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APULIAN CAVES AS NATURAL HYDROGEOLOGICAL LABORATORIES

ISABELLA SERENA LISO, LIDIA LOIOTINE, GIOACCHINO FRANCESCO ANDRIANI & MARIO PARISE

University of Bari Aldo Moro - Department of Earth and Environmental Sciences – Bari, Italy
Corresponding author: isabella.liso@uniba.it

EXTENDED ABSTRACT

Rispetto a qualche decennio fa, la popolazione mondiale cresce a ritmi esponenziali ed è per questo importante preservare alcune delle meraviglie naturali e risorse del nostro Pianeta al fine di assicurare prosperità e sopravvivenza alla natura e all'umanità. Senza dubbio, l'acqua dolce fa parte delle risorse preziose da tutelare, poiché tutti gli organismi che vivono sulla Terra, animali o vegetali, dipendono da essa. Solo una piccola parte di acqua dolce scorre libera sulla superficie del Pianeta, la parte più cospicua è "intrappolata" negli ammassi ghiacciati delle calotte polari oppure sotto la superficie terrestre. Le risorse idriche sotterranee sono la principale o unica fonte di approvvigionamento idrico per molti paesi; nonostante ciò, l'inquinamento ha ridotto notevolmente la disponibilità di tale risorsa. Il problema della scarsità di acqua dolce, quindi, riguarda sia la qualità e anche la quantità (i.e. disponibilità) delle acque dolci sotterranee; per questo motivo, negli ultimi anni, si sta ponendo sempre maggiore attenzione alle modalità di ricerca e di monitoraggio di tali risorse. Giungere ad una buona conoscenza delle dinamiche idrogeologiche, relative alle falde idriche, richiede azioni di monitoraggio specifiche, in particolare negli acquiferi carsici, dove l'anisotropia spaziale e temporale delle caratteristiche idrauliche rende estremamente complessa la comprensione dei processi idrologici.

In Puglia (Italia meridionale), il più importante serbatoio di acqua dolce è ospitato all'interno delle rocce della piattaforma carbonatica mesozoica; la Puglia, infatti, possiede risorse idriche superficiali molto esigue perché l'acqua piovana si infiltra rapidamente attraverso discontinuità dell'ammasso roccioso (fratture, inghiottitoi), ricaricando naturalmente l'acquifero. Essendo una regione carsica, la Puglia presenta oltre 2000 grotte registrate all'interno dell'inventario regionale (Catasto Regionale delle Grotte Naturali); tra queste, soltanto in due casi gli speleologi hanno raggiunto fisicamente la falda idrica, ovvero all'Inghiottitoio di Masseria Rotolo (Murge) e in Vora Bosco (Salento). Così, queste due grotte sono diventate speciali laboratori naturali in cui è possibile studiare direttamente la falda idrica profonda e i suoi processi idrogeologici.

Lo scopo di questa ricerca è di valutare la qualità e la quantità della risorsa idrica sotterranea pugliese e di comprendere meglio le dinamiche idrogeologiche carsiche a scala regionale, sfruttando i vantaggi del monitoraggio diretto delle acque sotterranee nelle due grotte precedentemente citate. Per realizzare questa ricerca sono state eseguite alcune azioni di monitoraggio all'interno delle grotte, e altre saranno implementate nel prossimo futuro.

Innanzitutto, all'interno delle grotte, sono state installate sonde multi-parametriche al di sotto della tavola d'acqua, per fornire dati in continuo di temperatura, conduttività elettrica e livello dell'acqua. Utilizzando i dati derivati dalle sonde e quelli relativi alle precipitazioni, registrati dalle vicine stazioni pluviometriche, sono stati realizzati i diagrammi di correlazione tra il livello dell'acqua e la pioggia per studiare la risposta dei due sistemi carsici agli eventi meteorologici. Inoltre, per valutare la qualità delle acque sotterranee, sono state condotte analisi chimiche e microbiologiche su campioni d'acqua prelevati direttamente in grotta e sono stati effettuati campionamenti bio-speleologici. Questi ultimi hanno rivelato un'importante presenza di stigofauna, alcune specie della quale possono essere considerate come indicatori di ambienti non inquinati o comunque privi di contaminazione antropica.

Per quanto riguarda la valutazione dei volumi (quantità) di acqua sotterranea disponibile, è necessaria l'implementazione di un modello matematico di flusso che simuli lo scorrimento dell'acqua nel sottosuolo. La realizzazione di un tale modello all'interno degli acquiferi carsici fratturati è piuttosto difficile, a causa delle peculiari caratteristiche idrogeologiche, estremamente anisotrope ed eterogenee. Finora, la maggior parte dei modellisti ha utilizzato l'approccio del Mezzo Poroso Equivalente (EPM), abbastanza lontano dal comportamento reale degli acquiferi carsici.

Con questa ricerca ci si propone l'obiettivo di ridurre il divario esistente tra i modelli di flusso attualmente utilizzati e l'ambiente reale naturale, fondendo insieme due approcci modellistici differenti: il primo implementa il flusso laminare all'interno delle fratture e il secondo il flusso turbolento all'interno dei condotti carsici. A questo scopo, devono essere raccolti ulteriori dati geologici e idrogeologici: caratterizzazione petrologica e strutturale delle successioni stratigrafiche in cui si sviluppano le due grotte; indagini geomorfologiche dettagliate sulle grotte; dati idrologici derivati da pozzi circostanti i due siti di studio; dati climatici (pioggia, temperatura, radiazione solare, pressione); uso del suolo. La raccolta dettagliata di elementi utili alla caratterizzazione idrogeologica porterà ad una migliore conoscenza delle dinamiche e dei processi naturali dei territori carsici, consentendo così alle Autorità di identificare e scegliere le migliori azioni di salvaguardia e protezione della preziosa risorsa sotterranea di acqua dolce della Regione Puglia. L'approccio così descritto, geologico-modellistico, potrà essere utilizzato in qualsiasi altro territorio carsico.

ABSTRACT

In Apulia (Southern Italy), there is a huge amount of freshwater resources stored within fractured limestone rocks. Being a karst region, Apulia presents over 2000 caves registered in the Regional Inventory; among these, only in two cases speleologists have physically reached the water table, namely at *Inghiottitoio di Masseria Rotolo* and at *Vora Bosco*. Thus, these two caves have become special and natural laboratories in which it is possible to directly study groundwater and its hydrogeological processes.

The aim of this research is to assess Apulian groundwater quality and quantity starting from these two caves; for this, some actions have been performed inside the cave systems, and others have to be implemented in the next future.

To evaluate groundwater quality, chemical and microbiological analyses have been conducted on groundwater samples, and bio-speleological sampling have been performed too. As regards groundwater quantity, the implementation of the mathematical groundwater flow model is needed. So far, modelers have used Equivalents Porous Media (EPM) approaches that are quite far from the real behavior of karst aquifers. Another purpose of this research is to reduce the existing gap between current models and the natural environment, merging two different approaches: the first implements the laminar flow within fractures and, the second, the turbulent flux inside karst conduits. At this aim, additional geological and hydrogeological data have to be collected. This phase of work will eventually result in getting a better knowledge of the natural dynamics and processes in karst, thus allowing identifying the best actions in order to safeguard and protect the underground freshwater resource.

KEYWORDS: *hydrogeology, karst, caves, modeling, Apulia*

INTRODUCTION

The world population grows at exponential rates, and actually in the last fifty years, it has doubled (THATCHER *et alii*, 2017); it is, therefore, important to preserve some wonders of nature and resources of our Planet in order to ensure prosperity and survival to nature and humanity. Without a doubt, fresh water is part of the extremely valuable resources to be protected, since all living organisms on Earth, animal or plant, depend on it. Only a small part of freshwater flows free on the planet's surface, the most conspicuous volume being "trapped" in the polar ice caps or below the earth surface. Underground water resources are the main source of water supply for many countries, also in Apulia (Southern Italy) where the groundwater have historically been the first source of water supply for residents, covering a very important socio-economic role. This region is characterized by a high percentage of soluble outcropping rocks, essentially Cretaceous limestone (Fig. 1).

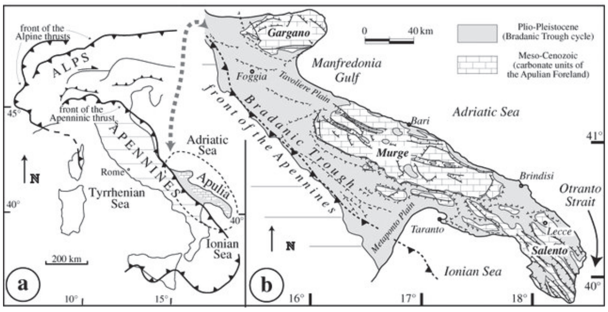

Fig. 1 - a) Schematic map of Italy with location of the Apulia Region; b) Schematic geological map of Apulia region (after TROPEANO & SPALLUTO*, 2006).*

The action of weakly acidic waters on the Apulian carbonate rocks has allowed the development of widespread karst phenomena, giving back a multiplicity of surface and sub-surface karst landforms (PARISE, 2011). Surface water in karst areas is rather limited because the fluid rapidly infiltrates into the subsoil, once a preferential access pathway is detected, such as a fracture or a sinkhole (Parise et al., 2015). Therefore, most of the fresh water movement is observed in the subsoil, below the ground.

The Mesozoic Apulian platform rocks, in fact, host a large amount of fresh water (MAGGIORE & PAGLIARULO, 2004), which moves guided by hydraulic gradients. This is achieved thanks to the peculiar geological setting of the Apulian territory, in which the karst processes play an essential role. Karst groundwaters are extremely vulnerable to pollution, compared to other types of aquifers (WHITE, 1988; FORD & WILLIAMS, 2007; PARISE & GUNN, 2007). For example, sinkholes are preferential sites for pollutants entry into the ground, placing in direct contact the surface with the vadose zone. Furthermore, in coastal areas, the phenomenon of marine intrusion is widely observed, due to the progressive retreat of the Ghyben-Herzberg interface (MASCIOPINTO & LISO, 2016; MASCIOPINTO *et alii*, 2017). This phenomenon has a strong impact on local life; the population is unable to use the water extracted from their own wells, because it is too saline for both agricultural and human purposes.

Politicians, legislators and civil society have understood the relevance of karst aquifers and that their protection from contamination must be managed with care and competence (WHITE, 2015). The study of karst areas and the underground water circulation characteristics is important not only for planning the use and safeguarding of the water resources, but also for the preparation of measures to protect population against hydrogeological risks (STEVANOVIC, 2015). The research in geology, hydrogeology and speleology has been used to deal with the contamination of karst aquifers and other problems that characterize these territories, with multi-disciplinary approaches (LA MOREAUX & STEVANOVIC, 2015). Therefore, the geological and hydrogeological characterization (aimed at the collection of lithological, petrographic, structural, geomorphological and hydrogeological data) constitutes a good starting point to choose the best actions and measures for the underground water resources protection and safeguarding. The geological features of a territory, indeed, greatly influence the underground flow pathway (MAGGIORE & PAGLIARULO, 2004). For example, the degree of rocks compaction determines how water infiltrates below the ground; poorly cemented rocks provoke diffuse infiltration, while highly cemented rocks determine concentrated flows at the fractures (GOLDSCHEIDER & DREW, 2007). Furthermore, the faults can be both hydraulic connection element between aquifers or hydraulic barriers, depending on three main aspects: the type of filling material located within the damage fault zone, the extension of the fault plane, and the amount of the movement. Finally, a detailed stratigraphic knowledge allows a more correct interpretation of the stratigraphic column as a hydrogeological sequence (GOLDSCHEIDER & DREW, 2007). The location of the aquifer geological and hydrodynamic limits, as well as the boundary of recharging, flow and springs areas, are the basic steps for both: the groundwater conceptual model construction (CASTANY, 1985; GUNN, 2007) and computational mathematical flow models implementation. The development of the latter, concerning the circulation of fluids within the aquifer, is very important not only for the detailed hydrogeological and geological characterization and protection of the study area, but also for water, gas and oil research.

DARCY (1856) discovered one of the fundamental laws in hydrogeology, which was also used in oil engineering and soil sciences, as well as in other cases involving the liquids flux through porous media. The Darcy law laid the foundations for quantifying the groundwater presence, storage and discharge and it has become a fundamental tool for all aspects of environmental planning. Later, quantitative methods to determine groundwater velocity and rock permeability have been developed. These tools require the detailed definition of the physical characteristics and thickness of karst rocks. One of the most difficult problems to manage groundwater was the application of quantitative methods to karst rocks, which have extremely anisotropic physical characteristics. In 1935, Theis published an equation to describe the non-stationary groundwater flow, which represented an important step forward in the modern quantitative investigations.

The models concerning groundwater flow range from simple analytical models to more complex numerical ones. Mathematical models can be defined as specific tools for the quantitative representation of the aquifer hydraulic behavior (KOVACS & SAUTER, 2007). With technological advancement, numerical modeling has become a very valid, useful and reliable support tool (if applied appropriately) for hydrogeologists in order to improve their knowledge about underground water systems in karst areas, and to test hypotheses and assumptions. The basis of almost all models is Darcy's law; in most cases, the modeling of water flow in fractured karst aquifers is carried out by assimilating the fractured aquifer to Equivalents Porous Media (EPM). However, in karst terrain the physical complexity of the underground environment (extremely heterogeneous and anisotropic) makes the EPM approach highly questionable. Very often, the approximations lead to errors in results estimation and evaluation, since Darcy's law does not properly describe the water flow within conduits; here the Reynolds numbers are high and turbulent flow occurs. The application of numerical methods in karst hydrogeology requires specific adaptations for the correct models implementation (PALMER *et alii*, 1999). This, as previously mentioned, depends on the particular complexity associated with the extreme flow field heterogeneity in fractured karst aquifers (KIRÀLY, 1994). The mathematical model is constructed by applying the differential equations that describe the processes, knowing the detailed geometry of the aquifer, the specific flow parameters and the boundary conditions (KOVACS & SAUTER, 2007). The hydraulic parameters used in groundwater flow models are generally obtained from the interpolation between values relative to discrete field observations (parameters obtained in wells, for example). Once again, due to the extreme heterogeneity of karst aquifers, interpolation techniques are not adequate for representation of the hydrogeological reality. The uncertainties of the results of the simulations, compared to the heterogeneity of the natural system, are definitely greater in the karst aquifers than in the porous ones (KOVACS & SAUTER, 2007). Recently, specific tools have been developed (KRESIC & PANDAY, 2018) in a MODFLOW environment to simulate the turbulent flux inside karst conduits. In other words, the authors implement the turbulent flow through a karstic conduit, which is immersed in a porous matrix. For the use of these tools, precise location, orientation and internal morphology of the conduits are required. Despite the difficulties, research in the sector is constantly evolving, as the groundwater flow models are the best tools for planning actions to protect the underground water resource. A numerical model, that represents the fractured rock matrix and the karst conduits, will allow hydrogeologists to better understand the water and solutes transport within the single conduit, between various conduits, and between these and the rock mass (MIKSZEWSKI & KRESIC, 2015).

An interesting contribution to the knowledge of water flow dynamics in fractured aquifers is that presented by MASCIOPINTO & PALMIOTTA (2013). Starting from experimental field data, the authors simulate the water pathways inside fractured rock masses, identifying the preferential flow paths, by means of an analytical solution of the Navier-Stockes equations. The input model data are essentially: the groundwater flow velocity, the hydraulic loads, and the gradients. These data can be obtained by performing field tests, such as pumping tests. So far, a groundwater flow model that contemplates the flow of water inside the fractures and, simultaneously, inside the conduits and/or the caves, or rather, a model that adequately simulates water flux inside fractured karst aquifers, is not available.

RESEARCH ACTIVITIES

As previously mentioned, the water circulation in fractured karst aquifers can considerably vary, depending on the peculiar characteristics of the site investigated. For this reason, the choice of the study area is a crucial step in the research program. In Apulia Region, there are two very interesting sites, the first located in the Murge and the second in the Salento Peninsula. These two caves directly reach the water table (Fig. 2).

The Inghiottitoio of Masseria Rotolo (PU 355) (Fig.2) is located in the Monopoli territory. The cave opens at the bottom of the polje, locally named Canale di Pirro, and reaches the water table at a depth of about -260 m below the ground. Vora Bosco (PU 1613) (Fig. 2), instead, is located in the Galatina territory. The karst system reaches the groundwater at depth of about -60 m below the topographic surface. The possibility to direct monitor the aquifer hydrological conditions, through speleological investigations, was the key in the choice of these two sites.

The first aim of this research program involves the detailed characterization of the geological, hydrogeological and hydraulic characteristics at the two chosen sites, leading to construction of specific thematic maps; also, databases will be built. The detailed study of the karst systems will provide a contribution for a good scientific knowledge in the comprehension of the complex dynamics and processes that act in karst environments. These databases will then be used for the construction of the aquifer conceptual model and, subsequently, for the implementation of the mathematical model. Another aim of this research is, in fact, to try to implement a mathematical model that overcomes the current gap between available models and real natural karst environment. A model close to reality will produce results that are more reliable, and this would allow to better planning any action and measure of underground water resource use, safeguard and protection.

Furthermore, the application of such mathematical models could also be useful in planning protection measures for locals, in areas subjected to particular karst hazards (e.g. sinkholes and flashfloods) (GUTIERREZ *et alii*, 2014; PARISE *et alii*, 2015, 2018; MARTINOTTI *et alii*, 2017).

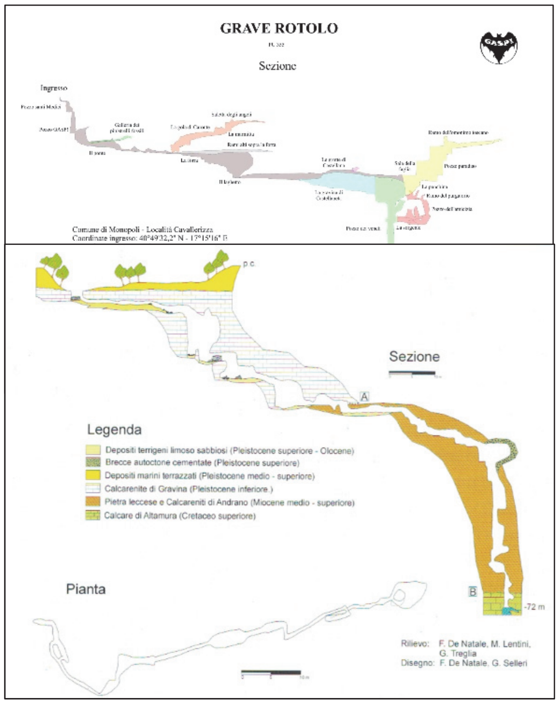

Fig. 2 - Above schematic section of Grotta Rotolo; below Schematic section of Vora Bosco.

The multidisciplinary approach of this research involves the use of various methodologies: the geological and speleological methods, for the detailed geomechanical characterization of the rock mass within which the caves develop; hydrological methods, such as the installation of multi-parameter probes in wells or directly below the water table, wells monitoring, meteorological data collection; hydraulic methods, like pumping tests (CELICO, 1986) and infiltrometric tests; tracking methods (CELICO, 1986; BENISCHKE *et alii*, 2007); modeling methods and, finally, experimental methods. The construction of an experimental apparatus in the laboratory, which simulates the underground karst environment, could be very useful for understanding the dynamics of water flow within a heterogeneous environment such as fractured karst aquifers. The physical model would be able to simulate the flow from a karst conduit to lateral fractures.

Applying an appropriate hydraulic gradient it will be possible to experimentally measure the system response times. This would help to validate the mathematical models previously implemented.

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