Apulian Karst Springs: A Review

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Abstract: Apulia (southeastern Italy) is an elongated peninsula, located between the Ionian and the Adriatic seas, characterized by a semi-arid climate. It is an almost entirely karst region, with very limited availability of surface freshwater resources. The groundwater, the only water resource of Apulia, is affected by severe pollution problems related to both antropogenic and seawater intrusion phenomena. This is further exacerbated by the strong tourist vocation of the area, with heavy pressure by touristic water demand, especially during summertime. The Apulian geography and related freshwater problems require a thorough knowledge about karst processes, with specific regard to springs and aquifers. Despite this, in recent decades the attention on regional karst water resources was quite limited, and there is the huge need to implement new research in this field, aimed at reaching a better understanding of the Apulian karst. In this work we present a review on the main Apulian karst springs, divided in the three main sub-karst areas (Gargano, Murge, and Salento), based upon critical revision of the existing scientific literature. The aims are to build a database of known karst springs, and, further, to highlight the widespread and remarkable presence of karst phenomena in the region.

Keywords: Karst, Spring, Aquifers, Water, Apulia.

INTRODUCTION: IMPORTANCE OF KARST GROUNDWATER

Karst aquifers are among the main reliable sources of global water supply, providing drinking water to almost a quarter of the world's population; this is due to the fact that karst lands cover about 14% of the total land surface on Earth, with some countries entirely depending upon karst as the main potable water source [1-4]. It is well known that the use of karst aquifers and springs has a long history and tradition. In ancient times, the 11 long aqueducts, serving the old city of Rome (Italy), delivered to the urban area over 13 m^3/s of spring water, from distances ranging from 16 to 91 km [5]. Similar hydraulic works, with significant underground development, were widespread all over Italy and in the rest of the Roman Empire as well [6], with many of them capturing water from karst springs. This long tradition is still working nowadays in many parts of Europe: for instance, the largest karst water supply system in Europe supplies the city of Vienna, mostly by karst groundwater [7].

In recent decades, stress on groundwater resources has significantly increased [8, 9], due to a variety of reasons including, but not being limited to, excessive number of irrigated farmlands [10], pollution by fertilizers and pesticides [11], and other anthropogenic and industrial actions [12-15].

There is high relevance of karst water for human supply, and an urgent need to safeguard the future karst water availability. Being extremely heterogeneous and anisotropic in their physics and hydraulic characteristics [9, 16-18], karst aquifers are very different from others, in terms of both evolution and hydrological behavior; they need specific exploration, monitoring techniques and modeling approaches as well. Among the main peculiarity of karst, the difficulty in delineating the areal extension of the hydrological catchments has to be considered [13, 19-22]: this results in greater complexity for hydrogeological studies, essentially due to lack of correspondence between topographic divides at the surface and the subterranean hydrogeological boundaries. In karst coastal areas, the situation is further complicated by the occurrence of saline intrusion problems, related to inland advancement of the transition area between brackish water and freshwater [23-28], often exhacerbated by anthropogenic actions such as overexploitation of the aquifers due to high tourist pressure during the summer season [29].

In recent years, several international efforts have been done to improve the knowledge about karst aquifers: the first was the production of the World Karst Aquifer Map (WOKAM), as a supplement to the existing map of Groundwater Resources of the World (WHYMAP) [30]. This map, which is the most updated document about karst aquifers in the world, shows the outcrop areas of carbonate and evaporite rocks, but also displays deep confined karst aquifers, large karst springs including thermal and mineral springs, drinking water abstraction sites, and selected caves [31-34]. Further, a collection of karst springs hydrographs and data (World Karst Spring hydrograph, WoKaS)

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widespread around the world was recently published [35].

In Apulia (southeastern Italy) Cretaceous limestones crop out in a very high percentage of the regional territory. Over than 4 milions of Apulian inhabitants depend for water supply by nearby regions: the Caposele spring (discharge greater than 4 m^3/sec), located in the Picentini Mountains (Campania) is the main source feeding the Acquedotto Pugliese.

Given relevance of the issue of karst aquifers, and the need to have available as much information as possible on karst aquifers worldwide, in this work we present a review of the main karst springs in Apulia (Figure **1**), providing the basic data for the different karst sectors of the region.

THE APULIAN KARST

Apulia represents the outcropping sector of the south Apennines Foreland, connected to the Late Oligocene - Early Pleistocene westward subduction of the Adria Plate underneath the Apennine Chain [36, 37, 38, 39]. The Apulian Foreland corresponds to a wide WNW-ESE trending antiform [40, 41], produced by buckling of the subducting slab. The monoclinal structure, gently dipping to the SE, is subdivided by high dip, mostly NW-SE striking, faults into uplifted and lowered blocks [42-45]. It represents the less uplifted block and shows the lowest topographic relief, where the overall carbonate sedimentary succession of Apulia crops out, consisting of 3 to 5 km thick Jurassic-Cretaceous limestones and dolostones, unconformably overlain by Palaeogene to Neogene calcarenites and calcirudites, eventually capped by Quaternary terraced marine calcarenites. Since the Lower Pleistocene the whole region was interested by a general uplifting, until it reached the present configuration [46]. It has to be pointed out that, in the present work, we deal exclusively with the karst sectors of Apulia, not taking into account the Daunia Apennine (that is, the inland area at the contact with the inner Southern Italian Apennines) and the Bradano plain, at the SW boundary with Basilicata Region.

Overall, Apulia is a NW-SE elongated peninsula, and includes three main karst sub-areas (Figure **1**): from N to S, the Gargano promontory (where the highest elevations, over 1000 m a.s.l., are reached), the Murge plateau, and Salento.

Morphology of the Gargano Promontory is mostly controlled by E-W and NW-SE-trending faults [43, 45, 47]. Karst is well-developed over the entire area, with a multitude of sinkholes, reaching a maximum density of up to 100 per square kilometer [48-50]. Due to widespread outcroppings of soluble rocks [51], surface

Figure 1: Location map of Apulia, with indication of the karst springs.

hydrography is limited to a few, short, ephemeral drainages along the slopes bounding the elevated central plateau and to minor drainages in the alluvial and coastal plains surrounding the promontory.

The Lesina and Varano coastal lakes separate the northern side of the promontory from the sea. In the Gargano sub-karst area, elevation ranges from sea level to 1056 m a.s.l. with a mean value of about 400 m, and morphology is controlled by E–W and NW–SE-trending faults [43, 47]. The promontory hosts the Gargano National Park and towns and villages that collectively represent an important touristic area and a significant economic resource.

Murge is the main karst area in central Apulia, extending some tens of kilometers inland from the Adriatic coastline, and is typically subdivided into High Murge, and Low Murge. The first one is the upper portion of the plateau, at elevations between 400 and 679 m a.s.l., limited by clear step-like scarps on the SW edge. This plateau was an island in the Plio-Pleistocene sea, which experienced multi-stage karst processes that led to development of polygonal karst landscape [49, 52], showing remnants of fluvio-karst landforms and features such as valleys of different sizes and development, dolines, endhoreic basins, and caves. Dolines are often concentrated in doline fields, or they coalesce into a single landform, thus indicating their likely genesis in a low relief cockpit karst [52]. Over such landscape, developed in Upper Tertiary, a hydrographic pattern was superimposed, that partly opened some of the depressions, also dismantling sectors of the karst relief and producing talus deposits [53]. As in the other sectors of Apulian karst, the spatial distribution of dolines is clearly controlled by the pattern of the main tectonic discontinuities [54, 55]. The largest dolines belong to the collapse or cover-collapse type (see [56, 57]): these include, among the others, the Altamura Pulo and the Gravina Pulicchio (Pulo and Pulicchio are local terms to descrive deep karst depressions; [58]).

Moving toward the sea, the karst morphology becomes smoother in the Low Murge, where, however, some remarkable features are present, as the 12 km-long Canale di Pirro polje: this is the site where the deepest cave of Apulia was recently discovered, reaching the water table at depth of -264 m from the topographic surface [59, 60]. Even though the possibility of water accumulation at the surface is extremely remote in this setting, perennial or temporary lakes can be identified in Low Murge, typically hosted at the bottom of dolines and slight depressions, where silty clays to silty sands infillings are present [61, 62].

The Salento peninsula, hosting the southernmost carbonate block of the region, is entirely modeled by karst processes, and strongly affected by doline development, involving not only the Cretaceous limestone bedrock, but also the overlying Tertiary and Quaternary clastic carbonates [54, 63-66]. Starting from the Early Triassic, the area was part of the Apulian carbonate platform, characterized by shallow-water carbonate sedimentation [36]. Since Cretaceous times, it experienced a number of transgression–regression phases, giving rise to a succession constituted by multiple unconformities. Eventually, during the Middle Pleistocene, the area underwent a severe regional uplift [46]. Salento is characterized by the presence of wide marshlands in proximity of the coasts [67], diffuse coastal springs and caves, and a large number of swallow holes, that are sites where rapid infiltration of rainwater occurs undergound, recharging the karst aquifers. Because of the geological configuration, low topography, and due to overexploitation of the underground water resource for agricultural purposes, the Salento peninsula is definitely the sector most strongly affected by seawater intrusion phenomena, making brackish a wide sector extending inland for some kilometers [28, 29, 68-73].

KARST SPRINGS IN APULIA

Overall, Apulian karst springs have a total discharge of some 20 m^3/s (6 m^3/s in Gargano, 8 m^3/s in Murgia, the Brindisi Plain and the Ionian Arc, and 6 m^3/s in Salento) [28]. This total discharge corresponds to about 1/5 of the estimated recharge to Apulian water tables, which highlights the presence of a significant amount, not yet quantified, of water coming out along the coasts. Discharge to the sea typically occurs in diffuse way along wide stretches of the coastlines, through karst conduits showing also significant differences (in terms of conductivity, T, etc.) in the main hydrological parameters of the emerging waters [74, 75]. While submarine springs can be identified at variable distance from the shoreline, estavelle are located in its proximity, as a function of the morphology of both coast and tides, that determine alternating behaviour in functioning as springs or swallow holes.

Apulian coastal springs derive from emergence of the water table hosted within the karstified Mesozoic carbonate rocks; contribution from infiltrating water is only partial. Further, they are strongly exposed to seawater intrusion phenomena [69, 73, 74]. The high diffusion of submarine springs in Apulia was the main outcome of multi-spectral aerial surveys (visible, infrared and thermal infrared), carried out in the 1970's [28, 76] along 390 km of the coastlines. 245 thermal anomalies were detected, due to differences in temperatures between spring water and seawater. Among these, 170 were attributed to springs, while the remaining were likely linked to water courses or anthropogenic discharges.

In Apulia, inland karst springs are very rare, and show limited discharge. They are generally linked to Quaternary deposits with low permeability layers covering the bedrock, a situation locally resulting in small perched water tables, that contributed to foundation of some urban centers.

As concerns the main karst spring classification [1, 77-79] Apulian emergences can be subdivided into the following categories:

- *Free draining springs*: groundwater is drained in free conditions through springs coming out at sea level, or along the bedding planes and joints within the outcropping carbonate rock mass. In some cases, close to the coastline, the high degree of limestone fracturing forces the water table to reach the sea level before the shoreline, and springs emerge inland, again in free draining conditions.
- *Dammed springs*: the flow toward the sea does not occur in free draining conditions but is rather controlled by presence, near the coastline, of massive carbonates and/or low-permeability Quaternary deposits, overlying the permeable carbonate rock mass.
- *Submarine springs*: situation similar to the previous one; in this case, however, the impermeable cover has not significant thickness, so that the water table keeps moving toward the sea, beyond the coastline, and comes out along discontinuities in the impervious cover (this type of spring is locally known as *citro*, and is characterized by ascending column of water, producing at the surface a sub-rounded shape turbulence).

The main regional karst springs have a quite stable regime, with moderate variation in discharge, despite the irregularities in the pluviometric regime. This is due to both large size of the catchments and storage capacity of the aquifer. They typically show brackish water, and a typical chemistry of the mixing of seawater and a chlorine-alcaline facies, accompanied by clear prevalence of Mg and solphates over Ca and bicarbonates. Large part of the springs show temperatures in the range 16 - 20°C; only locally, lower temperatures are recorded (for instance, at some springs in Gargano), probably related to lack of thermal influence of the seawater on the overlying freshwater. Higher temperatures, on the other hand, are registered at S. Nazario spring in Gargano and at Santa Cesarea Terme springs in Salento.

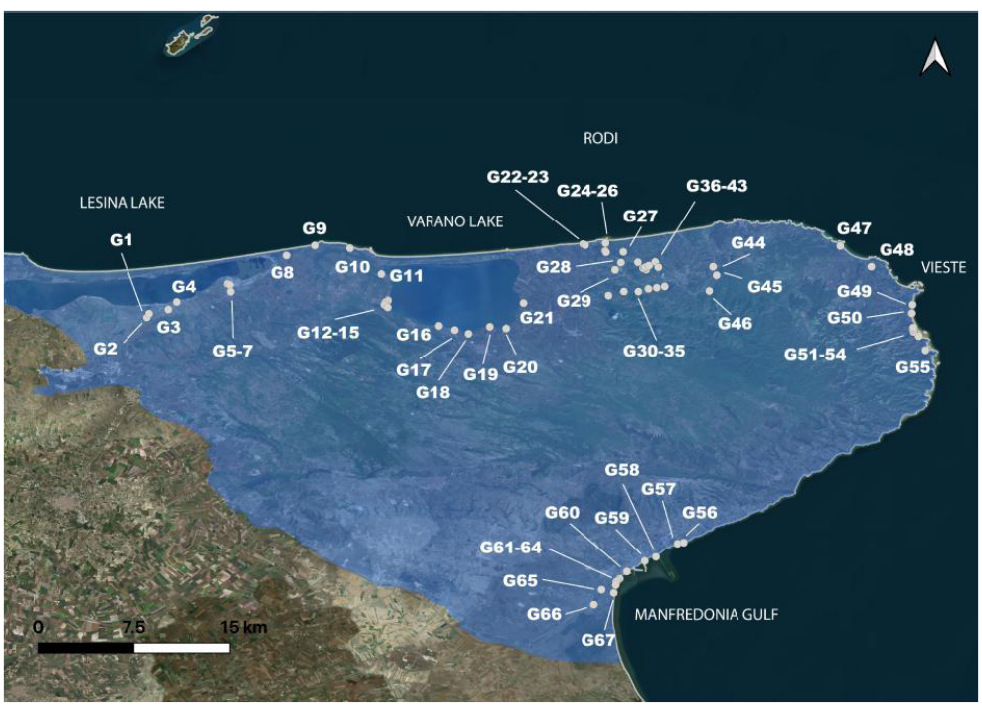

Figure 2: Karst springs of Gargano. Spring labels refer to Table 1.

SPRING DISTRIBUTION AND FEATURES

Gargano Sub-Karst Area

Gargano karst springs (Figure **2**, Table **1**) are located along the SE rims of the two lakes Lesina (average total discharge: about 2.000 l/s) and Varano (1.500 l/s), between Vieste and Testa del Gargano (1.500 l/s) and at Manfredonia – Siponto (1.000 l/s). As concerns typology, several types of springs are present, mainly belonging to the dammed (confined) type, but also including free draining and submarine springs as well. In the confined type, the dam is typically represented by low permeability Quaternary deposits.

Table 1: Springs of Gargano Sub-Karst Area (Location shown in Figure 2)

ID	Spring Name	ID	Spring Name
G1	Caldoli	G35	Acqua del moroso
G2	San Nazario	G36	San Nicola I, II
G3	Mascolo	G37	Colaciocco
G4	Zanella	G38	Carnevale
G5	Mascione	G39	Montenero I
G6	Lauro	G40	Montenero II
G7	Canale alto	G41	Asciatizza I, II, III
G8	Milena	G42	Canneto
G9	Mileto	G43	Acqua D'Antra
G10	Calarossa	G44	Chirce
G11	Baresella	G45	Vasto
G12	San Nicola Varano 1	G46	San Giacomo
G13	San Nicola Varano 2	G47	La salata
G14	San Nicola Varano 3	G48	Molinello
G15	Fascia	G49	Scialara
G16	Valle Sant'Angelo	G50	Torre del ponte
G17	Costa del Pozzone	G51	Calcari
G18	Bagno	G52	Caruso
G19	Arancio - Orti di Tullio	G53	Lago Santa Chiara
G20	Fiumicello	G54	Torre porto - Nuovo
G21	Irchio	G55	Cala San Felice
G22	Santa Lucia	G56	Convento
G23	Santa Barbara	G57	Acque di Cristo
G24	Pincio	G58	San Pietro - Castello
G25	Ciccotonno	G59	Porto
G26	Mortero	G60	Molo - Orto delle brecce
G27	Soriense	G61	Conchiglia
G28	Galluccio	G62	Papa Orsini
G29	Fontana di Ischitella	G63	Foce canale
G30	San Francato	G64	Centrone
G31	Acque di Vezzaro	G65	Capparella
G32	Acqua del confine	G66	Gruppo S. ve - Siponto
G33	Acqua del prete	G67	Mascherone
G34	Maddalena		

The highest discharge springs are located at some distance from the coastline, and at few meters of elevation above the sea level: S. Nazario (2,1 km, 250 l/s), Lauro (1,75 km, 450 l/s), Centrone (0,7 km, 150 l/s). All these springs have saline concentration of about 2÷3g/l.

At the free draining springs between Vieste and Testa del Gargano, water rises mostly from the bedding planes of the rock mass, while at the Varano Lake borders, and at Manfredonia–Siponto, it comes out from sub-vertical fractures within the carbonates [80]. Saline contents are typically high, greater than 3 g/l, and up to 8÷9 g/l. Frequently, the freshwater comes out at sea, even at some distance from the coast, due to presence of impermeable or low-permeability deposits overlying the carbonate rock mass; this can be observed at the Varano lake, below which a freshwater circulation can be identified, and that is bounded by several ascending submarine springs.

Near Siponto, small subaerial springs come out close to the sea level, forming small surface channels going to the sea after crossing the beaches. They show a limited discharge, the most significant being Conchiglia and Foce Canale (100-130 l/s). Even at great distance from the shoreline, ascending submarine springs with high discharge are located S of Testa del Gargano, near Manfredonia, at the SE margins of Lesina Lake, and SW from Siponto (Mascherone km 1,3, 100 l/s; Caldoli km 1,28, 200 l/s; Mascolo km 1,0, 150 l/s; Milena km 0,8); the saline content is 2÷5 g/l.

At higher elevations, springs are present at Vico Ischitella (Asciatizza I and II, Canneto, Montenero I and II), showing a total discharge of about 150 l/s, very low saline content 0.3-0.4 g/l, and total lack of seawater influence [81]. This is a unique situation in Apulia, the aquifer showing an impervious surface at the base, constituted by the Cretaceous Scaglia Formation: this water table shows a chemistry derived only by circulation within the carbonates, without any contact with the intruding seawater.

In the following, we provide some details about the most significant karst springs of Gargano.

San Nazario

San Nazario is a dammed spring in the territory of Sannicandro Garganico, about 2 km from the Lesina Lake, at the contact between limestones and alluvial deposits, along an area of about 1000 m^2 (Figure **3**). After coming at the surface the water flow in a channel, before reaching the Lesina Lake. The saline concentration is greater than 2 g/l, due to mixing with seawater, and high temperatures (26-27°C) are registered in all seasons [82]. Actually, the different campaigns provided variable results: the discharge changes from some tens of litres per second to values higher than 300 l/s, with dry weight at 180°C between 2 and 4,3 g/l.

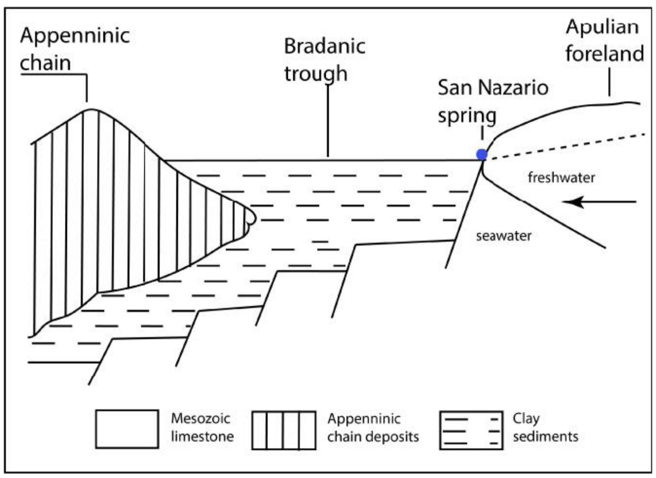

Figure 3: Sketch of the San Nazario spring in Gargano (modified after [129]).

Lauro

The Lauro spring (again at Sannicandro Garganico, 1,75 km far from the Lesina Lake) flows in the lake through a channel. It is fed by water emerging from fractures in the Cretaceous limestones at the contact with the overlying low-permeability Quaternary deposits. Discharge is about 450 l/s, but the last surveys indicate dispersion in the data. Salinity is high, about 3-5 g/l, due to marine intrusion, temperature is 16,8° C (March 2011 measurement [28]).

Irchio and Bagno

These are two free draining springs from the Mesozozic limestones around the Varano Lake, along a 1 km-long strip, at elevation not higher than 0,5 m a.s.l. Due to this low elevation, both springs significantly show high saline contents, in particular 2 g/l at Bagno, 4 g/l at Irchio, with water temperature at 14,1°C and 14,5°C, respectively. Close to the lake, the limestones dip below the impervious Quaternary calcarenite and alluvial deposits, which act as a dam. There are differences between the emergence conditions at the two springs: at Irchio, water comes out from joints in the Cretaceous limestone, whilst at Bagno it emerges from the few fractures affecting the Miocene calcareous sandstones, in turn taking water from the underlying Cretaceous aquifer. The most recent measurements point out to a decrease in discharge at Irchio, accompanied by a sensible salinity increase. Small tapping works have been realized at both the springs.

Caruso

Caruso spring consists of many small emergences about 5 km S of Vieste, at the foothills of two mountain ridges transversal to the beach. Water flows inside two channels, bounding the rock ridges, that merge in a single channel near the tip of the southern ridge. A significant difference in salinity content is observed in the channels: 7 g/l (T=18,6°C) in the first one, and 8,4 g/l (T=19,8°C) in the second, to testify a higher degree of mixing with seawater. Discharge sensibly decreased from values higher than 250 l/s in the 1950s, to lower than 50 l/s in the last years. It seems the spring is disappearing, which is also confirmed by values of dry weight and the Schoeller chart, showing an increasing effect of seawater intrusion [28].

Murge Sub-Karst Area

Table 2: Springs of Murge Sub-Karst Area (Location Shown in Figure 4)

ID	Spring Name
M1	Collettore sinistro Trani
M2	Collettore destro Trani
M3	Vasca di Trani
M4	Corratoio
M5	Fiume Grande
M6	Fiume Piccolo
M7	Fiume Morello
M8	Cervarolo
M9	Chiaradonna and Gruppo sorgivo Stornara
M10	Follerato
M11	Speziale
M12	Matrice
M13	Fontana calza
M14	Chiatona

M15	Patemisco
M16	Tara
M17	Galeso (citro)
M18	Galese
M19	Marangio
M20	Lavandaia
M21	Battentieri
M22	Riso

Along the Adriatic side of the Murge plateau, the geological conditions show wide stretches of outcropping limestones, hosting the main freshwater table, and characterized by diffuse fracturing in the rock mass, thus allowing the occurrence of several free draining springs. Locally, occurrence of concentrated, significant, springs may be encountered too, due to particular geo-structural conditions. As before mentioned, it must be stressed that many submarine springs, still unknown, are present along the coastlines. Three main zones of interest can be identified for karst springs (Figure **4**; Table **2**), the first one being located N of Bari, at Trani, the second in the Fasano area between Bari and Brindisi, and the third near the Gulf of Taranto.

Between Barletta and Trani, the springs, named Right and Left Collector of the Trani Reclamation, come out in an area originally known as “The Marshes”, since emergence of the water table formed wide marshlands (a situation very common along many sectors of Apulian coastlines; see [67]). A system of channels, built following the natural slopes, was therefore realized to reclaim the site. Available discharge measurements for the Right Collector spring indicate a constant discharge of around 500 l/s. However, recent surveys highlighted very different values, with maximum greater than 2.000 l/s, and saline content in the order of 3÷5 g/l (that is, with significant influence of marine ingression).

Not far from these springs, the Vasca di Trani originates from the water of many emergences in a wide depression close to the sea, partly occupied by marsh vegetation. The water flows as small courses, then merging into a natural channel, reaching the sea after 150 m. Discharge is in the range 150÷200 l/s (maximum greater than 300 l/s, minimum about 100 l/s). The dry weight at 180°C, in the order of 4 g/l, indicates a significant marine influence.

In the Fasano area, along a 1 km-long stretch of coastline, three main springs are present.

Morello River (Figure **5**) and Piccolo River are two dammed springs, originated by fossil dunes deposited over the Cretaceous limestones during the last post-glacial transgression, and partially covered by the present dunes (Figures **6** and **7**). Such line, obstructing the natural groundwater flow to the sea, causes the water to emerge along a trend parallel to the coastline.

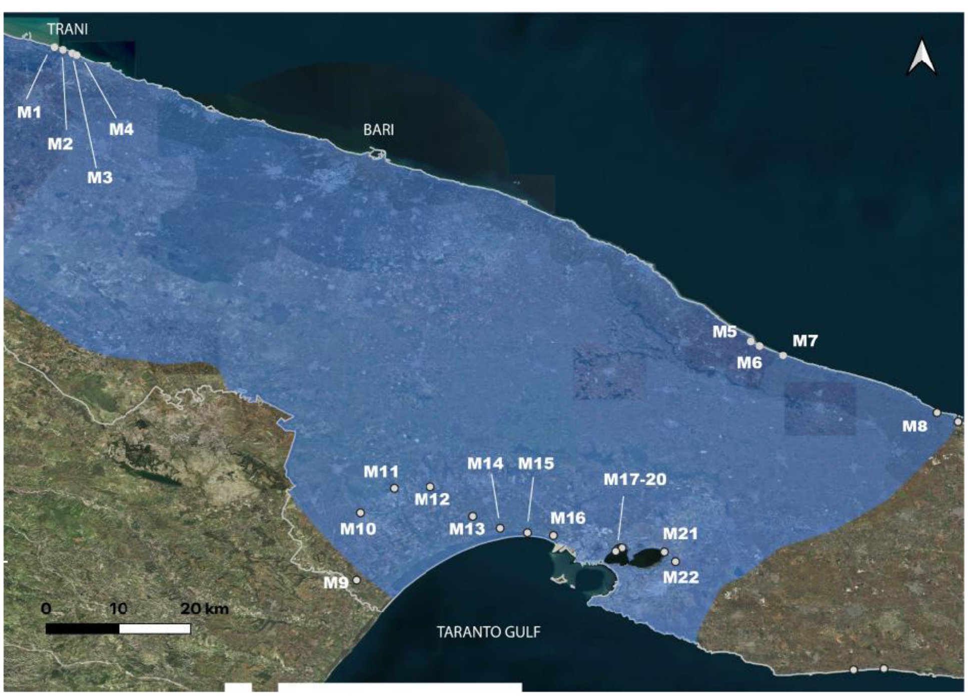

Figure 4: Karst springs of Murge. Spring labels refer to Table 2.

Figure 5: Bird's eye view of the Morello River (after [130]).

The discharges are about similar at both the springs (in average 300÷400 l/s), even though available data are quite variable, and a significant reduction was recently observed at Morello River. Both springs show a very high saline contamination, with salinity content up to 20 g/l.

The third spring is Grande River. Notwithstanding the proximity to the previous two, it shows very different ways of outflow. In this case, stretches of Cretaceous limestones, covered by paleosoils and present beach deposits, crop out along the coast. High fracturing in the rock mass allows a strong concentration of the outflows, thus causing the lowering of water table to the sea level before reaching the coastline. Spring water, once emerged at the surface, go to the sea through a man-made channel. Discharge is here greater, averaging 600 l/s, with maximum peaks slightly lower than 1.200 l/s. The chemical features are strongly influenced by marine intrusion. A progressive reduction in the water quality at the spring has been recorded at least for the last 30 years.

The other sector of high hydrogeological interest, in the sub-karst area of Murge, is its southwestern part, degrading toward the Gulf of Taranto (Figure **8**). As a

Figure 6: Pictures along the coastal area of emergence of the Morello River.

Figure 7: Pictures of the main spring area at Piccolo River, near Fasano.

matter of fact, in the Ionian Arc the carbonate rock mass dips to the SW with a block structure, and is overlain by impervious calcarenites and clays of Calabrian age. When the thickness of the latter deposits below sea level becomes significant, there is the occurrence of subaerial dammed springs (Tara, Galese, Battentieri, Riso, Lavandaia, Marangio, Patemisco). In case of limited thickness, on the other hand, water keeps flowing and, due to the high hydraulic heads, ascending submarine springs are produced (they are locally named *citri*, and are typical of the Mar Piccolo, close to Taranto). Piezometric data (Figure **8**) clearly indicate the existence of a N-S subterranean hydrogeological divide, separating the water feeding the Tara spring (from the carbonate rock mass W of the divide) from the subaerial and submarine springs in the Mar Piccolo, mainly fed by the carbonates located to the E [82-84].

Galese

Galese is a dammed spring in a wide depression between a province road and the railway, about 1 km N from Mar Piccolo. The main emergences form a small lake, which water slowly flows toward Mar Piccolo. The spring originates from the water table in the Cretaceous limestones that, dammed in their flow by the overlying clays, come out from the discontinuities in the rock mass, until elevation of 1.6 m above sea level. Discharge is about 400÷600 l/s, with the last measurements indicating much higher values (up to 1.400 l/s); this was also observed for the dry weight at 180°C; in the 1950s it was about 1,7 g/l, whilst later it reached values of 3÷3,5 g/l.

Tara

Within the Taranto area, the most important spring is definitely Tara. It is located about 7 km NW from the

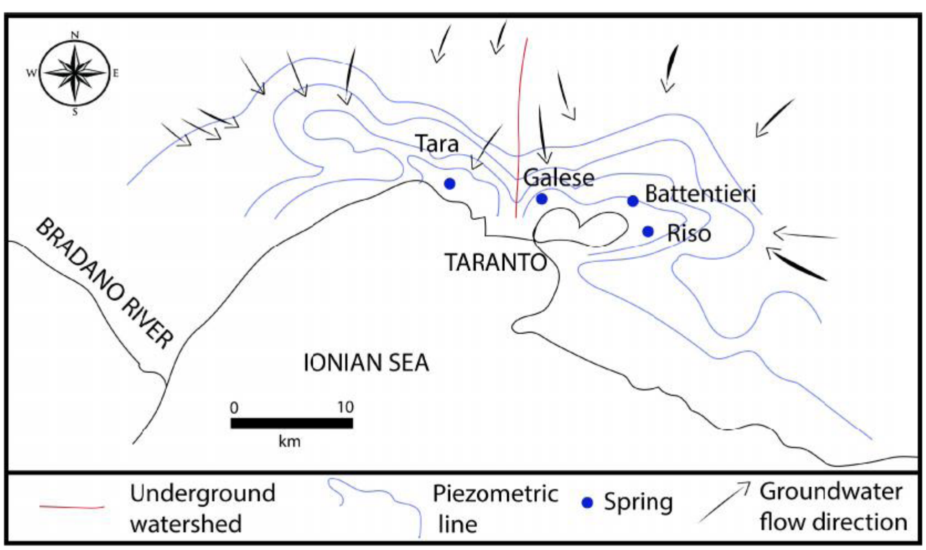

Figure 8: Piezometric lines around the Gulf of Taranto, showing the groundwater watershed separating the flow emerging at Tara spring from that to the east (redrawn and modified after [82]).

city, and consists of many freshwater spill points, locally named *polle*, fed from the Cretaceous aquifer, then flowing in a natural perennial water course (Tara river), reaching the Ionian Sea after a winding route of some 3 km. Tara maximum discharge is > 4.000 l/s, with values of saline concentration of 2 g/l [84-87]. Given the good quality (small salt concentration) of this water spring, it has been used, since the 1950s, for agricultural and industrial purposes. Hydraulic works on the Tara River and a derivation channel were built to bring the spring water to a rising plant, and from here to a distribution site. This plant started to work in 1951 [87], and today provides water for a maximum discharge of 2.000 l/s.

The area of the Tara spring is characterized by SSW-dipping Cretaceous limestones, unconformably overlain by Calabrian marine sedimentary deposits of the Bradanic Trough, and by Pleistocene and recent transgressive deposits: Gravina Calcarenite, in thickness < 10 m; 3-4 m thick clay marls passing to silts with sands (Subapennine Clays); calcarenites, sands, and gravel sands (post-Calabrian terraced marine deposits); recent terrains (marsh and alluvial deposits, dunes and actual beaches) [84, 87, 88]. Due to the overall structural setting, the roof of the carbonate, progressively deepening toward the coast, is covered by an increasing thickness of Subapennine Clays, in turn covered by the most recent deposits.

From a morphological standpoint, the area corresponds to a surface slightly inclined toward the Ionian Sea, degrading from inland elevations of about 70 m a.s.l. through a series of flat-lying surfaces connected by small winding scarps, with trend about parallel to the coastline.

The Cretaceous limestones host the groundwater that flows from the SW sectors of Murge toward the Ionian Arc. In the area of Tara spring, a topographic depression marks the sector where the Subapennine Clays have limited thickness or are not present. Being under pressure, water comes out in two groups, at elevations ranging from 3,5 - 1,5 m a.s.l. [88]. The first group is within the main spring area, extending about 1 km^2 and corresponding to a deep incision; the second group is in the NW area, from where the spring water reaches the Patemisco channel, flowing in the Ionian Sea, about 5 km W from the outlet of the Tara River. It has a discharge ranging from few tens of liters per second to about 250 l/s [84]. Discharge changes as a function of both the hydrogeological conditions of the water table and the tides (these latter working on both the piezometric values of water table and river levels). Further, a slight subterranean circulation is present in the area, substained at the base by the Subapennine Clays, and contained within the deposits permeable for porosity. The Cretaceous aquifer is affected by marine intrusion, with freshwater, feeding the Tara spring, floating over the seawater. Mixing between the twos is responsible of the significant saline concentration of the springs.

The first monitoring actions at Tara were performed in the period 1926÷1954 [82, 85, 87], resulting in minimum discharge of about 2.500 l/s and maximum of 4.300 l/s. It has to be pointed out that, being the Tara River a tide channel, its discharge variations cannot always be related to the rainfalls [85]. Significant differences have been appreciated between the discharge at different sites, meaning that the water extracted from the uprising plant only partly comes from the Tara and that the derivation channel collects, along its path, further significant water contributions. The overall hydraulic system is of high complexity, as demonstrated by the reversal in the water flow direction, in function of the amount of water extracted by the uprising plant.

The chemical-physical parameters of the Tara spring water is in agreement with those of the water table: the saline concentration shows variations between 1,5÷3 g/l, to be linked to modifications in the balance between freshwater and the underlying seawater. Chemistry is highly variable: the first available measure of dry weight, dating back to 1952, gave value of 1,7 g/l, whilst the last (2007÷2010) provided higher values, between 2,42÷2,95 g/l. Salinity measurements at the derivation channel in the period 1968÷1978 resulted in significant variability, in the range 1,7÷2,2 g/l [84, 89]. It appears extremely difficult to interpret the data, due to their discontinuity in time; further, in some cases the precise location of the measurements is unknown. Nevertheless, based upon comparison among salinometric logs and piezometric monitoring in the period 1995-2007, an aquifer overexploitation seems to have occurred. This might be due to the presence of a very high number of drilled wells (10 to 100 wells per km^2, for which it is not possible to estimate the overall amount of withdrawn water) in the area upstream from the spring [84].

Citro Galeso

As before mentioned, the word *citro* is locally used to indicate submarine springs, typically concentrated in the Taranto Gulf (Figure **9**). The use of terms derived from the local dialect is very common in Apulian karst, with a variety of terms, often changing from area to

Figure 9: Springs in the Mar Piccolo of Taranto: to the left, the emergence of one of the main citri; to the right, a channel collecting water emerging from several springs.

Figure 10: The Battendieri spring, along the shore of the Taranto Gulf: above, a general view of the area, showing the buildings used for wool manufacture; below, the channel linking the area of water emergencies to the sea (left) and inner view of the tank for wool manufacture (right).

area in function of the linguistic differences among the spoken dialects [58]. The Citro Galeso is located in Mar Piccolo, about 250 m from the shoreline, at 18 m below sea level, and has discharge of 800 l/s. It is visible at the surface due to the ascending column of water. The submarine spring consists of a main opening with high discharge, and of several other minor karst water spills, distributed along the flanks and bottom of a wide funnel-shaped depression, about 18-20 m-wide.

Water flux velocity measurements, at the main opening, provided average values in the range 0,85 - 0,95 m/s. It represents an important resource, quite brackish, nowadays not used but with sure potential, giving water with saline concentration on the order of 4,0 g/l [90].

Battentieri

The Battentieri spring opens along the eastern margin of Mar Piccolo, in a small depression some hundreds of meters from the shore (Figure **10**). It consists of several karst water emergences widespread over a large area. The spring water presents high salinity values, and for this reason it is not usable for human purposes. The discharge is highly variable, with maximum value of 300 l/s.

Riso

The Riso spring is located E of Mar Piccolo. The emergences feeding the springs are grouped in a wide area of about 1500 m^2. Discharge values are variable in time: from 30÷100 l/s in the 1920s, to 100÷120 l/s in the 1930s, to lower values again in the 1940s÷50s. Even recently, discharge measurements changed from about 0 to 130 l/s. These variations are not easy to be interpreted, also because the salinity seems to have increased during the last 20 years.

Salento sub-karst area

Table 3: Springs of Salento Sub-Karst Area (Location Shown in Figure 11)

ID	Spring Name
S1	Pozzella
S2	Lapani
S3	Siedi
S4	Idume
S5	Giammateo
S6	Acquatina
S7	Santa Cesarea Terme
S8	Chidro
S9	Boraco

In the Salento peninsula, the southern sub-karst area of Apulia, the karst springs are mostly located along the Adriatic coast (Figure **11**, Table **3**), the only exceptions being represented by the Santa Cesarea Terme springs (isolated along the southeastern sector of the peninsula) and the Chidro and Boraco on the Ionian side.

Salento is a remarkable area as concerns biodiversity in cave water environment, hosting many peculiar species and stygofauna that is of high interest

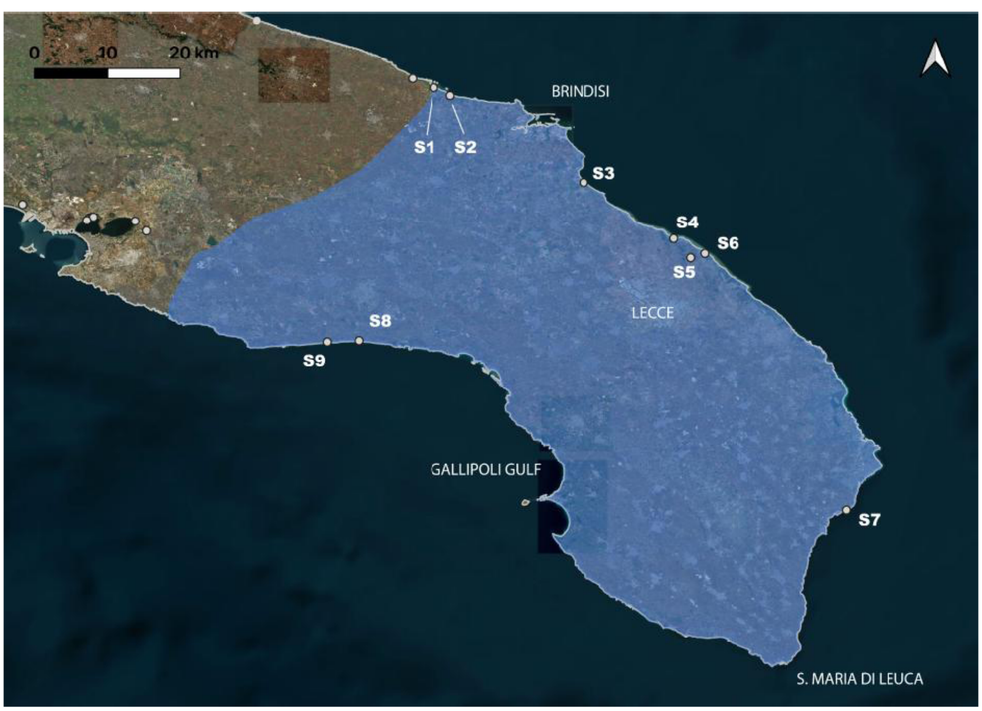

Figure 11: Karst springs of Salento. Spring labels refer to Table 3.

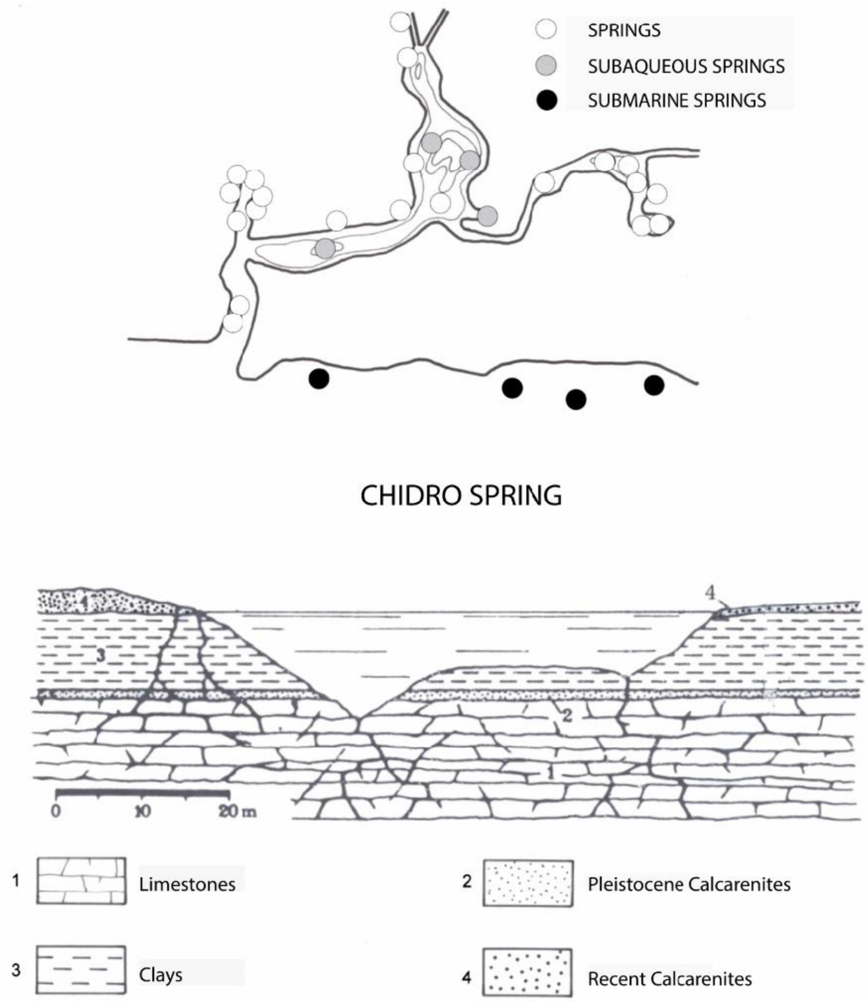

Figure 12: Sketch of the Chidro spring (modified after [127]).

for scientists [91]. Studying the stygofauna from wells and caves in Salento is providing very useful information about biodiversity and quality of water in karst aquifers because many species are markers of unpolluted environment [92-95].

Idume

At the Adriatic coastline of Salento, about 12,5 km N from Lecce, the Idume spring (Figure **13**) consists of several water emergences, flowing toward the Adriatic Sea, with a discharge of 1000 l/s and high saline

Figure 13: View to the north of the Idume River, along the Adriatic coast NE of Lecce, in Salento: from left to right, the emergences area and the sand beach.

Figure 14: The basin at Acquatina, along the Adriatic coast.

content, variable in function of the sea level oscillations. For a long time, spring water occupied a wide marshland, as typical along this stretch of coast (see also the Acquatina area; Figure **14**) which was reclaimed and collected in the channels Rauccio, Fetida and Gelsi, then merging in a single channel, about 300 m-long, called Idume River [67, 96]. From a hydrogeological standpoint, the area was object of many survey campaigns, the first measurements going back to 1920s, showing a discharge in the range 750÷1650 l/s. Higher values were recorded in the period 1946÷1952, with maximum greater than 2000 l/s, while the most recent measurements indicate definitely lower values, below 1200 l/s. Dry weight at 180°C is highly variable, ranging from 2,5 and 11-12 g/l. There is a clear influence of marine intrusion, causing a chlorine-alkaline facies.

Groundwater circulation in this stretch of the Apulian coast is very complex, due to presence of two distinct water tables: the first is contained within the Cretaceous calcareous and calcareous-dolomitic rock masses; whilst the other, closer to the surface, is within the permeable post-Cretaceous rocks. The twos are separated by a thick, practically impervious, Miocene calcarenite-marly level, sustaining the superficial water table at the bottom; the deeper water table floats over the seawater of continental intrusion [68, 97, 98]. Idume spring apparently drains the water of the superficial water table, but the high and variable salinity, together with the high discharges, let to hypothesize a significant contribution from deeper sectors as well.

The draining capacity of the channels is strictly linked to the periodic and aperiodic variations of the sea level, causing changes in the hydraulic heads at the emergences, and conditioning the free outflow to the sea (Figure **15**). The maximum discharge measured in low tide condition is 1.180 l/s at the outflow channel (the other channels had in the same period discharges of 1.068 and 127 l/s); in high tide the discharges were slightly lower: 1.039 l/s at the outflow, 1.008 l/s at Rauccio and 76 l/s at Grande.

All groundwaters are affected by seawater contamination, with particular regard to the Idume spring. Saline content, measured in some boreholes, revealed a saline stratification also for the superficial water table, with salinity values ranging from 0,3 to 2 g/l. The direct ingression of seawater in the permeable post-Cretaceous rocks reaches a maximum distance of about 500 m from the coast. As concerns the deeper water table, salinity measures in boreholes reaching the Cretaceous limestones show that thickness of the water table, measured from the phreatic surface to the roof of the transition zone (this latter being about 30 m-thick), decreases gradually from 64 m, until becoming null at a distance of 1,5 km from the sea; at shorter distances, the Cretaceous aquifer contains only seawater.

Santa Cesarea Terme

The sulfur-rich caves at Santa Cesarea Terme (SCT), in southeastern Apulia, are hosted in upper Cretaceous micritic limestones and dolostones, resting above Late Triassic evaporites and unconformably overlain by Cenozoic calcareous successions [42, 51, 99, 100]. The system consists of four caves, developed along a 500 m-long stretch of the Adriatic coastline [101, 102]. As concerns the geological-structural setting, the SCT area shows extensional and trans-tensional structures, with related pull-apart features: the NW–SE trans-tensional faults are the most diffuse

Figure 15: The River Idume flowing to the Adriatic Sea.

and appear to be the youngest system [103], that controlled the development of the main surface and subsurface karst landforms in the area [55, 104].

Known and described by several scholars since 1800 [105-108], and used as spa since the 1930s [109], the set of caves at SCT represents a significant tourist attraction in this sector of Apulia, and an important source of income for the local economy. In these environments, mixing of sulfuric acid and seawater occurs, producing sulfuric acid speleogenesis morphologies, and making this set among the best examples of caves of hypogenic origin (sensu [110-114]) in southern Italy [101, 115]. Saltwater strongly interacts with the freshwater not only along the halocline, but also inland, thus creating saltwater intrusion problems due to intense water withdrawal for agriculture and human settlements [116].

Water mixing [101, 117] is highlighted at the sea surface, in particular conditions of sea currents and winds, by white plumes coming out from the caves (Figure **16**). In the innermost part of the caves, sulfur-rich thermal water enters the caves from below. The cave enlargement occurred downstream of the sulfur springs, where the oxidation of hydrogen sulfide produces sulfuric acid that immediately reacts with the host rock replacing calcite with gypsum. This process appears to be active essentially above the water level, on the wet walls and ceiling. Dissolution rates, being monitored in recent years (October 2015 – present), indicate that dissolution at the water–air interface is faster in the median cave sector (where mixing between sea and deep water occurs), while dissolution in air is higher in the deeper part of the cave, where H_2S degassing is more abundant [101, 115, 118].

The SCT thermal water is distributed in the Na–Cl–SO_4 quadrant of the Ludwig–Langelier diagram, with pH ranging from 6.9 (when dominated by deep water) to 7.3 (mainly influenced by seawater–deep water mixing). Chemical–physical properties of water (ion chloride content, hydrogen, temperature, etc.) change essentially in function of the tides [119]. The deep water presents a very high salt concentration (58 g/L) and temperature of 22–33 °C. The high lithium content and the tritium concentration, ranging from 0.46 to 0.33 TU (lower than the present seawater, 2.2 TU) are clear indicators of very long residence time of groundwater in the aquifer [120]. This evidence, together with data from stable isotope analyses, suggests that the thermal springs appear to be at least partially fed by groundwater connected to a deep circulation system [103, 121].

So far, no accordance exists about origin of the springs, and several hypotheses have been presented [122-124]. The temperature values, several degrees higher than those of water coming from shallow sources, are probably due to the exothermic reaction of

Figure 16: White plumes of sulfur-rich water coming out of the thermal sulfuric acid speleogenesis caves at Santa Cesarea Terme.

sulfate contained in the seawater interacting with organic matter in the Miocene calcarenite layers [122, 123].

Sulfur-rich thermal water in Salento sub-karst area is not limited only to the SCT area, but it has been identified also at other sites, as on the Ionian coast near Ugento, where a well showed presence of sulfur water below a thick layer of Lower Pleistocene clays [125].

Chidro

After Tara, Chidro is the largest karst spring in Apulia. Located SE of Manduria, along the Ionian coast, it has an average discharge of 2600 l/s (reduced to 1000 l/s due to water table overexploitation). It consists of several sites where the water comes up to the surface, as subaerial springs, but also emerges below the water level in channels and tanks (subaqueous springs in Figure **12**) and at sea (Figure **12**). Among the different springs, there is great variability in salinity and discharge related to the tides [126-128]. Overall, a significant decrease in discharge has been observed over the years [28]. The water table is contained in the Cretacous limestone bedrock, that is overlain by a succession made of Pleistocene calcarenites and clays, eventually capped by recent calcarenites (Figure **12**). As in the nearby Boraco spring, location of the emergences is related to limited thickness along the coastline of the clay deposits, that were eventually broken by water in pressure coming from the underlying limestones (likely, also with the contribution of surface erosion, in turn producing lowering of the clay layer).

Boraco

Only 4 km away from Chidro, Boraco spring shows similar characteristics, both for modality of emergence, and hydrologic regime. Boraco is formed by two depressions, about 100 m apart, collecting the water of several emergences from the bottom, and transported to the sea by means of a channel [126, 127]. As concerns the discharge, there is a strong dispersion of data, which does not show the fall in discharge observed at Chidro [128]. On the contrary, an increase in discharge was observed in the period 2007÷2010, but the last surveys highlight a qualitative deterioration of the water [28].

FUTURE PERSPECTIVES

Apulia is worldwide known as a remarkable area for karst research, since its land is almost entirely karstic, and presents a significant number of karst caves, where many scientific activities have been carried out in the last years, with many others still ongoing. Nevertheless, knowledge about Apulian karst, with particular regard to karst aquifers and springs, definitely needs to be improved, especially as concerns continuous data monitoring, in order to better understand the recharge mode, transport and outflow in the different sectors of the region. It is worth to be noted that, after a systematic survey campaign, started in 1995÷1996, to assess the Apulian water springs quality, in the framework of the monitoring network of underground water ([28], and references therein), no other action was continuously conducted to collect availabile data on which to build a sound comprehension of the karst aquifers. Actually, this monitoring was later on abandoned by Apulia Region authorities, thus testifying the lack of attention paid by the administrators and decision-makers toward this really important issue. Given the climatic condition of the area, which often suffers from lack of superficial water resource and a limited amount of rainfall (thus resulting in limited karst groundwater natural recharge), it would be extremely important to facilitate further studies and research dedicated to data collection and analysis, aimed at promoting the development of good practices for protection and a sustainable use of the Apulian water resources.

REFERENCES

[1] Ford DC, Williams P. Karst hydrogeology and geomorphology. Wiley, Chichester 2007. https://doi.org/10.1002/9781118684986

[2] Kresic N. Water in karst. Management, vulnerability and restoration. McGraw Hill, New York 2013.

[3] Stevanović Z. Major springs of southeastern Europe and their utilization. In: Kresic N, Stevanović Z (eds) Groundwater hydrology of springs: engineering, theory, management and sustainability. Elsevier Inc. 2010, Burlington-Oxford: 389-410. https://doi.org/10.1016/B978-1-85617-502-9.00010-4

[4] Stevanovic Z. Karst water resources in a changing world: Karst waters in potable water supply: a global scale overview. Environmental Earth Sciences 2019; 78: 662. https://doi.org/10.1007/s12665-019-8670-9

[5] Lombardi L, Corazza A. L'acqua e la città in epoca antica. In: La Geologia di Roma, dal centro storico alla periferia. Memorie Servizio Geologico d'Italia 2008; 80: 189-219.

[6] Parise M, Galeazzi C, Germani C, Bixio R, Del Prete S, Sammarco M. The map of ancient underground aqueducts in Italy: updating of the project, and future perspectives. Proceedings of the International Congress in Artificial Cavities "Hypogea 2015", Rome, March 11-17, 2015: p. 235-243.

[7] Benischke R. Karst water resources of Austria, hydrogeological aspects and problems. In: Proceedings of the conf. "Karst 2018 Expect the Unexpected" 2018, 6-9 June 2018, Trebinje: 23-29.

[8] Wada Y, van Beek LPH, van Kempen CM, Reckman JWTM, Vasak S, Bierkens MFP. Global depletion of groundwater resources, Geophysical Research Letters 2010; 37: L20402. https://doi.org/10.1029/2010GL044571

[9] Hartmann A, Goldscheider N, Wagener T, Lange J, Weiler M. Karst water resources in a changing world: review of hydrological modeling approaches. Reviews of Geophysics 2014; 52: 218-242. https://doi.org/10.1002/2013RG000443

[10] Aeschbach-Hertig W, Gleeson T. Regional strategies for the accelerating global problem of groundwater depletion, Nat. Geosci. 2012; 5(12): 853-861. https://doi.org/10.1038/ngeo1617

[11] Foley JA, *et al*. Solutions for a cultivated planet. Nature 2011; 478(7369): 337-342. https://doi.org/10.1038/nature10452

[12] Gleeson TY, Wada M, Bierkens F, van Beek LP. Water balance of global aquifers revealed by groundwater footprint. Nature 2012; 488(7410): 197-200. https://doi.org/10.1038/nature11295

[13] Parise M, Ravbar N, Živanovic V, Mikszewski A, Kresic N, Mádl-Szo ́nyi J, Kukuric N. Hazards in Karst and Managing Water Resources Quality. In: Stevanovic Z, Ed. Karst Aquifers - Characterization and Engineering. Professional Practice in Earth Sciences, Springer 2015; pp. 601-687. https://doi.org/10.1007/978-3-319-12850-4_17

[14] Stevanović Z. Global distribution and use of water from karst aquifers. In: Parise M, Gabrovsek F, Kaufmann G, Ravbar N, Eds. Advances in Karst research: theory, fieldwork and applications. Geological Society of London 2018; 466(sp publ): 217-236. https://doi.org/10.1144/SP466.26

[15] Stevanović Z. Karst aquifers in the arid world of Africa and Middle East: sustainability or humanity? In: Younos T, Scheriber M, Kosič Ficco K, Eds. Karst water environment: advances in research, management and policy. The handbook of environmental chemistry. Springer 2018; 68: 1-43. https://doi.org/10.1007/978-3-319-77368-1_1

[16] Bonacci O. Karst springs hydrographs as indicators of karst aquifers. Hydrological Sciences Journal 1993; 38(1): 51-62. https://doi.org/10.1080/02626669309492639

[17] Bonacci O. Analysis of the maximum discharge of karst springs. Hydrogeology Journal 2001; 9: 328-338. https://doi.org/10.1007/s100400100142

[18] Parise M, Gabrovsek F, Kaufmann G, Ravbar N. Recent advances in karst research: from theory to fieldwork and applications. In: Parise M, Gabrovsek F, Kaufmann G, Ravbar N, Eds. Advances in Karst Research: Theory, Fieldwork and Applications. Geological Society, London 2018; 466: pp. 1-24. https://doi.org/10.1144/SP466.26

[19] Bonacci O, Jukic D, Ljubenkov I. Definition of catchment area in karst: case of the rivers Krcic and Krka, Croatia. Hydrological Sciences Journal 2006; 51(4): 682-699. https://doi.org/10.1623/hysj.51.4.682

[20] Gunn J. Contributory area definition for groundwater source protection and hazard mitigation in carbonate aquifers. In: Parise M, Gunn J, Eds. Natural and anthropogenic hazards in karst areas: Recognition, Analysis and Mitigation. Geological Society, London 2007; 279(sp publ): 97-109. https://doi.org/10.1144/SP279.9

[21] Bonacci O, Andric I. Karst spring catchment: an example from Dinaric karst. Environmental Earth Sciences 2015; 74: 6211-6223. https://doi.org/10.1007/s12665-015-4644-8

[22] Parise M. How confident are we about the definition of boundaries in karst? Difficulties in managing and planning in a typical transboundary environment. In: Stevanovic Z, Kresic N, Kukuric N., Eds. Karst without boundaries. IAH-Selected Papers on Hydrogeology, 23, ISBN 9781138029682, CRC Press, 2016: 27-38. https://doi.org/10.1201/b21380-4

[23] Bonacci O, Roje-Bonacci T. Sea water intrusion in coastal karst springs: example of the Blaž Spring (Croatia). Hydrological Sciences Journal 1997; 42 (1): 89-100. https://doi.org/10.1080/02626669709492008

[24] Bear J. Seawater Intrusion in Coastal Aquifers, Concepts, Methods and Practices. Science and Business Media, Springer, New York City, N. Y. 1999 https://doi.org/10.1007/978-94-017-2969-7

[25] Arfib B, De Marsily G. Modeling the salinity of an inland coastal brackish karstic spring with a conduit-matrix model.

Water Resour. Res. 2004; 40.
https://doi.org/10.1029/2004WR003147

[26] Fleury P, Bakalowicz M, de Marsily G. Submarine springs and coastal karst aquifers: A review, J. Hydrol. 2007; 339(1): 79- 92.
https://doi.org/10.1016/j.jhydrol.2007.03.009

[27] Irany V, Marino-Tapia I, Enriquez C. Effects of drought and subtidal sea-level variability on salt intrusion in a coastal karst aquifer. Marine and Freshwater Research 2012; 63: 485-493.
https://doi.org/10.1071/MF11270

[28] Cotecchia, V. Le acque sotterranee e l'intrusione marina in Puglia: dalla ricerca all'emergenza nella salvaguardia della risorsa. Memorie Descrittive Carta Geologica d'Italia 2014; 92: 416 pp.

[29] Tulipano L, Fidelibus MD. Mechanisms of groundwaters salinisation in a coastal karstic aquifer subject to over-exploitation. Proceedings 17th SWIM, Delft (The Netherlands) 2002; pp. 39-49.

[30] Richts A, Struckmeier WF, Zaepke M. WHYMAP and the groundwater resources of the World 1:25,000,000. In: Jones JAA (ed) Sustaining Groundwater Resources 2011: pp. 159-173.
https://doi.org/10.1007/978-90-481-3426-7_10

[31] Goldscheider N, Chen Z, WOKAM Team. The world karst aquifer mapping project - WOKAM. In: Kukurić N, Stevanović Z, Krešić N, Eds. Proceedings of the DIKTAS Conference: "Karst without boundaries", Trebinje, June 11-15, 2014: pp. 391.

[32] Goldscheider N, Chen Z, Auler A, Bakalowicz M, Broda S, Drew D, Harmann J, Guanghui J, Moosdorf N, Richts A, Stevanović Z, Veni G, Dumont A, Aureli A. World-wide hydrogeological mapping: the world karst aquifer map. 44th Congress International Association of Hydrogeologists (IAH), Book of Abstracts, Dubrovnik 2017, pp 55.

[33] Stevanović Z, Goldscheider N, Chen Z, WOKAM Team. WOKAM - the world karst aquifer mapping project, examples from South East Europe, Near and Middle East and Eastern Africa. In: Stevanović Z, Krešić N, Kukurić N, Eds. Karst Without Boundaries. CRC Press/Balkema, EH Leiden 2016; Taylor and Francis Group, London: 39-51.
https://doi.org/10.1201/b21380-5

[34] Chen Z, Auler AS, Bakalowicz M, Drew D, Griger F, Hartmann J, Jiang G, Moosdorf N, Richts A, Stevanović Z, Veni G, Goldscheider N. The world karst aquifer mapping project - concept, mapping procedure and map of Europe. Hydrogeology Journal 2017; 25(3): 771-785.
https://doi.org/10.1007/s10040-016-1519-3

[35] Olarinoye T, Gleeson T, Marx V, Seeger S, Adinehvand R, Allocca V *et al*. Global karst springs hydrograph dataset for research and management of the world's fastest flowing groundwater. Scientific Data 2020; 7: 59.
https://doi.org/10.1038/s41597-019-0346-5

[36] Mostardini F, Merlini S. Appennino centro meridionale. Sezioni geologiche e proposta di modello strutturale. Memorie della Società Geologica Italiana 1986; 35: 177-202.

[37] Casero P, Roure F, Endignoux L, Moretti I, Muller I, Muller C, Sage L, Vially R. Neogene geodynamic evolution of the southern Apennines. Mem. Soc. Geol. Ital. 1988; 41: 109-120.

[38] Boccaletti M, Nicolich R, Tortorici L. New data and hypothesis on the development of the Tyrrhenian basin. Palaeogeography, Palaeoclimatology, Palaeoecology 1990; 77: 15-40.
https://doi.org/10.1016/0031-0182(90)90096-P

[39] Doglioni C. A proposal of kinematic modelling for W-dipping subductions - Possible applications to the Tyrrenian-Apennines system. Terra Nova 1991; 3: 423-434.
https://doi.org/10.1111/j.1365-3121.1991.tb00172.x

[40] Ricchetti G. Contributo alla conoscenza strutturale della Fossa Bradanica e delle Murge. Boll. Soc. Geol. It. 1980: 49(4): 421-430.

[41] Royden L, Patacca E, Scandone P. Segmentation and configuration of subducted lithosphere in Italy: an important control on thrust-belt and foredeep-basin evolution. Geology 1987; 15: 714-717.
https://doi.org/10.1130/0091-7613(1987)15<714:SACOSL>2.0.CO;2

[42] Ricchetti G, Ciaranfi N, Luperto Sinni E, Mongelli F, Pieri P. Geodinamica ed evoluzione sedimentaria e tettonica dell'Avampaese Apulo. Memorie della Società Geologica Italiana 1988; 41: 57-82.

[43] Funiciello R, Montone P, Parotto M, Salvini F, Tozzi M. Geodynamic evolution of an intra- orogenic foreland: the Apulia case history (Italy). Boll. Soc. Geol. It.1991; 110: 419-425.

[44] Bosellini A, Parente M. The Apulia Platform margin in the Salento peninsula (southern Italy). Giornale di Geologia 1994; 56(2): 167-177.

[45] Gambini R, Tozzi M. Tertiary geodynamic evolution of the Southern Adria microplate. Terra Nova 1996; 8: 593-602.
https://doi.org/10.1111/j.1365-3121.1996.tb00789.x

[46] Doglioni C, Mongelli F, Pieri P. The Puglia uplift (SE Italy): an anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere. Tectonics 1994; 13: 1309-1321.
https://doi.org/10.1029/94TC01501

[47] Brankman CM, Aydin A. Uplift and contractional deformation along a segmented strike-slip fault system: the Gragano promontory, southern Italy. Journal of Structural Geology 2004; 26: 807-824.
https://doi.org/10.1016/j.jsg.2003.08.018

[48] Castiglioni B, Sauro U. Large collapse dolines in Puglia (southern Italy): the cases of "Dolina Pozzatina" in the Gargano plateau and of "puli" in the Murge. Acta Carsologica 2000; 29 (2): 83-93
https://doi.org/10.3986/ac.v29i2.450

[49] Parise M. Surface and subsurface karst geomorphology in the Murge (Apulia, southern Italy). Acta Carsologica 2011; 40 (1): 79-93.
https://doi.org/10.3986/ac.v40i1.30

[50] Simone O, Fiore A. Five large collapse dolines in Apulia (Southern Italy) - the Dolina Pozzatina and the Murgian Puli. Geoheritage 2014; 6(4): 291−303.
https://doi.org/10.1007/s12371-014-0122-z

[51] Bosellini A, Bosellini FR, Colalongo ML, Parente M, Russo A, Vescogni A. Stratigraphic architecture of the Salento coast from Capo d'Otranto to Santa Maria di Leuca (Apulia, southern Italy). Riv. Ital. Paleont. Strat. 1999; 105(3): 397-416.

[52] Sauro U. A polygonal karst in Alte Murge (Puglia, Southern Italy). Zeitschrift für Geomorphologie 1991; 35(2): 207-223.

[53] Caldara M, Ciaranfi N. Le brecce polifasiche quaternarie delle Murge settentrionali. Mem. Soc. Geol. It. 1988; 41(1): 685-695.

[54] Festa V, Fiore A, Parise M, Siniscalchi A. Sinkhole evolution in the Apulian karst of southern Italy: a case study, with some considerations on sinkhole hazards. Journal of Cave and Karst Studies 2012; 74(2): 137-147.
https://doi.org/10.4311/2011JCKS0211

[55] Pepe M, Parise M. Structural control on development of karst landscape in the Salento Peninsula (Apulia, SE Italy). Acta Carsologica 2014; 43(1): 101-114.
https://doi.org/10.3986/ac.v43i1.643

[56] Gutierrez F, Parise M, De Waele J, Jourde H. A review on natural and human-induced geohazards and impacts in karst. Earth Science Reviews 2014; 138: 61-88.
https://doi.org/10.1016/j.earscirev.2014.08.002

[57] Parise M. Sinkholes. In: White WB, Culver DC, Pipan T, Eds. Encyclopedia of Caves. Academic Press, Elsevier 2019, 3rd ed: 934-942. https://doi.org/10.1016/B978-0-12-814124-3.00110-2

[58] Parise M, Federico A, Delle Rose M, Sammarco M. Karst terminology in Apulia (southern Italy). Acta Carsologica 2003; 32(2): 65-82. https://doi.org/10.3986/ac.v32i2.337

[59] Parise M. Geomorphology of the Canale di Pirro karst polje (Apulia, Southern Italy). Zeitschrift für Geomorphologie 2006; 147: 143-158.

[60] Parise M, Benedetto L. Surface landforms and speleological investigation for a better understanding of karst hydrogeological processes: a history of research in southeastern Italy. In: Parise M, Gabrovsek F, Kaufmann G, Ravbar N, Eds. Advances in Karst Research: Theory, Fieldwork and Applications. Geological Society, London 2018; 466: pp. 137-153. https://doi.org/10.1144/SP466.25

[61] Lopez N, Spizzico V, Parise M. Geomorphological, pedological, and hydrological characteristics of karst lakes at Conversano (Apulia, southern Italy) as a basis for environmental protection. Environmental Geology 2009; 58(2): 327-337. https://doi.org/10.1007/s00254-008-1601-9

[62] Parise M. Lakes in the Apulian karst (Southern Italy): geology, karst morphology, and their role in the local history. In: Miranda FR, Bernard LM, Eds. Lake pollution research progress. Nova Science Publishers, Inc., New York 2009; pp. 63-80.

[63] Ciaranfi N, Pieri P, Ricchetti G. Note alla Carta geologica delle Murge e del Salento (Puglia centro-meridionale). Mem. Soc. Geol. Ital. 1988; 41 (I): 449-460.

[64] Delle Rose M, Federico A, Parise M. Sinkhole genesis and evolution in Apulia, and their interrelations with the anthropogenic environment. Natural Hazards and Earth System Sciences 2004; 4: 747-755. https://doi.org/10.5194/nhess-4-747-2004

[65] Delle Rose M, Parise M, Andriani GF. Evaluating the impact of quarrying on karst aquifers of Salento (southern Italy). In: Parise M, Gunn J, Eds. Natural and anthropogenic hazards in karst areas: Recognition, Analysis and Mitigation. Geological Society, London 2007; 279(sp publ): 153-171. https://doi.org/10.1144/SP279.13

[66] Festa V, Fiore A, Miccoli MN, Parise M, Spalluto L. Tectonics vs karst relationships in the Salento peninsula (Apulia, Southern Italy): implications for a comprehensive land-use planning. In: Lollino G, Manconi A, Guzzetti F, Culshaw M, Bobrowsky P, Luino F, Eds. Engineering Geology for Society and Territory. Volume 5 - Urban Geology, Sustainable Planning and Landscape Exploitation. Springer 2014; pp. 493-496. https://doi.org/10.1007/978-3-319-09048-1_95

[67] Margiotta S, Parise M. Hydraulic and Geomorphological Hazards at Wetland Geosites Along the Eastern Coast of Salento (SE Italy). Geoheritage 2019; 11: 1655-1666. https://doi.org/10.1007/s12371-019-00363-4

[68] Cotecchia V. Influenza dell'acqua marina sulle falde acquifere in zone costiere, con particolare riferimento alle ricerche d'acqua sotterranea in Puglia. Geotecnica 1955; 3.

[69] Cotecchia V. Studi e ricerche sulle acque sotterranee e sull'intrusione marina in Puglia (Penisola Salentina). Quaderni CNR IRSA 1977; 20: 461 pp.

[70] Rudnicki J. Karst in coastal areas - development of karst processes in the zone of mixing of fresh and saline water (with special reference to Apulia, Southern Italy). Studia Geologica Polonica 1980; 65: 9-59.

[71] Tulipano L, Cotecchia V, Fidelibus MD. An example of multitracing approach in the studies of karstic and coastal aquifers. Proceedings International Symposium and Field Seminar "Hydrogeologic processes in karst terranes", Antalya (Turkey), IAHS 1990; 207: pp. 381-389.

[72] Masciopinto C, Liso IS, Caputo MC, De Carlo L. An Integrated Approach Based on Numerical Modelling and Geophysical Survey to Map Groundwater Salinity in Fractured Coastal Aquifers. Water 2017; 9: 875. https://doi.org/10.3390/w9110875

[73] Masciopinto C, Liso IS. Assessment of the impact of sea-level rise due to climate change on coastal groundwater discharge. Science of the Total Environment 2016; 569-570: 672-680. https://doi.org/10.1016/j.scitotenv.2016.06.183

[74] Tadolini T, Tinelli R, Tulipano L. Discharge conditions and variations of the main hydrogeological parameters of some coastal Apulian springs relating to sea water influence of groundwater. Geologia Applicata e Idrogeologia 1983; 18(2): 117-127.

[75] Tulipano L. Temperature logs interpretation for the identification of preferential flow pathways in the coastal carbonatic and karstic aquifer of the Salento peninsula (Southern Italy). Proceedings 21st Congress IAH 1988; pp. 956-961.

[76] Cotecchia V. Studio sulle disponibilità idriche della Puglia - Penisola Salentina". Rilievo aereo multispettrale Puglia Progetto Speciale n. 14, Cassa per il Mezzogiorno 1976.

[77] White WB. Geomorphology and hydrology of karst terrains. Oxford Univ. Press 1988.

[78] White WB. Karst hydrology: recent developments and open questions. Engineering Geology 2002; 65: 85-105. https://doi.org/10.1016/S0013-7952(01)00116-8

[79] Stevanović Z. Characterization of karst aquifer: In: Stevanović Z, Ed. Karst Aquifers - Characterization and Engineering. Series: Professional practice in earth science, Springer Intern. Publ. 2015, Cham, Heidelberg, NY, Dordrecht, London: 47-126. https://doi.org/10.1007/978-3-319-12850-4_3

[80] Cotecchia V, Magri G. Idrogeologia del Gargano. Geologia Applicata e Idrogeologia 1966; 1: 1-86.

[81] Tadolini T, Tulipano L, Zanframundo P. La falda idrica della zona compresa tra Vico del Gargano ed Ischitella (Puglia): caratteristiche ed equilibrio idrogeologico. Giornale del Genio Civile 1976; 10-11-12: 423-433.

[82] Zorzi L, Reina C. Idrogeologia della Provincia di Taranto. Giorn. del Genio Civile 1962; 2: 149-166.

[83] Cotecchia F, Lollino G, Pagliarulo R, Stefanon A, Tadolini T, Trizzino R. Hydrogeological condition and field monitoring of the Galeso submarine spring in the Mar Piccolo of Taranto (Southern Italy). Proc. SWIM 11, Gdansk, (Poland), 1990.

[84] Tadolini T, Spizzico M. Caratterizzazione idrogeologica della zona delle sorgenti. Tara (Taranto). Mem. Soc. Geol. It. 1996; 51: 793-802.

[85] Cotecchia V, Ippolito F, Orabona E. Relazione generale sulle indagini idrogeologiche svolte in merito all'impiego della falda profonda contenuta nei calcari cretacici delle Murge e del Salento. Ente per lo Sviluppo dell'Irrigazione e la Trasformazione Fondiaria in Puglia e Lucania, Bari 1957.

[86] Vignola A. Cosimo De Giorgi - Descrizione Fisica, Geologica e Idrogeologica della Provincia di Lecce. Centro di Studi Salentini Lecce 1960.

[87] Bergamin G, Scorcia M, Trimigliozzi A. Prime risultanze di recenti studi sulle sorgenti Tara in Puglia. Annali dell'Ente per lo Sviluppo dell'Irrigazione e la Trasformazione Fondiaria in Puglia e Lucania, Bari 1980.

[88] Baldassarre G, Quarto R, Schiavone D. Indagini geologiche e geofisiche per lo sviluppo della sorgente Tara (prov. di Taranto). Geologia Applicata e Idrogeologia 1983; 18(1).

[89] Cotecchia V, Tadolini T, Tulipano L. Ground water temperature in the Murgia karst aquifer (Puglia - Southern Italy). Proc. Symp. on Karst Hydrology, Budapest 1978.

[90] Cotecchia V. Ricerca riguardante la individuazione e la captazione di sorgenti sottomarine e correlazione con la "Falda Profonda" sottostante al Mar Piccolo di Taranto. Agenzia per la Promozione dello Sviluppo del Mezzogiorno 1991.

[91] Hollingsworth E, Van Brahana, Inlander E, Slay M. Karst Regions of the World (KROW), Global karst datasets and maps to advance the protection of karst species and habitats worldwide. 2008; http://pubs.usgs.gov/sir/-2008/5023/pdf/06hol lings.pdf (accessed 25 April 2018).

[92] Masciopinto C, Semeraro F, La Mantia R, Inguscio S, Rossi E. Stygofauna abundance and distribution in the fissures and caves of the Nard. (Southern Italy) fractured aquifer subject to reclame water injections. Geomicrobiology Journal 2006; 23: 267-278. https://doi.org/10.1080/01490450600760690

[93] Inguscio S, Rossi E, Parise M. Biogeographical distribution of subterranean fauna in Apulia (Italy) in the context of the palaeo-geographic evolution of the area. Proceedings 15th International Congress of Speleology, Kerrville (Texas, USA), 19-26 July 2009; 2: 749-754.

[94] Liso IS, Loiotine L, Andriani GF, Parise M. Apulian caves as natural hydrogeological laboratories. Italian Journal of Engineering Geology and Environment 2019; 1(sp issue): 67-72.

[95] Liso IS, Chieco M, Fiore A, Pisano L, Parise M. Underground geosites and caving speleotourism: some considerations, from a case study in Southern Italy. Geoheritage 2020; 12: 13. https://doi.org/10.1007/s12371-020-00424-z

[96] Mainardi M. Cantieri di bonifica. Edizioni Grifo, Lecce 2017; 156 pp.

[97] Zorzi L, Reina C. Sulla necessità di controllare e disciplinare le utilizzazioni di acque sotterranee nella Penisola Salentina. Discussioni sulle probabili risorse idriche sotterranee disponibili e sulle possibilità di un razionale sfruttamento. 8th Conv. Naz. Ingegneri Italiani, Politecnico di Milano 1955.

[98] Margiotta S, Negri S. Alla ricerca dell'acqua perduta. Congedo Editore 2004, 191 pp.

[99] Azzaroli A. Calcare di Altamura. Note illustrative della Carta Geologica d'Italia. Formazioni geologiche 1967; 1: 151-156.

[100] Bossio A, Mazzei R, Monteforti B, Salvatorini G. Stratigrafia del Neogene e Quaternario del Salento sud-orientale (con rilevamento geologico alla scala 1:25.000). Geologica Romana 2005; 38: 31-60.

[101] D'Angeli IM, Vattano M, Parise M, De Waele J. The coastal sulfuric acid cave system of Santa Cesarea Terme (Southern Italy). In: Klimchouk A, Palmer AN, De Waele J, Auler AS, Audra P, Eds. Hypogene Karst Regions and Caves of the World. Cave and Karst Systems of the World, Springer 2017; pp. 161-168. https://doi.org/10.1007/978-3-319-53348-3_9

[102] D'Angeli IM, Ghezzi D, Leuko S, Firrincieli A, Parise M, Fiorucci A *et al*. Geomicrobiology of a seawater-influenced active sulfuric acid cave. Plos One 2019; 14(8): 33 pp. https://doi.org/10.1371/journal.pone.0220706

[103] Zuffianò LE, Palladino G, Santaloia F, Polemio M, Liotta D, Limoni PP, Parise M, Pepe M, Casarano D, Rizzo E, Minissale A, De Franco R. Geothermal resource in a foreland environment: the Santa Cesarea Terme thermal springs (Southern Italy). European Geothermal Congress 2013, Pisa, 3-7 June 2013: pp. 101-104.

[104] Pepe P, Parise M. Integration of geomorphological and speleological datasets in karst terrains. Rendiconti Online Società Geologica Italiana 2012; 21(1): 629-631.

[105] Mauget A. Note geologiche sulla Provincia di Lecce. 1875.

[106] De Giorgi C. I bagni solfurei di Santa Cesarea in Terra d'Otranto. Rivista Idrologica e Climatica Medica, Firenze 1882; 8.

[107] De Giorgi C. Le Terme Sulfuree di S. Cesaria sull'Adriatico. Tip. Salani, Lecce 1901.

[108] De Giorgi C. Descrizione fisica, geologica e idrografica della provincia di Lecce. Lecce, Tip. Ed. Salentina 1922.

[109] Corti E. Relazione sul Convegno Nazionale di Speleologia di Castro, 14-15-16 settembre 1936. Itinerari Speleologici 1992; 6: 89-97.

[110] Klimchouk A. Hypogean speleogenesis: hydrogeological and morphometric perspective. National Cave and Karst Research Institute 2007; 1(sp paper): 106 pp.

[111] Klimchouk A. Morphogenesis of hypogenic caves. Geomorphology 2009; 106: 100-117. https://doi.org/10.1016/j.geomorph.2008.09.013

[112] Klimchouk AB. Types and settings of hypogene karst. In: Klimchouk AB, Palmer AN, De Waele J, Auler A, Audra P, Eds. Hypogene karst regions and caves of the world. Springer 2017; pp. 1-39. https://doi.org/10.1007/978-3-319-53348-3_1

[113] Palmer AN. Sulfuric acid caves: morphology and evolution. In: Schroder J, Frumkin A, Eds. Treatise on Geomorphology. Academic Press, Karst Geomorphology 2013; 6: 241-257. https://doi.org/10.1016/B978-0-12-374739-6.00133-0

[114] De Waele J, Galdenzi S, Madonia G, Menichetti M, Parise M, Piccini L, Sanna L, Sauro F, Tognini P, Vattano M, Vigna B. A review on hypogene caves in Italy. In: Klimchouk A, Sasowski ID, Mylroie J, Engel SA, Summers Engel A, Eds. Hypogene cave morphologies. Karst Water Institute 2014; 18(sp publ): pp. 28-30.

[115] D'Angeli IM, Parise M, Vattano M, Madonia G, Galdenzi S, De Waele J. Sulfuric acid caves of Italy: a review. Geomorphology 2019; 333: 105-122. https://doi.org/10.1016/j.geomorph.2019.02.025

[116] Tadolini T, Bruno G. The influence of geostructural setting upon water thermo-mineralization in certain areas of Apulia (Southern Italy). Proceedings of the Antalya Symposium and Field Seminar Hydrogeological processes in karst terrains, IAHS 1993; 207: 75-83.

[117] D'Angeli IM, DeWaele J, Galdenzi S, Madonia G, Parise M, Piccini L, Vattano M. Sulfuric acid caves of Italy: an overview. In: Chavez T, Reehling P, Eds. Proceedings Deep Karst 2016: Origins, Resources, and Management of Hypogene Karst. National Cave and Karst Research Institute Symposium 2016; 6, pp. 85-88.

[118] D'Angeli IM, Carbone C, Nagostinis M, Parise M, Vattano M, Madonia G. De Waele J. New insights on secondary minerals from Italian sulphuric acid caves. International Journal of Speleology 2018; 47(3): 271-291. https://doi.org/10.5038/1827-806X.47.3.2175

[119] Visintin B. Studio sull'acqua della Grotta Gattulla delle Terme demaniali di S. Cesarea. Annali di Chimica Applicata 1945; 35(6-7): 97-111.

[120] Edmunds WM, Smedley PL. Residence time indicators in groundwater: the East Midlands Triassic sandstone aquifer. Applied Geochemistry 2000; 15: 737-752. https://doi.org/10.1016/S0883-2927(99)00079-7

[121] Santaloia F, Zuffianò LE, Palladino G, Limoni PP, Liotta D, Minissale A, Brogi A, Polemio M. Coastal thermal springs in a foreland setting: the Santa Cesarea Terme system (Italy). Geothermics 2016; 64: 344-361. https://doi.org/10.1016/j.geothermics.2016.06.013

[122] Zezza F. Le sorgenti ipotermali solfuree di Santa Cesarea Terme. Salentum 1980; 1-2.

[123] Calò GC, Spizzico M, Tinelli R, Zezza F. Hydrogeological investigations on the area surrounding Santa Cesarea Terme springs (southern Apulia). Geologia Applicata e Idrogeologia 1983; 18 (2): 129-144.

[124] Calò GC, Tinelli R. Systematic hydrogeological study of a hypothermal spring (S. Cesarea Terme, Apulia), Italy. Journal of Hydrology 1995; 165: 185-205. https://doi.org/10.1016/0022-1694(94)02565-S

[125] Calò G, Tinelli R. Le acque sulfuree nel contesto idrogeologico dell'area di Torre Mozza di Ugento (Penisola Salentina, Puglia). Acque sotterranee 2004; 89.

[126] Reina C. Le sorgenti carsiche salmastre del Chidro. Memoires de l'Association Internationale des Hydrogeologues, reunion Generale de Rome 1961; 4.

[127] Reina C. Fondamenti idrogeologici e possibilità pratiche di ridurre la salinità dell'acqua delle sorgenti carsiche salmastre del Chidro in Puglia. Bollettino di Geofisica Teorica e Applicata 1962; 4(16).

[128] Tadolini T, Zanframundo P. Sul regime dei deflussi delle sorgenti Chidro e Boraco. Giornale del Genio Civile 1975; 7-8-9: 303-309.

[129] Maggiore M, Pagliarulo P. Groundwater vulnerability and pollution sources in the Apulian region (Southern Italy). Proceedings 2nd Symposium "Protection of Groundwater from Pollution and Seawater Intrusion", Bari, 2003: pp. 9-20.

[130] Tulipano L. Modalità di deflusso a mare delle acque sotterranee degli acquiferi carbonatici costieri della Puglia. Grotte e dintorni 2002; 4: 261-270.

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