume Morello) and discharge hundreds of liters of freshwater per second, while several diffuse springs, often with unknown discharge, are submerged.

In such complex zone, caves adopted as groundwater monitoring spots, especially near the sea, where fresh water and sea water meet. The latter is also carried out by monitoring of stygofauna, i.e. animal species living exclusively within groundwater. Stygofauna can be considered environmental indicator and natural tracer, since it is highly sensitive to environmental variation; therefore, studying groundwater ecosystems will allow to characterize the groundwater quality and the main freshwater pathways.

Keywords: *coast, hydrogeology, hazard, sinkhole, Apulia.*

INTRODUCTION

Coastal areas worldwide can be considered intrinsically fragile environments, particularly susceptible to morphological modification due to the direct and simultaneous interaction of terrestrial, marine, and anthropogenic processes (Carter & Woodroffe, 1995; Delle Rose & Parise, 2004; Li *et alii*, 2009; Kennedy *et alii*, 2014; Massaro *et alii,* 2023). This is particularly true for coastal karst, where the underground is characterized by a complex network of fractures, voids, conduits, and caves (Palmer, 1991, 2007). In such a geological setting, the coastline morphology can be strongly controlled by sinkhole occurrence, whose development and evolution may eventually control the formation and preferential orientation of bays and inlets (Margiotta *et alii*, 2012). This is particularly visible at low-lying coasts in soluble rocks.

Coastal sectors show the occurrence of sinkholes of different typologies (Gutierrez *et alii*, 2014; Parise, 2019, 2022). Among the others, collapse sinkholes can be considered the most dangerous since their rapid kinematic often with no precursory signals; furthermore, in coastal settings, they are favored by seawater intrusion in coastal aquifers (Arfib *et alii*, 2002; Tulipano, 2003; Dasgupta *et alii*, 2007; De Filippis *et alii*, 2016; Masciopinto & Liso, 2016). The contact of the rock with the mixing of fresh and salt waters creates a solution over- or under-saturated leading to precipitation or dissolution of the solid phase (Runnells, 1969; Plummer, 1975). Given the specific water-rock interactions (Custodio & Llamas, 1976; Custodio, 1985; Mercado, 1985; Custodio & Bruggeman, 1986) a variety of dissolution processes occur, that eventually results in significantly increasing both porosity and permeability of the rock masses (Hanshaw & Back, 1979). The fresh-salt water mixing zone migrates in space and time, driven by tides and seasonal groundwater level fluctuations, affecting wide zones of coastal areas (Denizman & Randazzo, 2000; Mylroie *et alii*, 2008). Seawater intrusion, therefore, favors the formation of karst features due to the high dissolution capability of brackish water on the soluble rocks. Underground voids rapidly evolve, eventually leading to the coalescence of collapse sinkholes; further, when karst caves are in direct connection with the sea, the wave energy enhances the possibility of sinkhole occurrence, due to the mechanical erosion (Lace, 2008). This process is particularly effective in soft rocks such as calcarenites (Waterstrat *et alii*, 2010). In detail, the energy of sea waves can be considered as both a possible preparatory or triggering factor for coastal landslides, with serious issues in terms of land management and public safety, especially in high touristic places, such as at the well-known Grotta della Poesia UNESCO site, on the Adriatic coast of Apulia (Delle Rose & Parise, 2005; Liso & Parise, 2023).

To the above natural factors, various anthropogenic actions like building and infrastructure construction in the proximity of the coastlines and intensive groundwater exploitation may negatively contribute to the instability of the coastal cliffs, favoring and/or triggering ground instabilities. Eventually, the final result is the high vulnerability of coastal karst environment to a variety of interconnected geological hazards, with consequent high impact on the economy and society. In the last decades, the scientific community has paid increasing attention to coastal areas also due to the above reasons, since they are highly urbanized and populated, and attract a high number of tourists, especially during the summer season.

In this paper, a case study from Apulia (southern Italy) is presented to highlight the strong influence that geological and karst features may have in the development of ground instability processes, and in the coastline evolution as well.

CASE STUDY

The study area is located along the Adriatic coast of Apulia, between the provinces of Bari and Brindisi (Fig. 1), in one of the most touristic areas of the region. As concerns the geological setting, the Cretaceous limestone bedrock is overlain by Cenozoic calcarenites and by Quaternary marine terrace deposits (Vezzani, 1968; Cotecchia, 2014). The topography is controlled by structural discontinuities, mainly oriented in SW-NE direction. These structures are also reflected in the local toponym of the area, since the coast is formed by several small promontories and intervening bays: the toponym "Costa Merlata" means "merlon coast", with the rocky spurs resembling the merlons of a medieval castle. In this stretch of the Adriatic coastline, it is possible to observe important freshwater outflows, such as the main spa of central Apulia (Torre Canne spa), and several evidence of sinkholes, including recent ground collapses, located a few meters far from the coastline. Furthermore, different phases of sinkhole development are well documented, that can be described to highlight the evolution of this coastal stretch (see next sections).

The study area is characterized by the diffuse presence of karst features like ephemeral rivers (locally named lame; Parise *et alii*, 2003), caves, karst springs (Cotecchia, 2014, and references therein; Liso & Parise, 2020; Olarinoye *et alii*, 2020) and sinkholes (Vennari & Parise, 2022).

SEAWATER INTRUSION

Coastal plains are about 70% of the world's populated areas (Alfarrah and Walraevens, 2018), and many of these are in arid and semi-arid climates with insufficient surface water resources, leading to a critical dependence on groundwater (Miniabadi *et alii*, 2020; Vaux, 2011). Especially in karst settings, where water at the surface is scarce or absent, groundwater represents the only freshwater resource for locals; its intense exploitation significantly reduces the freshwater outflow to the sea and represents the most adverse effect in many coastal zones, promoting seawater to migrate inland replacing the freshwater and causing groundwater contamination (Michael *et alii*, 2017; Tully *et alii*, 2019; Polemio & Zuffianò, 2020).

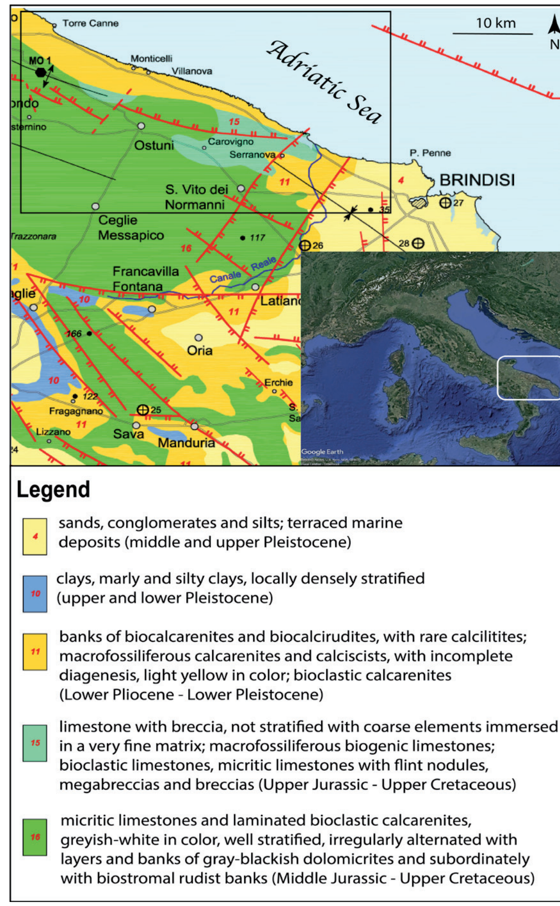

Fig. 1 - Study area location and geological details (mod. after Cotecchia, 2014)

Seawater intrusion in karst poses unique challenges due to the general high heterogeneity and transmissivity of the aquifers hosted in karstified rocks. The rapid movement of water through conduits and fractures facilitates the advancement of seawater inland, with significant implications for water resources availability, ecosystems, and communities that rely on these aquifers. Effective management strategies, such as monitoring groundwater quality and implementing measures to control over-pumping, are crucial in mitigating the impacts of seawater intrusion in karst environments (Hussain *et alii*, 2019).

As shown in figure 2, the coastal sector of Apulian groundwater is strongly affected by salinization, mostly in the Salento peninsula where the maximum groundwater head reaches only 5 m a.s.l. Flowing from inland areas toward the Adriatic and Ionian coastlines, groundwater outflows along the coast in both diffusive and concentrated ways (Fig. 3).

The sectors showing diffuse groundwater outflow are the most affected by seawater intrusion, that extends inland for some kilometers. This is mainly due to both natural and anthropogenic factors, including the effects related to climate changes like sea level rise and sea-storm energy increase.

Being the study area one of the main populated and attractive stretch of the Apulian coastline, the domestic, agricultural, and industrial water demands add to that from tourism, which is especially severe during the summer season. Hydrogeological investigations document a strong groundwater salinization ranging from 0,5 g/l to more than 5 g/l (Fidelibus & Tulipano, 2004). The area contaminated by salt fluctuates in space and time in function of the groundwater head and the sea-level, leading to salinization of large territories during the dry season due to the reduction of freshwater volume. This represents a serious issue for the local communities in terms of scarcity of freshwater.

Groundwater moves through a quite complex network of interconnected channels, possibly prone to collapse when close to the ground. In such complex settings, caves are direct windows on the water table, and represent ideal sites for the scientific research (Liso *et alii*, 2020; Parise *et alii*, 2020).

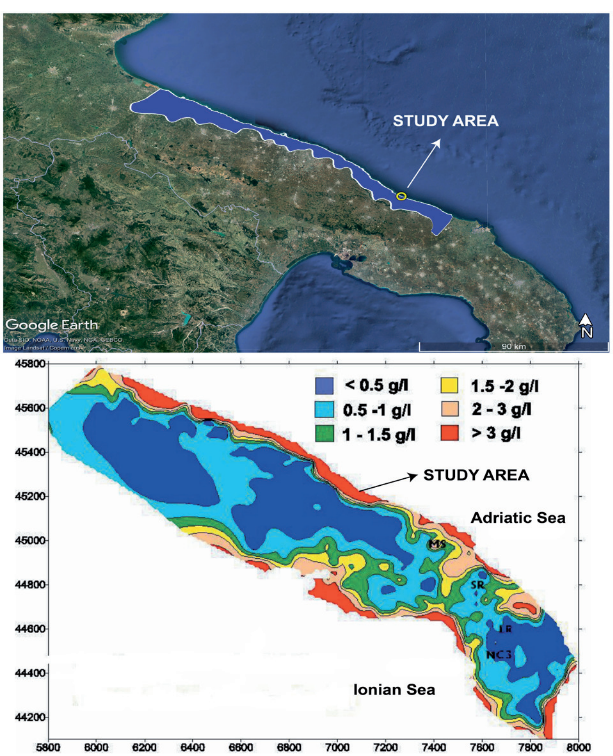

Fig. 2 - Above, coastal karst groundwater, almost entirely subjected to salinization. Below, distribution of groundwater salt content in the Apulian aquifers at 1989 (mod. after Fidelibus & Tulipano, 2004)

Fig. 3 - Karst springs and retro-dune lakes at Torre Canne. 1: Fiume Grande Spring; 2: Fiume Piccolo Spring; 3: Fiume Morello Spring

Direct groundwater monitoring, especially near the sea, offers a strategic point of view to perform investigation on the Ghyben-Herzberg interface fluctuation and to assess the degree of groundwater salinization. In addition to classical hydrogeological investigations, studying stygofauna, i.e. animal species living exclusively within groundwater, provides an additional valuable biological indicator for assessing seawater intrusion, since it is very susceptible to changes in the physio-chemical characteristics of water (Pipan & Culver, 2007; Sanchez-Fernandez *et alii*, 2021). Monitoring the response of stygofauna, i.e. changes in species diversity, abundance, and distribution can be used as indicators of seawater intrusion and may help scientists to gauge the extent of salinity changes, providing insights into the health of aquifers and potential consequences for ecosystems dependent on freshwater. At the study area, particularly at Grotta Puntore (PU_377 in the regional cadaster of natural caves, http://www.catasto.fspuglia.it), stygofauna monitoring is in progress. Being a coastal cave connected to the sea and filled with brackish water, Grotta Puntore can be described as an anchialine system. Located 500m far from the Adriatic coastline, it opens at 12 m a.s.l. as a collapse sinkhole, and consists of a single chamber, 20 m-wide and 12 m-deep, almost entirely filled with breakdown deposits, hosting a brackish water lake on its northern sector (Fig. 4). Outcomes from the first sampling campaigns (May, 2023) confirm the anchialine nature of the cave and suggest a biological environment entirely adapted at freshwater/saltwater transition zone (Galmarini *et alii*, 2023).

SINKHOLE EVOLUTION

Three different phases of sinkhole evolution can be pointed out to explain the current morphology of the coastline in the study area. The first stage (Fig. 5) consists of the opening of an individual sinkhole, as at Gorgognolo, where a single ground collapse developed about 15 m from the coastline. The following evolutional stage shows a typical situation at Torre Pozzella, where a large sinkhole opens inland, with presence of several other smaller sinkholes aligned between the main one and the bay.

Eventually, in the last stage of evolution, the likely coalescence of sinkholes creates well-developed bays, entering inland for some tens of meters; in such a context, the bay itself frequently produces protection from the direct arrival of sea waves, as at *Torre S. Sabina* (Fig. 5).

Fieldwork along the coast revealed many elliptical sinkholes whose major axes are preferentially oriented in a NE-SW direction (Fig. 6), roughly following the prevailing direction of the bays. This is the same orientation of the main regional tectonic trends, and of the ephemeral karst valleys (lame) as well. Therefore, the study area exhibits a strong control exerted by tectonic lineaments on development of karst landforms. Karst features like sinkholes, in turn, tend to be aligned following the tectonic direction, promoting the genesis of bays and inlets, through coalescence of sinkholes. This behavior has also been observed in other coastal stretches of Apulia, on both the Ionian (Bruno *et alii*, 2008) and the Adriatic side (Delle Rose & Parise, 2002).

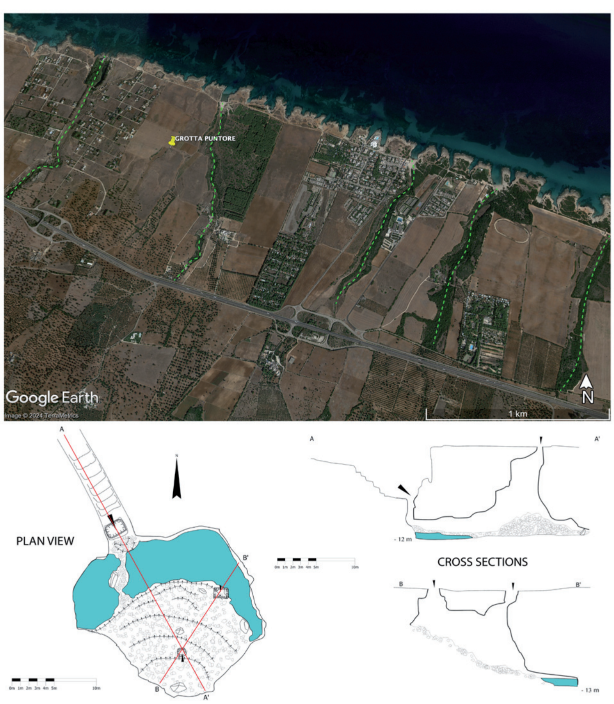

Fig. 4 - Above: Grotta Puntore location with respect to the coastline; green dotted lines represent the main traces of the ephemeral karst valles locally named "lame". Below: map view and cross sections of Grotta Puntore (mod. after survey by Gruppo Escursionistico Speleologico Ostunese – GEOS, on June 06, 2020); the light blue color highlights the brackish lake within the cave

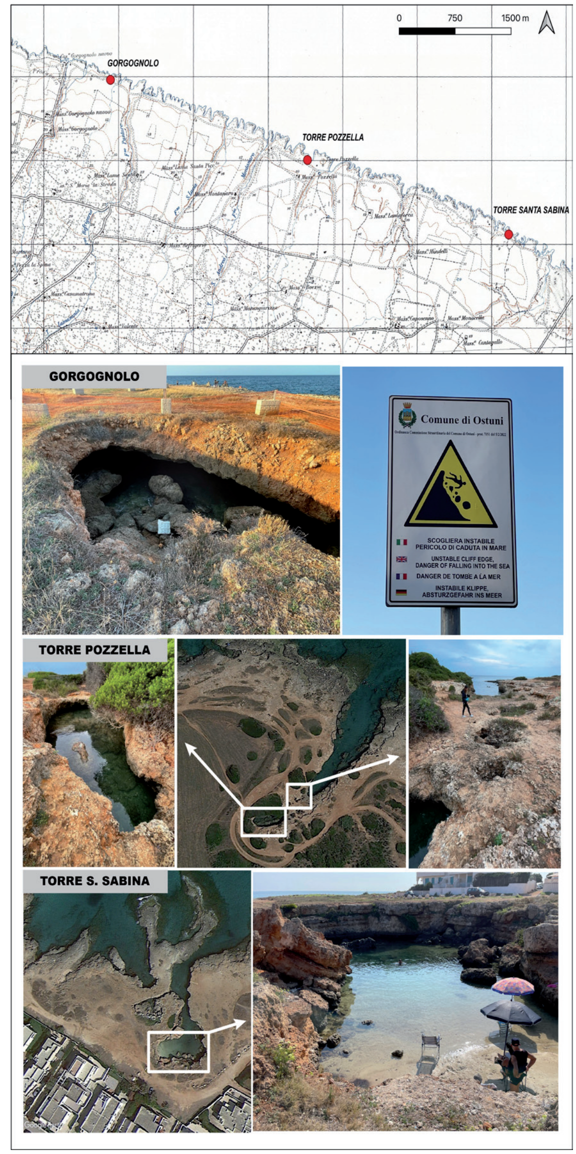

Fig. 5 - Above: topographic map of Costa Merlata area; below: details of sinkholes evolution stages at Gorgognolo (stage I), Torre Pozzella (stage II) and Torre Santa Sabina (stage III)

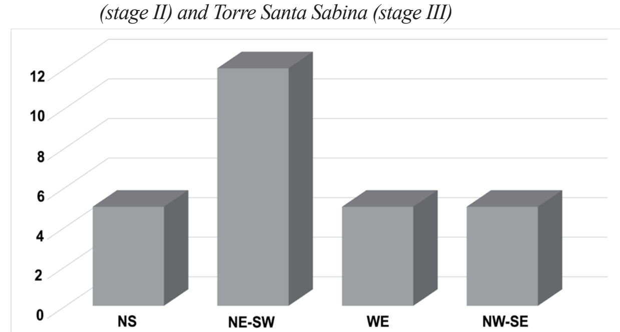

Fig. 6 - Graph showing the main orientation of sinkholes (sample of 27 significant and not circular sinkholes); data exclusively refer to the direction of the main axis for sinkholes of elliptical shape

CONCLUSIONS

Summarizing, figure 7 shows the location of all the karst features described throughout the manuscript like springs, sinkholes, and caves.

Fig. 7 - Map of Costa Merlata with location of analyzed springs (Fiume Grande, Fiume Piccolo and Fiume Morello), sinkholes (Gorgognolo, Torre Pozzella, Torre Santa Sabina), and the Grotta Puntore cave

The case study here presented highlights the strong influence of karst processes in the geomorphological evolution of the land, especially at coastal zone, where the terrestrial, marine and anthropogenic processes synergically act, getting faster the evolution of the coast.

Ground instabilities like coastal landslides and ground collapses are frequent at such a setting, resulting in potential damage to infrastructure and property. Additionally, if the caves at the origin of the sinkholes are directly connected to the sea, their collapse may also impact the local water resources. The rapid cinematic and evolution associated to these two processes induce rapid changes and modification in the coastal setting, increasing vulnerability of the built-up areas as well.

Understanding the geology and evaluating the potential hazards associated with coastal sinkholes and landslides is therefore crucial for an effective land-use planning and for developing strategies addressed to risk mitigation. This is especially true in karst environment since the high vulnerability of underground freshwater resources to seawater intrusion, and the related high dissolution power exerted by brackish water on soluble rocks.

For all stated above and considering the effect of climate changes on water resources, the implementation of actions to protect and safeguard coastal groundwater have to be seriously implemented, to guarantee freshwater availability in the future.

Multidisciplinary studies, like this, may help managing authority in building proper land and water management plans, and in promoting local events for a correct behavior in karst settings, to increase awareness in local communities.

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