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GEOPHYSICAL TECHNIQUES FOR MONITORING CARBONATE KARSTIC ROCKS

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EXTENDED ABSTRACT

Circa il 20% delle terre emerse presenti sul pianeta Terra sono costituite da rocce carsificate; buona parte di esse sono localizzate in zone a più alta densità di popolazione. In queste aree, una corretta pianificazione territoriale risulta assolutamente necessaria da un lato per sopperire alle difficoltà tecniche di insediamento e per tutelare e valorizzare le risorse naturali, dall'altro, non meno importante, per prevenire i rischi naturali ivi presenti. Infatti, l'estrema fragilità dei territori carsici e la conseguente vulnerabilità da numerose tipologie di eventi, insieme alla presenza di importanti risorse naturali (in primis, le risorse idriche sotterranee), paesaggistiche e storico-culturali, sono alla base delle attività di molte ricerche scientifiche finalizzate alla salvaguardia degli ambienti carsici e alla mitigazione dei rischi su questi esistenti. Inoltre, l'approvvigionamento potabile della popolazione europea è garantito per il 75% dalle acque sotterranee, di cui il 50% proviene proprio da acquiferi carsici.

Pertanto, la conoscenza dell'idrodinamica dei sistemi carsici rappresenta un elemento fondamentale da studiare e comprendere, sebbene molto complesso e peculiare. Infatti, proprio la grande variabilità dei parametri idrogeologici (i.e. permeabilità idraulica) è uno degli elementi che contraddistingue gli ambienti carsici rendendoli estremamente vulnerabili.

Tale complessità necessita sicuramente di un approccio multidisciplinare nello studio degli ambienti carsici. Una delle discipline di interesse agli ambienti carsici è la geofisica applicata, in particolare l'idrogeofisica, che con le sue modalità poco invasive e relativamente a basso costo riesce a fornire utili informazioni sul sottosuolo. In particolare, l'idrogeofisica introduce alcuni principali parametri geofisici (resistività elettrica, caricabilità, permittività, ecc.) integrandoli con quelli idrogeologici (porosità, permeabilità, ecc.) proprio per migliorare la caratterizzazione ed il monitoraggio dei processi connessi alle risorse idriche (flusso idrico, trasporti inquinanti, ecc.). La caratterizzazione ed il monitoraggio attraverso tecniche poco invasive e meno costose, come quelle idrogeofisiche, possono portare ad una migliore gestione delle risorse naturali e alla comprensione delle dinamiche dei sistemi naturali.

Il presente lavoro ha come obiettivo quello di migliorare scenari tecnologici di tipo idrogeofisico capaci di fornire informazioni sulla circolazione dei fluidi circolanti in contesti carbonatici carsici. Per raggiungere l'obiettivo prefissato il progetto è stato diviso in due differenti fasi. La prima fase prevede la realizzazione di un modello analogico di un ambiente carbonatico riprodotto in laboratorio (scala di circa $1m^3$) per simulare una circolazione dei fluidi attraverso vie preferenziali (fratture e/o cavità) da monitorare con tecniche idrogeofisiche. La seconda fase prevede di trasferire tale esperimento verso una scala reale con il monitoraggio geofisico di un'ambiente carbonatico naturale presso l'area carsica di Castel di Lepre (Marsico Nuovo, Basilicata).

In particolare, tale area è caratterizzata dalla presenza sia di una cavità carsica che un vecchio tunnel ferroviario abbandonato dove è possibile applicare le nuove metodologie idrogeofisiche. Pertanto, l'obiettivo è quello di ottenere informazioni sulla circolazione dei fluidi attraverso l'integrazione dei modelli numerici di circolazione dei fluidi con quelli geofisici.

ABSTRACT

Carbonate aquifer in karst systems are very important water reservoir and are recognized as the most difficult to characterize. Then, the purpose of this article is to present a PhD project aimed to understand the circulation of fluids in carbonate reservoirs through innovative hydrogeophysical methodologies both in the laboratory and in the field. In order to achieve the research objective, two phases will be analyzed. One of these phases will be characterized by laboratory experiments where different carbonate samples and analogic karstic model (from cm^3 to m^3) will be observed by geophysical measurements. The other phase consists to transfer the laboratory experiences in a natural carbonate complex where it will be evaluated the effectiveness of a hydrogeophysical approach for monitoring carbonate karstic aquifer. The last phase will be applied in the carbonate karst area of Castel di Lepre (Marsico Nuovo, Basilicata, Italy).

KEYWORDS: *carbonate karst aquifer, fluid circulation, hydrogeophysic*

INTRODUCTION

Clean water is vital to the survival and growth of all life and all economic and environmental processes. Water supply is likely to decrease due to climate change, overexploitation and pollution. It is therefore paramount to protect existing water resources from contamination and increase the use of alternative water resources as new conventional water resources will not become available.

Due to the wide geographical distribution, generally large catchment areas, their discharge towards individual springs and thus their potential for development, carbonate aquifers are very well suited for water supply. The water supply of approximately 25% of the world's population is extracted from carbonate aquifers. An average of about 20 % of the earth's surface is covered by karst or limestone terrains varying by as much as from 0 to 40 %. 75% of Europe's drinking water is supplied by groundwater, 50% of which comes from karst aquifers (STEVANOVIĆ, 2016).

Despite their widespread use, however, the management potential of carbonate aquifers is limited due to their low storage capacity (high hydraulic conductivity, low storage coefficients). Due to their high dynamics, fast reaction times and a low storage capacity, carbonate aquifers require dedicated management concepts.

Forecasting flow and mass transport is an essential part of groundwater resource management, especially for karst systems. There is a need for realistic predictions of the development of groundwater resources in karst systems in terms of quantity and quality due to the extreme variability in runoff behaviour and the high risk of pollutant inputs due to very high transport speeds. This characteristic is primarily a result of the pronounced heterogeneity in the hydraulic parameters and the high contrast in the hydraulic conductivities between highly transmissive fractures and low permeability finely fissured matrix.

Karst aquifers are commonly characterised by high heterogeneity and anisotropy. In mature karst areas, rapid infiltration and high flow velocities are commonplace. Contaminants can easily infiltrate into karst aquifers through sinkholes and other epikarst features and spread rapidly over large distances in the conduit network. Because of the absence of a significant soil cover or low permeability layer covering the karst, the natural attenuation of pollutants is commonly very low. Hence, pollution is not treated in the groundwater system but only transferred. These facts make karst aquifers extremely vulnerable to groundwater contamination (Fig. 1) (MARGANE *et alii*, 2011).

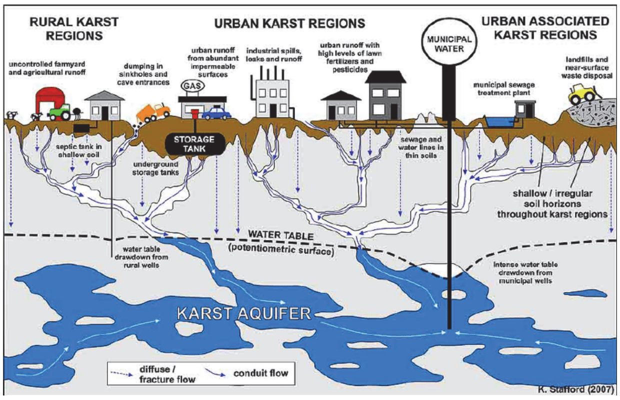

*Fig. 1 - Potential sources of contamination of groundwater and drinking water supplies due to rural and urban activities (*MARGANE *et alii, 2011)*

Knowledge of the hydrodynamics of karst systems is a fundamental element to understand the behaviour of pollutants within them. Available methods in karst hydrogeology include geological, geophysical and speleological methods, hydrologic and hydraulic techniques, the use of natural tracers, such as isotopes and hydrochemical parameters, as well as the application of artificial tracer tests (GOLDSCHEIDER & DREW, 2007). One of the scientific disciplines which deals with the study of the fluid circulation in the subsoil is the hydrogeophysics. It is based on the use of geophysical measures to evaluate parameters and to monitor certain processes which are important for hydrological studies, such as those associated with water resources, transport pollutants, ecological and climatic investigations (NAUDET *et alii*, 2004; CASSIANI *et alii*, 2010; GIAMPAOLO *et alii*, 2016).

Characterization and monitoring, improved by hydrogeophysical techniques, can lead to better management of natural resources and to the understanding of the natural systems dynamics (RIZZO *et alii*, 2019).

METHODOLOGY

The proposed study aims to investigate the hydrogeophysical behavior of carbonate rocks. It will be made with two distinct phases. One phase involves the implementation of some carbonate environment laboratory scales (<1m^3) affected by the fluids circulation. The heterogeneous property of karst aquifer system makes it difficult to study its groundwater. Therefore, groundwater modeling is a very useful tool for studying groundwater problems in karst aquifer systems. Laboratory experiment conditions and analog structures can be changed according to actual need, which shows the importance of laboratory study to field work (ZHANG *et alii*, 2015). It is possible to carry out this phase in the hydrogeosite laboratory of CNR-IMAA (Fig.2), Marsico Nuovo, where other experiments have already been carried out which have concerned the circulation of fluids in particular context, for example: pumping test, gasoline contamination and saline tracer test (GIAMPAOLO *et alii*, 2016; CHIDICHIMO *et alii*, 2015).

Fig. 2 - Hydrogeosite laboratory of Cnr-IMAA, Marsico Nuovo

This laboratory is equipped to conduct experiments on different scales (from 210 cubic metres to 3 cm). The idea is to build a small carbonate environment with calcium carbonate blocks characterised by fluid circulation across fractures and small cavities and to observe them by hydrogeophysical approaches. This experiment is being set up (Fig.3). The laboratory experiences are going to be transferred in a natural carbonate complex where a full scale test will be performed to evaluate the effectiveness of a hydrogeophysical approach for monitoring carbonate aquifer. This phase will be realized in the carbonate karst area of Castel di Lepre (Marsico Nuovo, Basilicata, Italy). Castel di Lepre karst area is located in Marsico Nuovo (Basilicata, Italy) (Fig. 4) and it is a karst system developed in the Maddalena Mts, a carbonate morphostructure of the Southern Apennines.

Fig. 3 – Installation of the small-scale experiment

Southern Apennines are a thrust-and-fold belt formed between the upper Oligocene and Quaternary (PATACCA & SCANDONE, 2007) as a response to convergence between the African plate and the European and contemporary retreat towards the SE of the ionic subduction (GUEGUEN *et alii*, 1998; DOGLIONI *et alii*, 1994).

Fig. 4 – Localization of Castel di Lepre cave (blue line) and old train rail tunnel (red line).

In particular, Castel di Lepre karst system develops in the Meso-Cenozoic carbonate substratum of the Apennine Platform overthrusted over Lagonegro Unit terrain (BOENZI *et alii,* 2004; PALLADINO *et alii*, 2008) (Fig. 5). The units of the Apennine Platform are settled in a paleogeographic domain that represented a high morphological and structural. The sequences belonging to this domain are in platform facies in the axial portion, while at the edge of the platform there are transition formations to the west with the Ligurian Basin and to the east with the Lagonegro Basin (PATACCA & SCANDONE, 2007). During the tectonic phase of extensional type of the lowerJurassic, the Apennine Platform was divided into three main domains that, from west to east are: Bulgheria-Verbicaro Mts

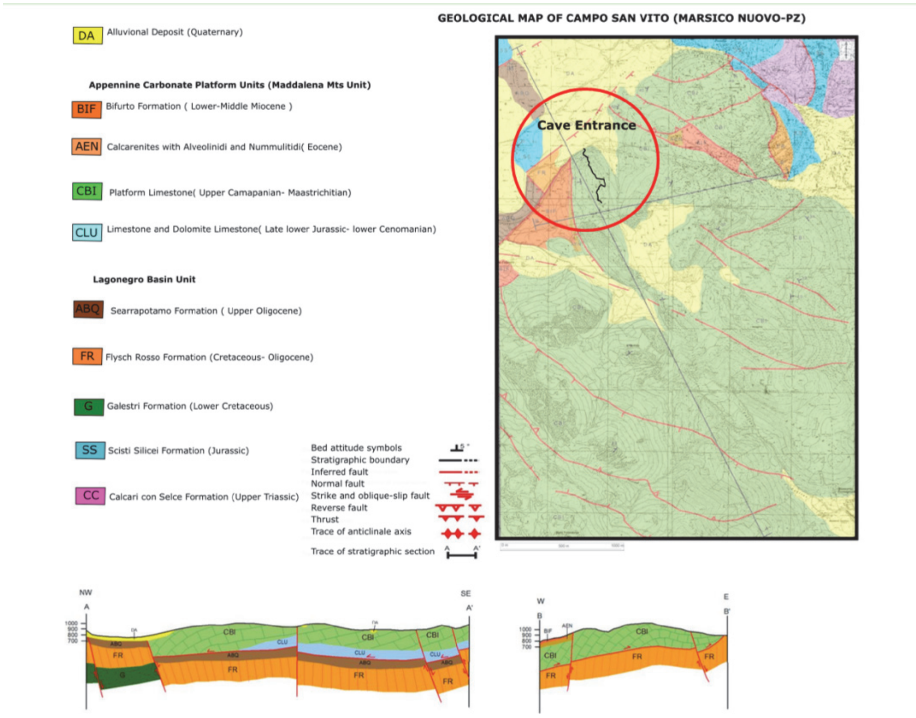

*Fig. 5 – Geological map of the Castel di Lepre area (*GUERRIERO *et alii, 2017)*

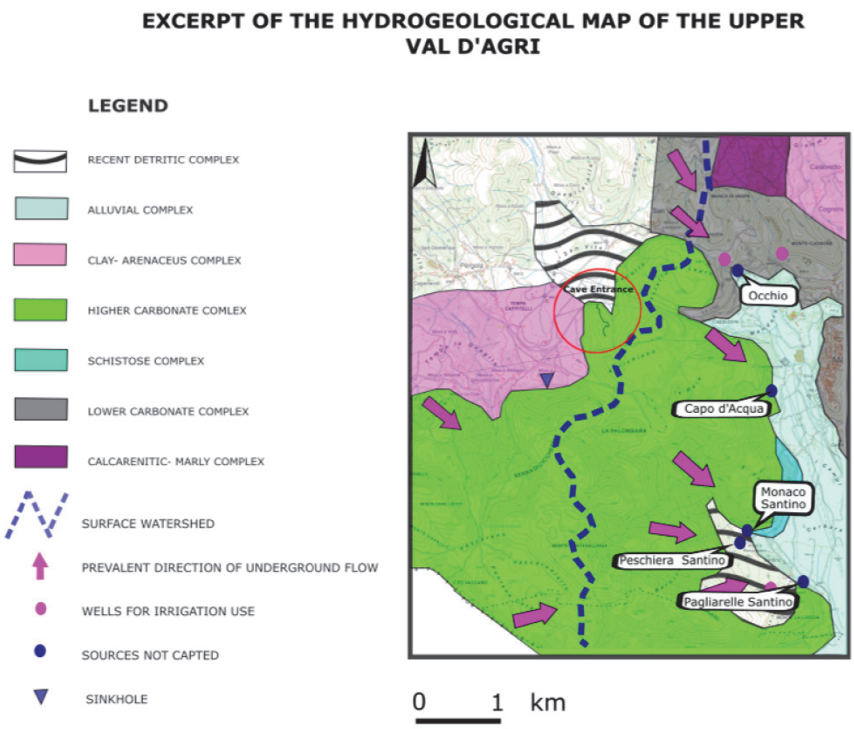

Fig. 6 – Hydrogeological map of the Castel di Lepre area.

Units, Alburno-Cervati Units, and Maddalena Mts Units (D'ARGENIO *et alii*, 1973, PATACCA & SCANDONE, 2007). In the study area, the Apennine Platform is represented by the Maddalena Mts Unity (D'ARGENIO *et alii*, 1973; PATACCA & SCANDONE, 2007), which constitutes the eastern (external) portion of the Apennine Platform. The Unit is formed by a powerful limestone dolomite succession of approximately 1000 m, aged between the upper Triassic and Eocene (PALLADINO *et alii*, 2008).

Castel di Lepre karst area falls between two hydrogeological basins: the Agri River basin and the Sele River basin. From the hydrogeological map (Fig. 6) of the mountain sector of the High Agri Valley it is possible to notice that the prevailing direction of the groundwater is from Sele River basin towards Agri River basin.

In particular, Castel di Lepre area falls in the Santino catchment (Fig.6) and lies in the higher Carbonate complex referring to Cretaceous Crystalline Limestones of the Maddalena Mts Unit (CIVITA *et alii*, 2003), which is characterized by: a high index of fracturing; deep karst only locally developed; a degree of relative permeability from very high to medium; a high index of surface karst.

Large and well-shaped karst landforms are widespread on the carbonate platform rocks of the Maddalena Mts Units.

In the karst area is located a cave (Castel di Lepre), which grows in the Monti della Maddalena mountain. Castel di Lepre cave has a total length of 1848 m and a depth of 146 m from the entrance. In the same karst area, an artificial tunnel (old not used train rail) is located (Fig.4). Castel di Lepre area has a remarkable scientific interest from researchers. In fact, Guerriero et al (2017) have experienced a new geoeletrical method in the Castel di Leper karst area: where a cross-hole ERT acquisition system was applied between cave development and surface. The Fig. 7 shows the 3D Electrical Resistivity Tomography of the Castel di Lepre karst area obtained with electrodes inside and outside the cave. It shows a range of electrical resistivity from 10 Ohm*m to about 3.000 Ohm*m. There are high resistivity zones (> 600 Ohm*m) that could be associated to fractured empty rock or massive carbonate. Moreover, there are some zones with low resistivity values (< 150 Ohm*m) that may be associated with zones with a good circulation fluids with saturated fractured rocks or caves.

Finally, a natural test site will be used to improve the knowledge of the fluid circulation in this rock formation which is characterized by an old railway tunnel. The tunnel has a length of 1229 m, and it is developed in the carbonate complex of the Maddalena Mountains. Inside the tunnel it is possible to notice the stratification and the fracturing of the carbonate rocks (Fig.8).

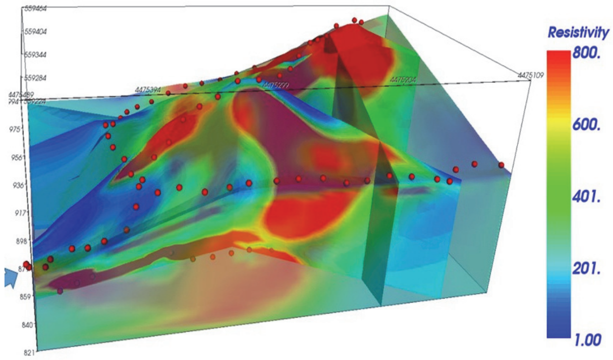

*Fig. 7 – 3D model of the final electrical resistivity (in ohm*m) (GUERRIERO et alii, 2017).*

Moreover, there are several dripping areas and various speleothems (Fig. 9). Therefore, the tunnel structure should be associated a great natural context to understand fluid circulation in a karst carbonate environment by hydrogeophysical approaches.

Fig. 8 – a) The old railway tunnel; b) Stratification and fracturing

EXPECTED RESULTS

The results expected from this project are to develop methodologies and new geophysical approaches with the ability to obtain observations of fluid circulation in fractured carbonate and karstic rocks.

This objective can be pursued through modelling applications both at the laboratory scale (scale from $1m^3$ to $200m^3$) and at the field scale (scale $1.000.000m^3$) capable of simulating the geological conditions of a reservoir.

This study will prove the feasibility of using a carbonate analog model to generate the data needed to understand the flow in fracture and conduit domains and provided a basis for further study.

The results obtained by Guerriero et al (2017) demonstrate the importance of geophysical surveys in the characterization of a carbonate environment.

The hydrogeological study (Caste di Lepre) and the preparation of geophysical equipment are in progress. It was made a survey of all the most evident features in the tunnels.

The integration of geophysical techniques and hydrogeological parameters (at different scale) will allow to develop a hydrogeophysical approach for the circulation of fluids in carbonate environments. Finally, the expected results can contribute to improving the study of carbonate environments in the context of natural risk, which is the product between the probability of a potentially dangerous natural phenomenon (hazard), the vulnerability of the concerned territory (including the assets in it) and the economic value of goods in the same territory.

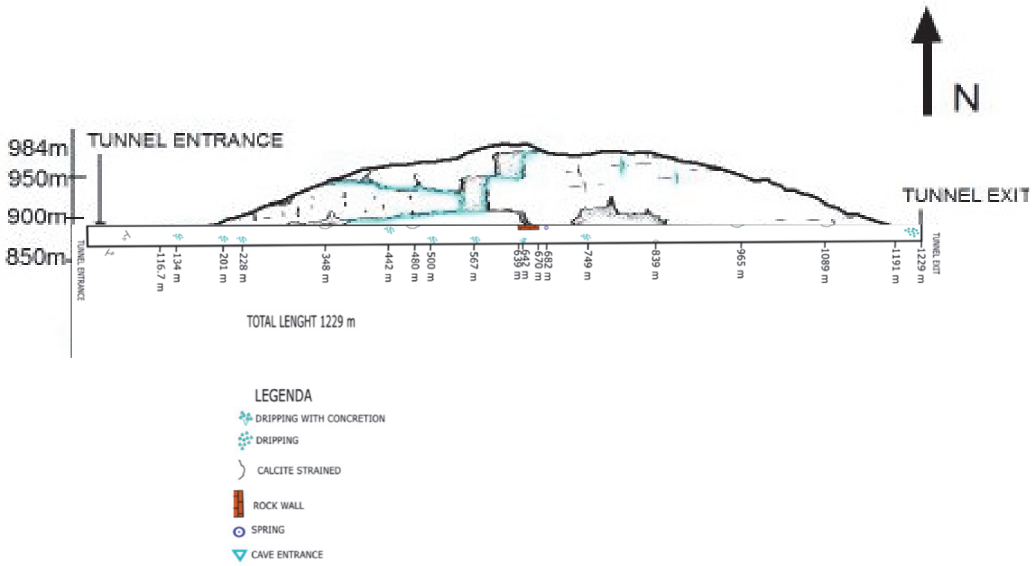

Fig. 9– Sketch of the karstic area above the tunnel.

REFERENCES

BOENZI F., CAPOLONGO D., CECARO G., D'ANDREA E., GIANO S. I., LAZZARI M. & SCHIATTARELLA M.(2004) - *Evoluzione geomorfologica polifasica e tassi di sollevamento del bordo sud-occidentale dell'alta Val d'Agri (Appennino meridionale).* Boll. Soc. Geol. It., **123**: 357-372.

CASSIANI G., ANDREW BINLEY, ALESSANDRO BROVELLI, RITA DEIANA, PETER DIETRICH, ADRIAN FLORES, ANDREAS KEMNA, RIZZO E. (2010*) - Static and dynamic aspects of near surface characterization through physics-based integration of GPR, ERT, SIP and SP data in the time-lapse mode.* 72nd European Association of Geoscientists and Engineers Conference and Exhibition Incorporating SPE EUROPEC 2010, Workshops pp. 179-182

CIVITA M., DE MAIO & VIGNA B. (2003) - Studio delle risorse sorgive degli acquiferi carbonatici dell'Alta Val d'Agri. In: A. Colella (Ed.) *"Le risorse idriche sotterranee dell'Alta Val d'Agri",* Collana Editoriale di studi e ricerche Autorità interregionale di bacino della Basilicata, **3**: 221-356

CHIDICHIMO, F., BIASE, M.D., RIZZO, E., MASI, S., STRAFACE, S. (2015) - *Hydrodynamic parameters estimation from self-potential data in a controlled full scale site*, Journal of Hydrology (2015), doi: http://dx.doi.org/10.1016/j.jhydrol. 2015.01.022

D'ARGENIO B., PESCATORE T., SCANDONE P. (1973) – *Schema geologico dell'Appennino meridionale (Campania- Lucania).* In: Atti del Convegno "Moderne vedute sulla Geologia dell'Appenino". Acc. Naz. Lincei, Quaderno, **183**: 49-72.

DOGLIONI C., MONELLI F., & PIERI P. (1994) – *The Puglia uplift (SE Italy): An anomaly in the foreland of the Appeninic subduction due to bucklingof a thick continental lithosphere.* Tectonics.

GIAMPAOLO V., DANIELA CALABRESE, AND ENZO RIZZO (2016) - *Transport Processes in Porous Media by Self-Potential Method, Applied and Environmental Soil Science*, vol. 2016, Article ID 3951486, 12 pages, 2016. doi:10.1155/2016/3951486

GOLDSCHEIDER N, DREW D (EDS) (2007B) - *methods in karst hydrogeology. International contribution to hydrogeology*, IAH. Taylor & Francis/Balkema, London

GUEGUEN E., DOGLIONI C. & FERNANDEZ M. (1998) – On the post-25 Ma *geodynamic evolution of the western Mediterranean*. Tectonophysics.

GUERRIERO M., RIZZO E., GUEGUEN E., CAPOZZOLI L., DE MARTINO G., PERCIANTE F- (2017) - *Cave-surface Electrical Resistivity Tomography in "Castello di Lepre" Karst System (Marsico Nuovo, Southern Italy)*, 23rd European Meeting of Environmental and Engineering Geophysics, Monitoring and Characterization of the Shallow Subsurface I, 03 September 2017 DOI: 10.3997/2214-4609.201702078

MARGANE, ARMIN & STEINEL, ANKE (2011) - Special Report No. 4: *proposed national standard for treated domestic wastewater reuse for irrigation.*

NAUDET V., A. REVIL, E. RIZZO, J. Y. BOTTERO , AND P. BÉGASSAT (2004) - *Groundwater redox conditions and conductivity in a contaminant plume from geoelectrical investigations.* Hydrology and Earth System Sciences, **8** (1): 8-22

PALLADINO G, PARENTE M., PROSSER G. &. DI STASO A (2008) - *Tectonic control on the deposition of the Lower Miocene sediments of the Monti della Maddalena ridge (Southern Apennines): synsedimentary extensional deformation in a foreland setting*, Boll.Soc.Geol.It. (Ital.J.Geosci.),**127**: 317-335.

PATACCA E. & SCANDONE P. (2007) – *Geology of the Southern Apennines*. Boll. Soc. Geol. It. **75**-119, 14, 1.

RIZZO E., CAPOZZOLI L., DE MARTINO G., GIAMPAOLO V., GUERRIERO M. & GUEGUEN E. (2018) - *Integrated geophysical approach for karst system characterization: Castello di Lepre karst cave (Marsico Nuovo, Basilicata Region, Italy)*, EGU General Assembly, Vienna, 8–13 April 2018

RIZZO E., GIAMPAOLO V., CAPOZZOLI V., GRIMALDI S. (2019) - *Deep Electrical Resistivity Tomography for the hydrogeological setting of Muro Lucano Mounts aquifer (Basilicata, Southern Italy).* Geofluids, vol. 2019, Article ID 6594983, 11 pages, 2019. https://doi.org/10.1155/2019/6594983

STEVANOVIĆ Z. (2016) - *Karst aquifers*—characterization and engineering. Environmental Earth Sciences. **75**. 10.1007/s12665-016-5412-0.

ZHANG CHUNYAN, SHU LONGCANG, APPIAH-ADJEI E, LOBEYO K. ANGELO G. A, TANG RAN, FAN JIANHUI (2015) - *Laboratory simulation of groundwater hydraulic head in a karst aquifer system with conduit and fracture domains*. Carbonates evaporites