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HYDROGEOLOGICAL CHARACTERIZATION AND GROUNDWATER VULNERABILITY TO POLLUTION ASSESSMENT OF THE HIGH BASENTO RIVER VALLEY CARBONATE HYDROSTRUCTURE (BASILICATA, SOUTHERN ITALY)

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EXTENDED ABSTRACT

Negli ultimi decenni la scarsità d'acqua è diventata una questione cruciale e rappresenta uno dei principali potenziali rischi che molte regioni del mondo devono affrontare. La crescita della popolazione mondiale, il miglioramento degli standard di vita, i cambiamenti nei modelli di consumo e l'incremento di pratiche agricole intensive rappresentano le principali forzanti che concorrono al costante aumento della domanda di acqua (VÖRÖSMARTY *et alii*, 2010; MEKONNEN *et alii*, 2016).

La carenza di acqua dolce rappresenta una seria minaccia per lo sviluppo sostenibile e svolgerà un ruolo chiave nel prossimo futuro nella definizione delle politiche ambientali e di sviluppo. Tuttavia, per una comprensione globale della futura disponibilità di acqua su scala globale e locale, al fine di attuare azioni di prevenzione per una corretta salvaguardia e tutela degli ecosistemi, è necessario considerare le interazioni tra gli impatti antropici e la variabilità dei cambiamenti climatici, l'uso del suolo, l'inquinamento delle acque superficiali e sotterranee, l'ingegneria delle acque e i sistemi umani, compreso l'adattamento della società alla mancanza d'acqua (VÖRÖSMARTY *et alii*, 2000; DISTEFANO *et alii,* 2017).

Secondo la recente normativa europea (Direttiva 2000/60CE e Direttiva 2006/118CE) e nazionale (D.Lgs.152/2006) in materia di tutela quali-quantitativa delle acque sotterranee, è necessario definire ed applicare le azioni e le procedure più appropriate, su scala idrogeologica, finalizzate alla pianificazione e alla gestione strategica in grado di prevenire o contenere il depauperamento ed inquinamento delle risorse idriche sotterranee, nonché tenendo conto delle strategie di mitigazione in relazione agli impatti dei cambiamenti climatici attraverso un uso razionale e sostenibile dell'acqua sotterranea (MAYS, 2013; COSGROVE & LOUCKS*,* 2015).

Nelle regioni del Mediterraneo, minacciate dalla scarsità d'acqua a causa soprattutto dell'aumento della domanda e degli effetti dei cambiamenti climatici, gli acquiferi carbonatici costituiscono i principali serbatoi idrici per l'approvvigionamento potabile (ZINI *et alii*, 2013; STEIAKAKIS, 2018; CANORA *et alii*, 2019). La conoscenza dettagliata dei sistemi idrogeologici, la valutazione sia delle risorse idriche sotterranee potenzialmente disponibili che della vulnerabilità all'inquinamento degli acquiferi costituiscono gli elementi necessari per un'efficace gestione e tutela delle risorse idriche sotterranee.

In questo studio, le attività di ricerca sono state rivolte alla definizione dei caratteri idrogeologici dell'idrostruttura carbonatica dell'Alta Valle del Fiume Basento (Basilicata, Italia meridionale), che alimenta importanti sorgenti captate e non, attraverso un approccio metodologico applicabile a contesti idrogeologici scarsamente studiati con disponibilità di dati limitata.

L'idrostruttura carbonatica, che costituisce una delle principali risorse idriche a scopo potabile della Regione Basilicata, si colloca geograficamente nella parte centrale della stessa regione e si sviluppa in direzione NNW-SSE, lungo il settore assiale della catena sud-appenninica. Il complesso assetto geologico-strutturale della dorsale carbonatica si riflette, condizionandolo, nell'altrettanto complesso ed articolato ambiente idrogeologico.

A partire dalle indagini geologiche ed idrogeologiche condotte in situ è stato possibile procedere alla definizione di un quadro conoscitivo più approfondito dell'idrogeologia del dominio carbonatico. Questo lavoro ha consentito, attraverso indagini geostrutturali in campo, la definizione del ruolo esercitato dalle discontinuità presenti negli ammassi carbonatici, in relazione alle modalità di circolazione idrica all'interno dei mezzi rocciosi fratturati (SCESI & GATTINONI, 2007, 2012); il bilancio idrogeologico, effettuato sulla base dell'analisi dei dati climatici e delle portate erogate dalle sorgenti, ha permesso di ottenere informazioni quantitative sulla risorsa idrica sotterranea e a determinare l'entità dell'infiltrazione efficace della struttura idrogeologica (CIVITA, 2005; CANORA *et alii*, 2018); in ultima analisi, è stata valutata la vulnerabilità del sistema acquifero all'inquinamento (CIVITA, 2005, 2010).

L'approccio utilizzato ha permesso di definire gli elementi indispensabili per la corretta gestione delle risorse idriche e per la valutazione del potenziale impatto degli inquinanti nelle acque sotterranee.

ABSTRACT

The High Basento River Valley, located in the central-western sector of the Basilicata region (southern Italy), is a productive carbonate hydrostructure of the Lucanian Apennines, which represents a strategic water resource for drinking purposes. Huge discharges, quantified at about 10 Mm^3/y, flow from several exploited springs afferent to the groundwater system, many other springs are not picked up, even if characterized by a considerable amount of water.

The aim of this study was to improve the understanding in the hydrogeological features of the aquifer system through performing geostructural field surveys finalized to define the effective hydraulic fracture permeability and the equivalent permeability of the carbonate hydrostructure. Furthermore, the application of an inverse hydrogeological water balance method to evaluate the effective recharge amount and the intrinsic vulnerability assessment of the hydrogeological basin were also performed.

The purpose of these investigations was to obtain a detailed understanding of the carbonate hydrostructure, which may be useful in order to define integrated action criteria and safeguard strategies for the effective protection and sustainable management of groundwater resources.

Keywords: *carbonate hydrostructure, hydrogeological characterization, vulnerability to pollution assessment, southern Italy*

INTRODUCTION

During the last few decades, water scarcity has become a crucial issue and represents one of the main potential risks to be faced by many regions in the world (Shiklomanov, 2000; Veldkamp *et alii*, 2017). World population growth, improvement of living standards, changes in consumption models, and the increase of intensively irrigated agriculture are the main driving forces for the steadily rising demand for water (Vörösmarty *et alii*, 2010; Mekonnen *et alii*, 2016).

Freshwater shortage is becoming a threat to the sustainable development of human societies and is going to play a key role in the near future for the definition of both environmental and development policies. Changes in population growth and economic development dictate the relationship between water supply and demand. However, for a comprehensive understanding, of future water availability at global and local scale, it is necessary to consider the interactions among climate change impacts and variability, soil degradation, changes in land use (Canora *et alii*, 2012, 2015), groundwater pollution, and water engineering and human systems including societal adaptations to water scarcity (Vörösmarty *et alii*, 2000; Distefano *et alii,* 2017).

In the assessment of the impact of these main drivers, natural processes and their interactions are the key issues to consider in defining the implementation of efficient water management projects and actions in relation to water supply and water demand, quantitative and qualitative protection strategies, and opportune conservation measures.

Nowadays groundwater planning and protection are important and complex problems to deal with in terms of the issues of aquifer safety and groundwater control in order to ensurerational and sustainable use. According to the EU Water Framework Directive 2000/60 and the EU Directive 2006/118 on the protection of groundwater, the most appropriate actions and procedures at the hydrogeological basin scale, should be applied to define strategic management processes, to prevent or contain the groundwater resources, potential depletion and pollution. In addition, these actions must take into account mitigation strategies for the impacts of climate change (Mays, 2013; Cosgrove & Loucks, 2015).

Karst and fractured carbonate aquifers have always constituted important freshwater resources in many Mediterranean regions that are threatened by water scarcity mainly due to increased demand and the effects of climate change (Zini *et alii*, 2013; Steiakakis, 2018; Canora *et alii*, 2019). Detailed knowledge of the hydrogeological systems, of the potential available groundwater and of the groundwater's aquifer vulnerability to pollution contribute to the successful management of groundwater resources. Therefore, through appropriate monitoring plans, it is possible to intervene promptly and maintain or reinstate the optimal characteristics of a given groundwater source.

The understanding of groundwater flow paths into fractured carbonate hydrogeological systems is a complex task because it is controlled by the fractures features and the hydrological parameters (Scesi & Gattinoni, 2007, 2012). In order to characterize the fractured aquifers, specific focus should be directed towards geostructural analyses. These are of interest in different geoscience fields such as hydrogeology, petroleum reservoir exploitation, civil engineering, mining and environmental waste repositories (Berkowitz, 2002). The analysis of the distribution of discontinuities and the interpretation of the fracture geometry and properties in the carbonate rock masses allows the definition of the fracturing state. Discontinuities allow storage and flow, for this reason it's important to understand and describe the structure of the rock-mass, and quantify the pattern and nature of its discontinuities (Van Golf-Racht, 1982; De Marsily, 1986; Lee & Farmer, 1993). The fracture network system plays a significant role in determining and controlling the effective permeability of the rock masses. The discontinuities, such as faults, bedding planes, and joint and fracture sets, make carbonate rocks a highly heterogeneous media and strongly condition the main flow velocity and path (SINGHAL & GUPTA, 1999).

The sustainable water resources management requires an understanding of the hydrological processes and the accurate estimation of the groundwater balance parameters, which in turn are essential to estimate the potential groundwater recharge under the given climatic conditions. Understanding groundwater recharge is a prerequisite for the meaningful groundwater flow, and, therefore, the successful management of renewable water resources.

Vulnerability to pollution is the term usually used to define an intrinsic property of a groundwater system to human and/or natural impacts, taking into account the inherent geological, hydrological and hydrogeological characteristics of the aquifer system (ALBINET & MARGAT, 1970; FOSTER, 1987; VRBA & ZAPOROZEC, 1994; GOGU & DASSARGUES, 2000).

In the last few decades, many approaches have been developed to assess groundwater vulnerability. They can be divided into several different categories: hydrogeological complex setting methods, overlay/index methods, and process-based and statistical methods (GOGU & DASSARGUES, 2000; LIANG, 2016). The choice of the method to assess the intrinsic vulnerability depends on several factors such as the hydrogeological data availability, the geology, the aquifer system features, and the scale of the study area (ALBINET & MARGAT, 1970; FOSTER, 1987; CIVITA & DE MAIO, 1997; ZWAHLEN, 2004).

In the Basilicata region, extensive and wide fractured carbonate aquifers are present (CANORA *et alii*, 2019). In this study, in order to define the hydrogeological setting and vulnerability to pollution assessment of the High Basento River Valley hydrostructure, a comprehensive methodological approach was applied. Investigations included geological and hydrogeological field studies to understand the peculiar characteristics of the hydrogeological system, detailed field geostructural investigations of the limestone rock masses, hydrogeological water balance applicationand intrinsic vulnerability assessment finalized to groundwater quali-quantitative safeguarding and protection.

STUDY AREA

The High Basento River Valley is geographically located over the Pierfaone (1737 m a.s.l.) and Arioso (1707 m a.s.l.) Mounts, in the central-western part of the Basilicata region (southern Apennine, Italy) (Fig. 1).

It is characterized by a fractured carbonate hydrostructure drained by several springs that are important freshwater resources for human consumption in the region.

The springs, present throughout the study area, are characterized by variable amounts of groundwater discharge that contribute to the feeding of the upper part of the Basento River hydrographic network. Among the torrents, the most important is Fossa Cupa from which the Basento River is born.

In the area, characterized by temperate climate, varying according to latitude and altitude, present higher precipitation in winter on Pierfaone and Arioso Mounts. At about 1700 m, rainfall increases, are frequent snowfalls and low temperatures.

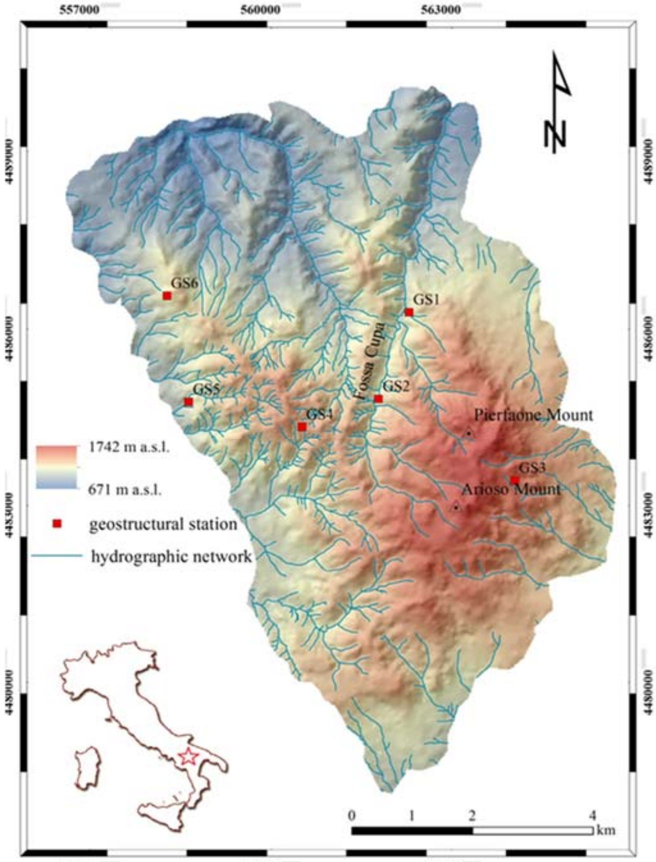

Fig. 1 - Geographic location of the study area: High Basento River Valley elevation map with the hydrographic network and the geostructural test sites.

GEOLOGICAL SETTING

The High Basento River Valley morphostructure extends in the NNW-SSE direction in the inner part of the Southern Apennine Chain that, together with the Apulian Foreland and Bradanic Foredeep, form the three great geological structures of southern Italy. In this sector of the Apennine Chain, there exists outcrops of the formations of the two Lagonegro Units (SCANDONE, 1972; PATACCA & SCANDONE, 2007). These deep basin allochthonous units were originally located between the internal Apennine platform and the external Apulian platform (MOSTARDINI & MERLINI, 1986). The Lagonegro Units originated in a deep-water basin, evolving into a Miocene wide foredeep (COCCO *et alii*, 1972) that is localized to the west of the

Apennines-Apulia platform complex (MARSELLA *et alii*, 1995). These basin units became involved with the allochthonous western carbonate units after their placement as a complex accretionary wedge over much of the carbonate complex. Therefore, it is possible to find the basin units both under (IETTO, 1963; SCANDONE, 1972; D'ARGENIO *et alii*, 1973; TURCO, 1976; PALLADINO *et alii*, 2010) and over the western platform units (IETTO, 1963; MARSELLA *et alii*, 1995; D'ARGENIO *et alii*, 1973; TURCO, 1976; FERRANTI & PAPPONE, 1992; IETTO & BARILARO, 1993; PALLADINO *et alii*, 2010).

In this complex geological and structural setting, outcrops only occur in the Mesozoic pelagic successions of the Lagonegro II Unit or Monte Arioso Unit (PESCATORE *et alii*, 1999). Tectonically, the Lagonegro II Unit lies above the Lagonegro I Unit and is represented in the area by the clayey-marly Galestri formation (Lower-Middle Cretaceous).

It is formed by black shale, siliceous mudstones, jaspers, and grey siliceous marls succession (SCANDONE, 1972) (Fig. 2).

From the bottom to the top, the Lagonegro II sedimentary succession shows different geological formations:

• Monte Facito (Lower-Middle Triassic), which is subdivided into two distinct units: the first is the terrigenous (silico-clastic) unit, made up of a succession of quartziferous calcarenites and mudstones, marls, shales and green micaceous sandstones. It is strongly deformed and frequently associated with gravels. The second is the organogenic unit, made up of grey massive limestones and fractured black limestones and marls. This is a chaotic formation and it is not possible to reconstruct a stratigraphic succession inside it (DONZELLI & CRESCENTI, 1970; WOOD, 1981; MICONNET, 1983; CIARAPICA *et alii*, 1990; MIETTO *et alii*, 1991):

• Cherty Limestone (Upper Triassic), overlying the Monte Facito formation, which is made up of centimeters to decimeters-thick layers of grey limestones with primarily beds and secondarily, nodules of black and white chert, marls and calcareous marls, mudstones and marly clays. This formation, which is well layered, is strongly fractured (SCANDONE, 1972). Slumps and debris-flow deposits prevail at the top of the formation (MARSELLA, 1988; AMODEO *et alii*, 1993).

• Siliceous Schists (Cretaceous-Jurassic) formed by thin-layered and fractured variegated cherty shales, partial cherty marls, graded pebbly limestones, and green and red radiolarites (SCANDONE, 1972; MICONNET, 1983; MARSELLA, 1988).

• Galestri (Jurassic Superior) formed by an alternation of grey shales, white or grey silty marls and grey and brown marly limestones with a decimetric thickness (SCANDONE, 1972; MARSELLA *et alii*, 1995).

Plio-Pleistocene deposits, discordant to the top of the structure, include recent alluvial deposits, sandy-silty deposits with gravel levels and chaotic accumulations of heterogeneous materials, occurring, locally in large blocks (SCHIATTARELLA *et alii*, 2003).

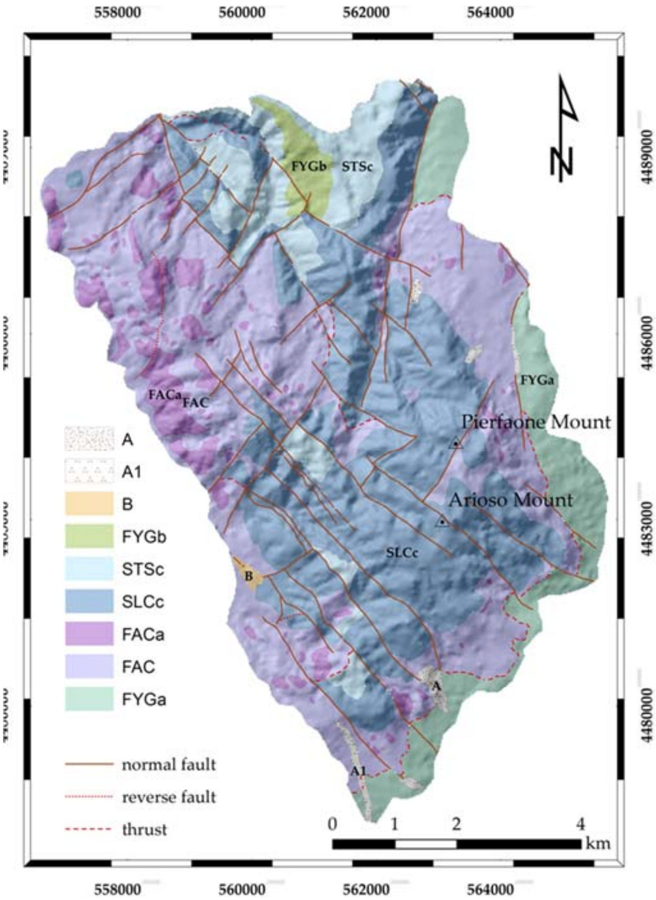

Fig. 2 - Geo-structural map of the High Basento River Valley Carbonate Hydrostructure adapted from ISPRA (2017) with geological units and structural elements. Geological Units: A — Slope Deposits (Holocene); A1 — Landslide Deposits (Holocene); B — Alluvial Deposits (Holocene); FYGb — Galestri Formation (Jurassic Superior); STSc — Siliceous Schists Formation (Cretaceous-Jurassic); SLCc — Cherty Limestone Formation (Upper Triassic); FACa — Monte Facito Formation (Organogenic Unit; Middle Triassic); FAC — Monte Facito Formation (Terrigenous Unit; Middle Triassic); FYGa — Galestri Formation (Lower-Middle Cretaceous)

The occurrence of wide fold-and-thrust structures, dissected by several prominent faults, some of wich show considerable horizontal displacement, distinguishes the tectonic setting of the study area. Folds and wide anticlines and synclines, affect the formations in this area, generally in association with thrust and back-thrust faults. In particular, a wide syncline folding, culminating in the Pierfaone and Arioso Mounts characterises the morphostructure. The plicative structures, with NNO-SSE orientations that were produced by the Oligocene-Pliocene compressive tectonics, have been displaced by direct faults generated during the Plio-Pleistocene uplift (Ogniben, 1969; Lentini *et alii*, 2002; Schiattarella *et alii*, 2003).

The siliceous-carbonate morphostructure of the Arioso-Pierfaone Mounts has an Apennine trend fault system with a N120±10° orientation and high-angle faults oriented N50–60° (Fig. 2). The top of the carbonate dorsal shows a low gradient paleo-erosional surface, with widely backward slopes. The NW-SE oriented structures and high-angle faults, oriented NE-SO, have lowered the erosional surface to the south-west and to the west (Martino, 2007). These sub-vertical faults, with hundreds of meters of displacement, are parallel and orthogonal to the fold axes.

These faults, mainly present in the cherty limestone-dolomite succession characterized by different permeability (medium to high), condition the groundwater flow directions and allow partially separated aquifers.

HYDROGEOLOGICAL CHARACTERISTICS

In Basilicata, carbonate series host the most important regional aquifer that supply the main drinkable water resources of the region. On the basis of their hydrogeological features, identify different carbonate aquifers typologies. The carbonate aquifers constituted by alternating limestone, limestone with chert, marl limestone and subordinately marls, are characterized by a permeability due chiefly to fracturing, and whose grade varies from medium to low, according to relative abundance of low-permeability lithotypes (De Vita *et alii*, 2018). The siliceous-limestone hydrostructure of the High Basento River Valley belongs to this group.

The geological and structural specificities and peculiarities of the morphostructure contribute to the complex geometry of the hydrogeological system, the groundwater flow and the emergence modalities of the springs. High-angle faults, tectonic deformation bands, thrusts, and a very variable fracturing state affect the hydrogeological systems, which are characterized by some narrow and deep ditches.

From the hydrogeological point of view, three main units with distinct lithological features and hydraulic characteristics characterize the hydrogeology of the study area (Fig. 3).

The Carbonate Complex made up of fissured-fractured siliceous limestones, grey massive limestones and marls limestones, represents the main aquifer system that feeds the most important springs of the area.

This hydrogeological unit includes two cherty limestone sub-complexes, distinguished by different permeability conditions, the fractured sub-complex of the Pierfaone and La Cerchiara sub-structures characterized by a high degree of permeability, and the fissured carbonate sub-complex (the Arioso Mount, San Michele, Betina and Serra della Criva sub-structures) belonging to the rest of hydrostructure with a medium-high degree of permeability.

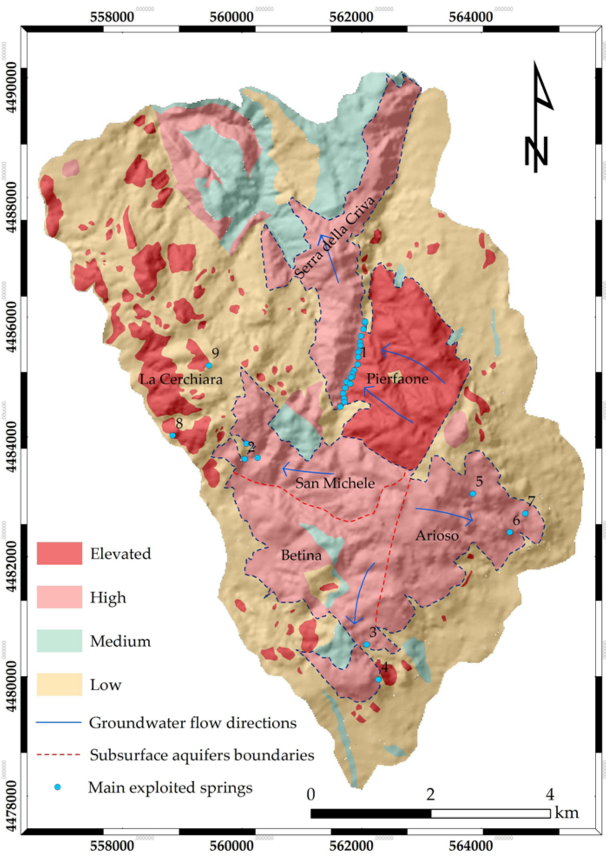

Fig. 3 - Hydrogeological map of the investigated area with the different permeability classes related to the hydrogeological complexes and the main exploited springs: 1–Fossa Cupa group; 2–San Michele group; 3–Fiumicello and 4–Betina springs; 5–Mar di Levante II, 6–Pantano di Mar Levante and 7–Croce Camillo springs; 8–Linise and 9–Macchitello springs. Also shown are the limits of the carbonate hydrostructure (black dashed line), the main groundwater flow directions (blue dotted line), and the sub-surface aquifer boundaries (red dashed line) and their indication

The Siliceous Schists Complex, which locally outcrops, has a medium-low degree of relative permeability, stores part of the total groundwater amount, transmits it slowly, and allows the emergence of small temporary springs.

The Clayey-Marly Complex, characterized by low permeability, belongs to the Monte Facito and Flysch Galestrino Formations and it represents the lithological unit bordering the hydrogeological system. The clayey-marly formations, which have a low degree of permeability, play an important hydrogeological role and border the carbonate structures, making them the permeability limit for groundwater outflows.

In small parts of the study area are present limited outcropping of the Detritical Complex and Fluvio-lacustrine Complex, (both referable in Fig. 2 to the geological formations identified, for the Detritical Complex with the abbreviations A and A1, and with the abbreviation B for the Fluvio-Lacustrine Complex). The Detritical Complex includes heterogeneous and heterometric lithotypes, mainly of arenites and subordinately of limestones of variable size and shape depending on the state of fracturing of the rocks, locally in large blocks, accumulated by gravity or linked to exogenous alteration processes. The structure consisting of blocks and clasts, melted or weakly cemented, immersed in scarce gravelly-sandy matrix, allows the fluid circulation providing a medium degree of relative permeability. The limited and shallow Fluvio-lacustrine Complex comprehends clays, silt and silty sands layered with gravel levels in clay matrix support, which determine the low degree of relative permeability.

The important structural elements present throughout the entire hydrostructure, such as faults, tectonic deformation bands, and rock fissuring and fracturing, define many underground watersheds and influence the sub-surface flow directions, distinguishing some hydrogeological sub-structures with different groundwater flows, specific hydrodynamic characteristics, and emergence of numerous springs (SDAO & LORENZO, 2003). The Pierfaone, Arioso, and San Michele sub-structures host the most important aquifers and the major exploited spring discharges (Fossa Cupa Group - mean discharge of 110 l/s; Mar di Levante, Pantano di Mar Levante and Croce Camillo springs—mean discharge of 72 l/s; San Michele Group - mean discharge of 103 l/s). The La Cerchiara, Betina and Serra della Criva sub-structures have smaller amounts of exploited groundwater (the Linise, Macchitello, Betina, and Fiumicello springs - mean discharge of about 85 l/s) (LANDSYSTEM, 1987).

The Carbonate Complex shows a high fracture intensity corresponding to the Pierfaone Mount sub-structure that, because of the presence of a synclinal structure, rests on the clayey-marly complex, with thicknesses varying between 200 m and 350 m (RAPTI-CAPUTO & SDAO, 2003).

The groundwater flow essentially occurs in two prevailing preferential directions - NE-SW and NW-SE - corresponding to the areas where the main springs are located. The groundwater paths are conditioned by the different fracturing degrees of the carbonate complex, which vary in relation to the different types of primary and secondary discontinuities characterized by specific geometric and intrinsic parameters (HENCHER, 2014).

In the northwestern area of the Pierfaone Mount, a notable amount of water travels along flow lines oriented SE-NW, promoted by discontinuity networks such as bedding planes, faults and fractures. In the southeastern area of the Arioso Mount and in the southwestern part of the carbonate complex, the extension of the fracturing state is limited, and a restrained flow is oriented in the NW-SE and S-SE directions (Fig. 2).

The complex geological and structural arrangement of the hydrogeological carbonate system and the low relative permeability of the confining clayey deposits have a strong influence on the recharge area and on the carbonate hydraulic conductivity, and consequently create the necessary conditions for the discharge of several springs of which many of them tapped by the aqueduct for drinking purposes. The Fossa Cupa Group are the most important springs of the hydrostructure. These springs drain the Pierfaone Mount sub-structure with an extension of about 7 km^2.

The springs consist of at least 24 water emergences, located corresponding to the riverbed of the Fossa Cupa stream, between 1149 and 1300 m a.s.l. and along the N10°-30°direct fault that dissects the carbonate complex at a N-S orientation. This direct fault, characterized by a diffuse cataclastic state, is the spring's superimposed permeability threshold.

The different captured emergencies of the San Michele Mount spring group, located between 1125 m and 1280 m a.s.l., drain the second important sub-structure. These springs occur at the tectonic contact between the carbonate complex and the clayey-marly complex. The entire hydrostructure has the mean water discharge of about 10 Mm^3/y.

MATERIALS AND METHODS

Geostructural Analysis

In order to understand the fracturing state of the rocks and the role of single discontinuities set and discontinuity systems, different geo-structural investigations have been performed.

Field surveys were carried out at six structural test sites (Fig. 1), located along the carbonate outcrops and distributed according to the geological features of the carbonate formations, the hydrogeological setting, and the structural rock mass properties. The aim was to measure the geometric and physical parameters of the discontinuity sets: orientation, spacing, aperture, fracture length (i.e. persistence), roughness, degree of alteration, and filling materials (BARTON, 1978).

The fractures are of primary importance in hydrogeological investigations, because of the significant water flow that take place through them.

Therefore, to characterize the hydraulic conductivity of such a rock mass, the fracture characteristics have been defined. Fracture geometry and properties, detected from geostructural field surveys are used in a simple approach based on fracture field mapping to assess the hydraulic conductivity of the fractured rock masses.

The discontinuities data, as controlling factors enhancing water flow, are necessary to determine the effective and equivalent permeability of the fractured cherty limestone formations, (SNOW, 1969; KIRÁLY, 1969; LOUIS, 1974).

The structural analysis on the outcropping limestone was performed using one-dimensional scanline methodology, which provides the measurements of the all fractures intersecting a reference line (linear scanline sampling) (WATKINS *et alii*, 2015). Along the scanlines, the discontinuities in the spatial distribution and the geometrical properties (PITEAU, 1973; PRIEST & HUDSON, 1981; PRIEST, 1983) were recorded following the recommendations suggested by the International Society for Rock Mechanics (ISRM) (BARTON, 1978), including the progressive location, orientation, length, spacing, aperture, filling materials, persistence, roughness, and fracture set number. The discontinuity data collection crossing the scanline was aimed at identifying the discontinuity sets in the rock mass, and estimating their hydraulic properties.

In order to define the structural rock mass properties for calculating effective and equivalent hydraulic conductivities, a field surveys were conducted at six structural scanline stations homogeneously distributed according to the geological and hydrogeological framework.

Fracture collection was carried out by field surveys in different study sites representative of the dominant geostructural setting of the rock masses, using linear scanlines ranging in length from 5–12 m, along cherty limestone outcrops (Fig. 4).

The measurements were carried out by placing a metric roll on the outcrop to define the fracture attributes, such as the orientation, length, aperture, spacing, roughness fracture and filling, of each fracture that intersected the metric roll (PRIEST & HUDSON,1981). The scanlines are oriented as to intersect all the present fracture sets (PRIEST,1983).

Orientation is the parameter used to define a single fracture plane in the space; several fracture planes with the same orientation create a fracture set. The fracture orientation data were recorded as dip/dip-direction, then were plotted in the lower hemispheric projection equal area contour plots of poles to fracture planes.

Systematic joints are roughly equidistant and possess parallelism, and therefore, the parameter spacing has significance. It has an important influence on rock mass permeability and groundwater flow. The fracture spacing on the surface outcrops is defined as the spatial locations between consecutive intersections of two fractures along the sampling line. The orthogonal distance between two adjacent discontinuities of the same set have been used to compute the average spacing of at single set. Fracture spacing is reciprocal of the fracture frequency or linear fracture intensity. It also controls fracture intensity and matrix block size. Fracture spacing is related to fracture frequency which is both a density and intensity measure (HUDSON & PRIEST, 1983). Fracture spacing is reciprocal of the fracture frequency.

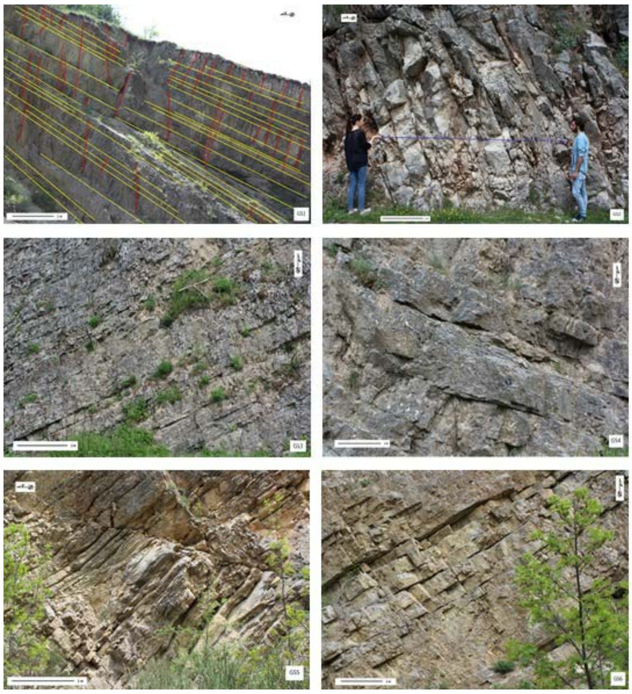

Fig. 4 - Carbonate outcrops of the surveyed sites distributed in the study area and localized in Fig. 1 (from GS1 to GS6). Sets of discontinuities (i.e. bedding planes (yellow lines) and joints (red lines) as e.g. in GS1), collected by the linear scanline method (GS2, blue line)

The fracture frequency can be described in terms of fracture density or fracture intensity and denoted using the P_{ij} system, where *i* gives the dimension of the sample and *j* the dimension of the measurement (DERSHOWITZ & HERDA, 1992).

Using the one dimensional scanline method on the outcrops, the linear fracture intensity was espressed by the number of fractures divided by the length of the scanline. To avoid errors due to the orientation of the discontinuities, the fracture intensity can be introduced and a correction inserted in equation (1) (TERZAGHI, 1965), in which the frequency along the scanline is represented by P_{10}:

$$P_{10} = N/ l * sin(\alpha), \quad (1)$$

where: N is the number of fractures measured on the scanline of length (l), and α is the acute angle between the scanline and the mean orientation of the fracture set.

The aperture is the perpendicular distance separating the adjacent rockwalls of the open discontinuity, the intervening space of which can be filled. The aperture may increase by dissolution, erosion, or other methods, particularly in the weathered zone. Commonly, rock masses have small apertures in the sub-surface, and these decrease from the surface with depth due to lithostatic pressure that tends to close the fracture opening.

Fracture persistence or trace length represents the measure of the extent of development of the discontinuity surface. It is a measure of the fractures penetration length in a rock mass. It can be therefore defined as the ratio between the area of the discontinuity and the total area of the plane in which the discontinuity is contained. Persistence is related to the size of the discontinuities, which in turn is related to the trace length on the exposures. It has been estimated by the one-dimensional extent of the discontinuity trace lengths on the surface of the exposures. The fractures of some sets can be more continuous than those of other sets. Minor sets tend to terminate against primary sets or may terminate in solid rock, reducing the persistence. Detailed data of the outcropping discontinuities for each station was carried out. For the major discontinuity sets the dip/dip-direction of each discontinuity, the aperture, the spacing, the roughness and the number of discontinuities were collected. Data of dip/dip-direction were plotted in stereographic projections using Stereonet10© software. The correlation of the mechanical and hydraulic apertures was described by introducing an empirical equation that represent the relationship between the mechanical and hydraulic apertures (BARTON *et alii*, 1985).

The hydraulic aperture, e, the idealized fracture aperture for the smooth parallel plates model (SNOW,1965), was derived from the mechanical aperture, e_m, measured in the field (2):

$$e = e^2_m / JRC^{2.5}, \qquad (2)$$

where: JRC is the Joint Roughness Coefficient.

The roughness defined by the Joint Roughness Coefficient (JRC) was estimated by visually comparing the fracture with a standard set of roughness profiles occurring directly in the outcrop rock (BARTON & CHOUBEY,1977).

Effective and Equivalent Fracture Permeability

The presence of discontinuities causes a high degree of permeability anisotropy in the fractured rock masses (SNOW, 2013). The hydraulic behaviour of these rocks depends mainly on the geometric characteristics of their discontinuities. Specifically, the permeability anisotropy of the fractured limestone is greatly affected by geometric features such as the spacing and interconnectivity of the fractures, and the aperture, roughness and length govern the hydraulic performance of each fracture (LOUIS, 1969; LONG & WITHERSPOON, 1985; BROWN, 1987; LIU, 2005; KLIMCZAK *et alii*, 2010). During recent decades, several methodologies developed correlating the geostructural data to the hydrogeological parameters.

Starting from geometric properties of the discontinuities surveyed in the field, the fracture effective hydraulic conductivity and effective permeability were calculated (SNOW, 1969; KIRÀLY, 1969; LOUIS, 1969). In previous studies, the fluid flow through fractures of rock masses was computed by the assumption of laminar flow between parallel plates (SNOW, 1965, 1969). The parallel-plate solution for the Navier-Stokes equations leads us to consider the hydraulic conductivity as proportional to the cubed aperture between the plates, as defined by the commonly used "cubic law" (SNOW, 1965; LOUIS, 1974; WITHERSPOON *et alii*, 1980, BROWN, 1987; LIU, 2005; KLIMCZAK *et alii*, 2010). The hydraulic conductivity can be assessed through analytical equations (SNOW, 1968; LOUIS, 1969), assuming that the water flows along discontinuities, it is influenced by the aperture, spacing, roughness and persistence. KIRÀLY (1969) suggested an analytical method that calculates the hydraulic conductivity of fractured rocks using equations, whose terms are derived through detailed fracture recognitions.

In this paper, deterministic approaches were taken as reference when considering water flow through joints commonly described by the parallel plate model and the flow under laminar in incompressible and steady conditions (SNOW, 1965, 1968), where the flow rate varies as the cube of the fracture aperture and frequency of fractures, according to the cubic law (SNOW, 1969). On the basis of detailed surveys of the fractures assessed on the scanlines, following the ISRM recommendations (BARTON, 1978), the determination of the analytical estimation of the limestone effective hydraulic conductivity was carried out through the application of the methods proposed by SNOW (1969), KIRÀLY (1969), and LOUIS (1974).

Given the joint is understood as being composed of two smooth parallel plates, the joint's hydraulic conductivity was derived using a simplified form of the Navier-Stokes equations, in which the water velocity in a smooth parallel plate fracture is directly proportional to the squared fracture aperture (ZIMMERMAN & YEO, 2000). Using this model the hydraulic conductivity of a single smooth fracture under a laminar flow regime, may be written as (3):

$$K = \frac{\gamma\, g\, e^2}{12\eta} = \frac{g\, e^2}{12\upsilon}, \qquad (3)$$

where: e is the hydraulic aperture (m) (2), g is the gravitational acceleration (9.81 m/s^2), and η, γ and υ are the water dynamic viscosity (10^{-3} Pa/s), water density (kg/m^3), and water kinematic viscosity (1.0×10^{-6} m^2/s), respectively.

The cubic law (HUITT, 1956; SNOW, 1968, 1969; ZIMMERMAN & BODVARSSON, 1996; ZIMMERMAN & YEO, 2000), assumes that a fracture set is characterized by aperture and frequency. Thus, for a single set of fractures the effective hydraulic conductivity K_i is (4):

$$Ki = \frac{g e_i^3 f_i}{12\upsilon}, \qquad (4)$$

where: f_i is the frequency of the *i-th* set (m^{-1}), e is the average hydraulic aperture of the *i-th* set (m), g is the gravitational acceleration (9.81 m/s^2), and υ is the kinematic viscosity (1.0* 10^{-6} m^2/s) of water.

To evaluate the permeability of a rock mass, where there are two or more systems of discontinuity, it is necessary to consider the orientation of the fractures in relation to the direction of the hydraulic gradient and the hydraulic conductivity can be therefore expressed as a tensor (KIRÀLY, 1969; LOUIS, 1974). Over the past few decades, the approach and concept of a permeability tensor have been investigated, developed, and applied to fractured rock masses (SNOW, 1969; KIRÀLY, 1969; LOUIS, 1974).

The permeability tensor of fractured rock masses as proposed by SNOW (1969), based on geometric characteristics of the specific oriented fractures, has been widely used in practice (LONG *et alii*, 1982; ODA, 1985; LI *et alii*, 2008; COLI *et alii*, 2008; CHESNAUX *et alii*, 2009).

To calculate the equivalent hydraulic conductivity of an anisotropic fractured rock mass, the approach proposed by SNOW (1969), LOUIS (1974) and KIRÀLY (1969) was adopted in this study.

The estimation of hydraulic conductivity is based on the fracture parameters that were collected during field surveys such as orientation, aperture,roughness, spacing and frequency.

The permeability in a fractured rock mass can be represented by a second order tensor $\overline{\overline{K}}$ (5) referred to as a specific coordinate system (LOUIS, 1974):

$$\overline{\overline{K}} = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \quad (5)$$

The tensor $\overline{\overline{K}}$ is symmetric and the principal permeabilities are defined in direction by the eigenvectors, and in magnitude by the corresponding eigenvalues, of $\overline{\overline{K}}$ (6):

$$= \begin{bmatrix} k_1 & & \\ & k_2 & \\ & & k_3 \end{bmatrix} \quad (6)$$

The magnitudes of the tensor components are strictly related to the distribution and geometrical properties of the fractures (SNOW, 1968; KIRÀLY, 1969) and the $\overline{\overline{K}}$ tensor can be expressed for different parallel fracture sets with equation (7) (KIRÀLY, 1969):

where: g is the gravity acceleration (9.81 m/s^2); υ is the is the kinematic viscosity (1.0 × 10^{-6} m^2/s); N is the number of sets;

$$\overline{\overline{K}} = \frac{g}{12\upsilon} \sum_{i=1}^{N} f_i e_i^3 \, [I - \vec{n_i} \otimes \vec{n_i}], \quad (7)$$

f_i is the average frequency of the i-set of fractures (m^{-1}); e_i is the effective hydraulic aperture of the i-set of fractures (m); I is the identity matrix; and n_i is the dimensionless unitary vector normal to the average plane of the fracture set.

The term $[I - \vec{n_i} \otimes \vec{n_i}]$ expressed in the matrix form is (8):

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} n_1^2 & n_1 n_2 & n_1 n_3 \\ n_2 n_1 & n_2^2 & n_2 n_3 \\ n_3 n_1 & n_3 n_1 & n_3^2 \end{bmatrix}, \quad (8)$$

Equation (8) allowed the calculation of the $\overline{\overline{K}}$ tensor from the geometrical parameters of the fractures measured during the surveys of the geostructural stations.

By the $\overline{\overline{K}}$ tensor, it is possible to calculate the equivalent hydraulic conductivity (*Keq*) using the following relationship (geometric mean; Louis 1974) (9):

$$Keq = (K_1 K_2 K_3)^{1/3} \quad (9)$$

Tensor $\overline{\overline{K}}$ was computed by implementation of Matlab (®MathWorks) to execute the tensor operations. The input data used to calculate the $\overline{\overline{K}}$ tensor include the average effective hydraulic opening e_i (m), average frequency f_i (m^{-1}), dip/dip-direction (°), for each fracture set. The permeability tensor is referred to the azimuthal (dip/dip-direction) spherical coordinate system.

Inverse Hydrogeological Water Balance

The groundwater quantitative assessment in the fractured carbonate aquifers strongly depends on the geostructural setting. Carbonate aquifers are able to host significant amounts of groundwater that is primarily used for human consumption and represent strategic groundwater resources for the region. Evaluation of the recharge amount (effective infiltration) is a useful tool to identify the priority protection measures for sustainable land use planning and groundwater management of the area. An increase in the demand for water for agricultural, industrial, and drinking use in Basilicata necessitates accurate planning and management of groundwater resources.

Several direct and indirect methods to estimate groundwater recharge are present in literature, each with a different degree of approximation depending on data availability and spatio-temporal scales (SIMMERS, 1988).

Direct groundwater balance or a physically based distributed water balance model both consider the major water balance components and describe the mechanism of water percolation from the soil to the aquifer by simulating water fluxes and storage at temporal and spatial resolutions based on meteorological, topographic, soil physical, land cover, and hydrogeological input parameters.

In most cases all of these data are not available and, for this reason, it is necessary to proceed with indirect methods that use variables that represent the flow of water through the soil (SCANLON *et alii*, 2002). In direct procedures measurement devices are used, while with indirect procedures it is necessary to define the relationship between flow and recharge.

To assess the annual groundwater recharge (i.e. effective infiltration) of the High Basento River Valley hydrogeological basin, the hydrological budget components estimation was defined by the inverse hydrogeological water balance approach (CELICO, 1988; CIVITA, 2005; CANORA *et alii*, 2018).

The inverse hydrogeological water balance was applied to the study area and the domain was discretized in grid cells of 20x20m, georeferencing the positions of the thermo-pluviometric gauging stations located inside or immediately outside of the basin of interest (Table 1), in a GIS environment (CIVITA, 1994; SAPPA *et alii*, 2016; CANORA *et alii*, 2018) and by using Quantum GIS (QGIS) software.

The effective infiltration amount was evaluated on daily precipitation and air temperatures series collected, in the period 2000–2016, from the Regional Civil Protection Agency.

Station	Lat. N	Long. E	m (a.s.l.)
Abriola Sellata-Pierfaone	40°30'20''	15°45'40''	1475
Marsico Nuovo	40°25'35''	15°43'46''	765
Potenza	40°38'13''	15°48'60''	829
Tito	40°34'27''	15°39'25''	729

Tab. 1 -. Meteorological stations considered in the inverse hydrogeological water balance with geographic location (degrees) and altitude (m. a.s.l.)

Despite the apparent homogeneous distribution of rain gauges and air temperature stations in the proximity of the territory of interest, the spatial distribution of these stations revealed an inhomogeneous scattering for altitude with a dominant presence in the lower-middle ranges. The scarcity of the climate-monitoring network at higher altitudes was recognized as a principal issue to overcome in order to assess the groundwater recharge of fractured aquifers, which have a mountainous morphology extending up to the highest altitudes. The commonly used indirect procedure is the inverse hydrogeological water balance, which uses precipitation as the main input variable into the system. The balance equation is a ratio of conservation of mass in which the system inputs are equal to the output, plus the change in storage (MARTIN *et alii*, 1990) (10):

$$P = ET_r + \Delta S + R \qquad (10)$$

where: P indicates the precipitation (mm); ET_r is the amount of actual evapotranspiration (mm); R is the direct runoff (mm), and ΔS is the change in total storage (mm).

Total storage consists of water storage in the soil and underground storage. Water in excess of the field capacity at the bottom soil layer is considered potentially available for groundwater recharge.

The magnitude of the change in storage at daily or monthly time scales is appreciable, while for the long-term annual mean estimation it can be assumed that the water storage in the soil is not significant; therefore, this term can be considered only as active recharge or effective infiltration.

Starting from these assumptions and equation (1), the effective rainfall (P_e) can be defined as the net flux of water to the surface, or the rate of the rainfall total amount deducted from the actual evapotranspiration amount; this water balance term contain the direct runoff and the effective infiltration, which is useful for understanding the effective recharge (11):

$$P_e = P - ET_r = I + R, \qquad (11)$$

where: P indicates the total precipitation amount (mm); ET_r is the amount of actual evapotranspiration (mm); I is the effective infiltration (mm), and R is the direct runoff (mm).

Taking into account the equation (11) and starting from the daily rainfall and temperature data, related to the reference period (2000–2016), the monthly and annual average of the pluviometric and thermometric data for each thermo-pluviometric gauging station (Table 1) were calculated. The spatial distribution of the annual precipitation across the study area was elaborated by a linear regression as a function of altitude $P = f(q)$ (12):

$$P\ (mm) = 0.2269 \times q\ (m\ a.s.l.) + 616.91\ (r^2 = 0.8628), \qquad (12)$$

The temperature data were used to calculate the mean annual corrected temperature, depending on the precipitation (T_c). The corrected temperature Tc is necessary to evaluate the actual evapotranspiration (TURC, 1954).

The T_c was determined for each thermometric station by using (13):

$$T_c = \frac{\sum P_i T_i}{\sum P_i}, \qquad (13)$$

where: P_i is the average monthly precipitation (mm), and T_i indicates the temperature (°C) of the *i-th* month.
Both referred to the reference period (2000–2016).

The analysis of the corrected temperature data allowed us to investigate the spatial variation in the study area. The average annual air temperature is correlated with the altitude by a unique and statistically robust linear regression model T_c (°C) = *f(q)* (14):

$$T_c\ (°C) = -0.0144 \times q\ (m\ a.s.l.) + 22.954\ (r^2=0.9937), \quad (14)$$

Due to the limited availability of temporal and spatial meteorological datasets, to evaluate the actual evapotranspiration the empirical Turc's formula was applied (TURC, 1954). This empirical model is based on annual precipitation and air temperature, its reliability has been confirmed by many studies conducted in the Mediterranean basin and European areas (TURC, 1954; SANTORO, 1970; PARAJKA & SZOLGAY, 1998; ALLOCCA *et alii*; 2014) (15):

$$ET_r = \frac{P}{\sqrt{0,9 + \left(\frac{P}{300+25T_C+0,05T_C^3}\right)^2}}, \quad (15)$$

where: ET_r is the average actual annual evapotranspiration (mm); P is the annual rainfall (mm); T_c is the average annual corrected temperature (°C) function of the precipitation.

The effective rainfall (P_e), in the annual reference period was calculated for each element of the grid as the difference between precipitation and actual evapotranspiration (16):

$$P_e = P - ET_r, \quad (16)$$

where: P indicates the mean precipitation (mm/year) and ET_r is the amount of annual mean actual evapotranspiration (mm).

Hydrogeological Complex	χ
Fractured Carbonate Complex	0.85
Fissured Carbonate Complex	0.70
Detritical Complex	0.50
Siliceous Schists Complex	0.40
Fluvio-Lacustrine Complex	0.30
Clayey-Marly Complex	0.20

Tab. 2 - Potential infiltration coefficients of the hydrogeological complexes present in the study area

The effective infiltration (the water rate that percolates underground), is related to the infiltration capacity of the hydrogeological complexes and is a function of many factors such as outcropping lithologies, soil textures, the fracturing density of the rock masses, land use and more, expressed by the identification of the appropriate set of potential infiltration coefficients, χ, (Table 2) (CIVITA, 2005; CANORA *et alii, 2018)*. The effective infiltration was calculated based on effective rainfall *Pe* values and potential infiltration coefficients (17):

$$I = P_e \times \chi, \quad (17)$$

where: I indicates the mean annual effective infiltration (mm); Pe indicates the mean annual effective precipitation (mm); and χ is the dimensionless potential infiltration coefficient.

Using the previous equation (17), the effective infiltration values in all cells of the grid were calculated. The runoff rate is calculated indirectly as the difference between the effective rainfall and infiltration.

The analysis of the hydrogeological water balance components, as described in the results section, proceeds with the calculation of the monthly and annual mean precipitation and temperature for each gauging station (Table 1), the corrected annual average temperature (T_c) as a function of the rainfall, the definition of the precipitation-elevation [$P = f(q)$], and the corrected temperature-elevation functions [$T_c = f(q)$].

These functions, which are valid for the whole study area, are used to compute the water balance within each elementary cell using a GIS procedure.

The difference between precipitation (P) and actual evapotranspiration (ET_r) gives the effective precipitation, which with the identification of the potential infiltration coefficients, χ, allowed us to calculate the effective infiltration.

Groundwater Vulnerability to Pollution

The groundwater intrinsic vulnerability to pollution represents a useful tool for the effective management and protection of groundwater resources. Its assessment in the study area has been defined by the GNDCI-CNR (National Group for Defense from Hydrogeological Catastrophes (GNDCI) of the National Research Council (CNR)) method (CIVITA, 1994, 2005) based on a survey of the hydrogeological complexes, characteristics, and setting (VRBA & ZAPOROZEC, 1994; CIVITA, 1994, 2010). This approach is based on hydrogeological homogeneous areas zoning, in which several hydrogeologic settings that can be found in Mediterranean countries are collected, and the intrinsic vulnerability characteristics of the aquifer are identified (PARISI *et alii*, 2013). The method is highly flexible and can be adapted even to situations that are not identified in the specific methodological protocol (CIVITA, 2010). The protocol has been defined for several typical medium-large scale Italian hydrogeological situations, in which each hydrogeological scenario is associated with a degree of vulnerability. The hydrogeological scenarios of reference, defined in the methodological protocol, are identified according to the main factors that influence the vulnerability of aquifers: the geometry of aquifers, lithology and their hydrogeological characteristics. The advantage of this method lies in the reliable intrinsic vulnerability assessment for vast hydrogeological basins, especially those located in mountainous contexts where the specific hydrogeological data are limited and scattered throughout the area.

The application of the qualitative GNDCI-CNR method does not require numerical input parameters, and the assessment of the hydrogeological intrinsic vulnerability was conducted by overlaying the maps on different levels of data (CIVITA, 1990). The most important hydrogeological factors that were considered to assess the aquifer intrinsic vulnerability degree are: lithological andstructural featuresof the hydrostructure; the fracturing distribution of the carbonate complex; the permeability degree of the different hydrogeological complexes; the geometry and type of aquifers; and the modes of feeding, the hydraulic conductivity of the carbonate hydrogeological complex, and the definition of preferential flow directions.

The vulnerability assessment was performed as follows: a) detailed definition of the hydrogeological conceptual model based on surveys and investigations; b) choice of the methodological approach for the vulnerability estimation taking into consideration the hydrogeological situation of the examined area; c) identification of the geological and hydrogeological parameters for the estimation of vulnerability; d) the comparison between the hydrogeological situations recognized in the area and the scenarios identified by the GNDCI-CNR protocol; e) the assignment of the relative qualitative vulnerability levels and f) the elaboration of the Vulnerability Map to pollution of the hydrogeological basin.

RESULTS AND DISCUSSION

Geostructural and Hydraulic Characterization

Fracture collection of the fractured carbonate sub-complexes was carried out in the field at six study sites, using the linear scanline method. The scanlines ranged in length from 5–12 m, running along cherty limestone outcrops and were used for recording a wide range of geometrical parameters and properties of the fractures.

The analysis of the fractures system shows that the investigated area has a complex structural framework. The fracture system of the limestone formation of the carbonate hydrostructure consists generally of different well-defined joint sets dipping sub-vertically. Four major discontinuity sets that were recognized in some parts of the study area were characterized by high fracture sets trending NW-SE, NE-SW, N-S, and NNE-SSW, respectively; two prevailing fracture sets trending NW-SE and NE-SW are present in the other parts of the hydrostructure.

In particular, from the scanline stations, the north-western sector of the hydrostructure results were affected by the presence of four main intersecting fracture sets, oriented respectively N–S, N30–40°, N60–80° and N120–130°. Two main discontinuity sets, striking respectively N120–150° and N60–80°, prevail in the rest of the limestone formation outcrops. The stereonets give an overall view of the predominant fracture system orientations within the limestone rock masses (Fig. 5).

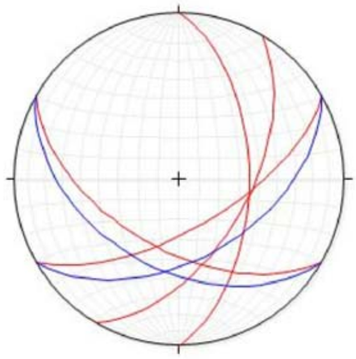

Fig. 5 - Equal area stereonet showing the great circles related to the orientations of the main fracture plane sets present within the carbonate formation of the High Basento River Valley. The red circles indicate the main fracture orientation of the high fractured carbonate sub-complex; the blue indicates the main fractures orientation of the fissured carbonate sub-complex

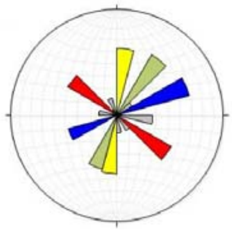

Fig. 6a - Rose diagrams of fractures' strike trends showing their prevalence in the cherty limestone formation. Four main fracture sets in the high fractured carbonate sub-complex

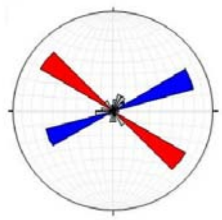

Fig. 6b - Rose diagrams of fractures' strike trends showing their prevalence in the cherty limestone formation. Two main discontinuity sets in the rest of the carbonate formation of the fissured sub-complex.

Rose diagrams show the relative statistical prevalence of the fractures' directional trends. The variation in orientation modes across the sample sites located along the limestone slopes in the north-western part of the study area, shows distinct fracture orientations with a greater number 801 of set orientation distributions (Fig. 6a). The scanlines located at the limestone outcrops present in the rest of the basin, mainly in the Arioso Mount and San Michele, have distinct fracture orientations with very little data scatter (Fig. 6b). The directions are represented along the radial axis, and the length of the petals represents a measure of the relative dominance of the trend.

High fractured limestones present primarily along the Pierfaone Mount northwestern side, pervaded by an elevated degree of interconnected discontinuity sets for which the spacing ranges from 10–40 cm, except for rare higher values that never exceed 50 cm. In the rest of the hydrostructure, the spacing generally ranges from 20–35 cm. In the study area, the structural setting measurements of the cherty limestones along the slopes shows that the openings range from 2–50 mm in the NW–SE and NE–SW directions. In the N–S and NNE–SSW directions, the openings range from 1–20 mm in the fracture collections of the limestone formations. Roughness is expressed by the Joint Roughness Coefficient (JRC) ranging from 0–4 **(**Barton**,** 1974). The roughness of the fractures reduces the total hydraulic flow and for this reason the equivalent aperture through which water can flow, called hydraulic aperture, is smaller than the actual mechanical aperture.

The fracture trace lengths in the study area are persistent and the fractures are interconnected. This suggests that the permeability and the effective hydraulic coefficient are increasing. The geometric parameters analysis of fractures derived from the scanlines and trace maps revealed that, along the Pierfaone Mount slopes, different deep fracture lengths are present, fracture intensities vary throughout the limestone mass, and the fracture frequency is high. Several intersecting intercommunicating fracture sets create a fracture network which promotes water flow. Systematic fractures are almost smoothly equidistant and possess parallelism, and therefore the parameter spacing assumes a high degree of significance. The evident persistence has an important influence on the siliceous limestone formation permeability.

The trace maps detected on the cherty limestone outcropping in the rest of the hydrostructure highlight the interconnected fractures network in places with contained persistence. Because of the different organization and intrinsic characteristics of the fractures, such as the limited fracture sets, smaller apertures, and greater spacing with relatedly lower frequency with respect the Pierfaone and La Cerchiara sides, the limestone formation outcroppings in the rest of extended area strongly affect the water flow. The existence of discontinuities makes a high degree of permeability anisotropy in fractured rock masses (Gale *et alii*, 1987)**.**

The elaboration of the collected structural data allowed the definition of the main fracture sets' orientation. In particular, in the north-western sector the results show that the NW–SE high angle oriented fractures dip-direction/dip values are 210/45, the NE–SW set as a dip-direction/dip of 150/40, the NNE–SSW oriented fractures have a dip-direction/dip of 120/50 and the N–S fracture sets' dip-direction/dip values are 90/55.

The domain was subdivided into similar fracture areas in which the hydraulic conductivity tensors were calculated, from and these values the equivalent permeability of the rock mass is easily defined **(**Louis**,** 1974). The fracture structure and organization of the calcareous-siliceous rocks gives rise to a system whose permeability is due only to the fracture network, neglecting the permeability of the matrix. The collection of surface fractures and analysis of the fractured limestone present in the entire study area, highlight two different rock mass models characterized by persistent discontinuities with a wide spatial distribution (four systems with significant dispersion of orientations), different fracture frequencies (i.e. strongly variable spacing) and values of the average opening variable in the defined sets.

The structural surveys carried out on the limestone outcrops of the High Basento River Valley define two different geostructural settings due to the similar geometrical parameters and physical properties of the fracture sets collected along the scanlines. The first geostructural setting characterized the high fractured north-western sector of the Pierfaone and La Cerchiara sub-structures, and consists of different fracture systems oriented NW–SE, NE–SW, N–S, and NNE–SSW. The second setting is related to the north area of the Serra della Criva substructure and the south sectors of the Arioso Mount and San Michele sub-structures, and shows two major different fracture systems oriented N120–150° and N60–80° that might be defined as fissured carbonate sub-complexes.

The results analysis of the fracture distribution shows that both the aperture and length of each fracture set within the individual layers increase downwards in accordance with the bed thicknesses. However, high permeability is quite significant in the rock masses in which the fractures cross all strata and have the greatest aperture values. The NW-SE and NE-SW oriented sets are the main elements that enhance fluid flow and provide a marked permeability tensor anisotropy.

In the north-western sector of the study area, mainly along the Pierfaone Mount and La Cerchiara sub-structures, the carbonate formation shows a high rock mass degree of fracturing, and the equivalent hydraulic conductivity of the rock masses is equal to $5*10^{-4}$ m/s. In the fissured sub-complex the equivalent hydraulic conductivity results to be $2*10^{-5}$ m/s.

Hydrogeological Water Balance Analysis

The most critical aspect of the hydrogeological explorations is the definition of the recharge process. This paper presents the results of the inverse hydrogeological water budget method application (CELICO, 1988; LERNER *et alii*, 1983; CIVITA & DE MAIO, 2001).

The inverse hydrogeological water balance application provides the distribution of all hydrogeological water balance components in the hydrogeological basin described above (Table 3). These values are averaged over the reference period of observations from 2000–2016.

Variable	mm/y	l/s
Direct Precipitation (P)	893.5	1699
Actual Evapotranspiration (ET_r)	455.2	866
Effective Infiltration (I)	232.6	442
Direct Runoff (R)	205.7	391

Tab. 3 - Annual mean amount of the inverse hydrogeological water balance variables

The results of the inverse hydrogeological water balance procedure applied to the hydrogeological basin of the High Basento River Valley, with an extension of about 50 km^2, show that the amount of effective infiltration (i.e. annual recharge) is of about 442 l/s.

The resulting inflows to the aquifer obtained from computing the effective infiltration (i.e. active recharge) are in agreement with the outflows data of the groundwater discharge amounts delivered to the exploited springs and to the springs that have not been tapped, whose total flow rates can be quantified at about 465 l/s. The comparison gives an error of less than 10%; therefore, the inverse groundwater balance carried out in the hydrogeological basin of the High Basento River Valley, can be considered reliable (CELICO, 1988; MARTELLI & GRANATI, 2007; BONI *et alii*, 2010).

The hydrogeological water balance of the aquifer system confirms that the input and output terms are in equilibrium. The groundwater active recharge is about 27% of the total amount of precipitation, as a consequence of the climate conditions, the topographic gradient of the area, and the geostructural features such as the fracture network density, and permeability of the outcropping geological formations. The spatial distribution of the mean annual effective infiltration shows changing behaviour throughout the entire basin due to the different infiltration capacities of the geologic formations. In particular, rock fracturing appears to be one of the major control factors of the recharge process and in its presence the groundwater recharge is maximised. The highest values are related to the presence of high fractured cherty limestone formations, on the contrary, lower values of effective infiltration are generally due to the lower permeability of the clayey marly formations.

Vulnerability degree	Hydrogeological complexes and setting features
High	Unconfined aquifer in highly fractured limestone, dolomite limestone, and dolomite with low presence or absence of karst phenomena. Unconfined aquifer in coarse to medium-grained alluvial deposits.
Medium	Aquifer in fissured limestone without karst phenomena. Aquifer in medium to fine-grained sand sediments. Strip aquifers in bedded sedimentary sequences (shale-limestone-sandstone flysch) with layer-by-layer highly variable flow rates.
Low	Aquifer in fissured sandstone or/and non-carbonate cemented conglomerate. Aquifer in shales and marls, pebbly limestones with prevalently fine-grained sedimentary rocks.
Very low	Clayey-marly sedimentary complexes, practically impermeable.

Tab. 4 - Standards of Italian hydrogeological settings (GNDCI-CNR method)

Vulnerability to Pollution Assessment

The vulnerability to pollution of the carbonate hydrostructure was assess based on the detailed investigations of the geological and hydrogeological framework of the study area, and taking into account the complexity of the aquifer system. The qualitative GNDCI method based on hydrogeological homogeneous areas zoning was applied, after being suitably calibrated with consideration of the reliable data of the local hydrogeological complex characteristics and comparing the situation of interest to the standard specific hydrogeological scenarios (Civita, 2010). This took into account the limited data reflecting direct hydrogeological measurements in the field (piezometers and wells data and permeability tests) and the area orography.

Based on the elaboration of data and the overlaying, by means of GIS techniques, of the geological-structural setting, hydrogeological complexes and hydrogeological peculiarities, along with the homogeneous zones with similar characteristics were identified (Table 4).

Subsequently, the characteristics of the areas have been compared with standard reference situations, estimating the vulnerability level for each of them.

The result is the vulnerability to pollution map of the High Basento River Valley hydrostructure (Fig. 7). The analysis of the vulnerability to pollution within this fragile hydrogeological system, which represents an important groundwater supply for the Basilicata region, has allowed us to identify different classes. The spatial distribution of these classes is the result of various influencing factors such as the lithological setting and the distribution of fracturing. The map identifies four classes of intrinsic vulnerability, ranging from very low to high level: 1) the very low vulnerability class refers to the clayey-marly complex, devoid of water circulation due to its low permeability; 2) the low degree of intrinsic vulnerability is attributed to the siliceous schists complex including siliceous shales, partial cherty marls, and graded pebbly limestones, characterized by a moderate degree of permeability; 3) and 4) the medium and high degree of vulnerability refer to the carbonate complex, including both the fissured limestone and the fractured limestone, which are characterized by the higher permeability.

The variability of the vulnerability of the hydrostructure is essentially due to the different types of rock fracturing that characterize different parts of the hydrogeological system. In particular, the Pierfaone Mount and the La Cerchiara sub-structures, where highly fractured carbonate complex outcrops exist and the discharge amount is higher than in the rest of the area, are characterized by a lower fracturing density and consequently, show a high degree of vulnerability. On the other hand, the sub-structures of San Michele and Arioso Mounts, Betina and Serra della Criva, characterized by a fissured carbonate complex, show a medium intrinsic vulnerability.

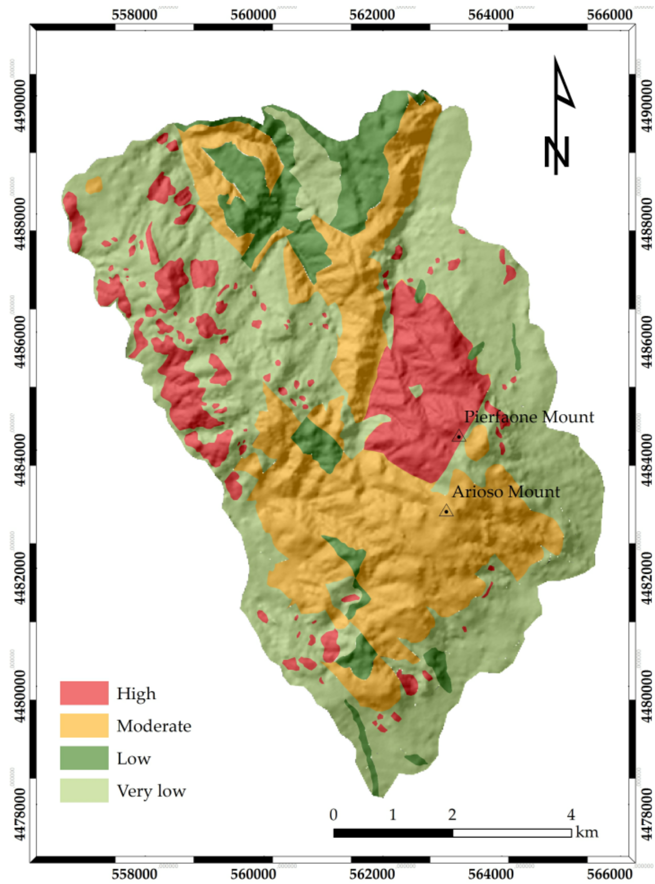

Fig. 7 – Map groundwater vulnerability to pollution of the High Basento River Valley hydrostructure with the different classes

By applying the GNDCI-CNR protocol for the assessment of vulnerability to pollution, making it the most appropriate method in relation to the available data and local conditions, it was possible to assess the vulnerability to pollution of the carbonate hydrostructure that represent one of the main drinking water resources of the region.

CONCLUSIONS

This research focused on the geological and hydrogeological characterization and intrinsic vulnerability assessment of the High Basento River Valley carbonate hydrostructure, starting with geological and hydrogeological field investigations in the study area. Geostructural surveys were carried out to assess the role exerted by individual and geostructural sets on the equivalent permeability and the hydraulic behaviour of the carbonate hydrostructure and the hydrogeological water balance was carried out to estimate the groundwater recharge. Finally, the vulnerability to pollution assessment was defined.

The discontinuities geometric parameters were the most important data used to predict the equivalent hydraulic conductivity of the fractured rock masses. Taking into account the surveys and analyses that were carried out, it is possible to conclude that the fracture network present within the rock mass provides a specific significant contribution to groundwater flow paths. The analysis records a strong orientation anisotropy between the fracture sets and interconnected fracture network within the carbonate formation in the Pierfaone Mount and La Cerchiara sub-structures. The results confirm the marked increase of equivalent permeability of the carbonate areas, as computed from structural data surveys. According to the intensity and the measured hydraulic apertures of the geostructural elements, the results suggest that hydraulic apertures affect the computed values of equivalent permeability. The hydraulic conductivity values that are obtained are mainly controlled by reciprocal orientations of fractures sets and hydraulic openings. The higher values of the hydraulic conductivity were encountered in the directions of NW-SE and NNE-SSW, which is in accordance with the structural domain of the area. The individual equivalent permeability is considered valid for the areas around the sampling sites and in the surroundings because the geostructural conditions of the rock masses are similar. Based on the hydraulic conductivities, the cherty limestone rock mass can be considered, depending on the state of fracturing, from moderately to highly conductive.

The geostructural features of the area strongly condition the active recharge and the hydrodynamic behaviour. The primary and secondary discontinuities play an important hydrogeological role in the system; they separate the carbonate hydrostructure from the marly-clayey formations, creating conditions for groundwater emergences or constituting watersheds and boundaries between the various aquifers forming the hydrostructure of the Arioso and Pierfaone Mounts. The evaluation of the effective recharge is a useful process to identify the priority quantitative protection measures for groundwater sustainable planning and management of the study area. The application of the inverse hydrogeological water balance approach allowed the estimation of effective infiltration for the entire hydrogeological basin. The outcome of this estimation was a volume equal to 442 l/sec. The vulnerability to pollution assessment represents a strategic tool for the management and protection of groundwater resources used for drinking water. In this fractured carbonate hydrogeological system the vulnerability levelsare mainly influenced by the local lithological and geostructural setting and by the fracturing state of the carbonate hydrogeological complex that confers different degrees of hydraulic permeability to the rock massess.

This study aimed to achieve a deeper understanding of the geological setting and hydrogeological features of the High Basento River Valley carbonate hydrostructure, using a methodological approach applying to the fractured carbonate aquifers, even in poorly studied hydrogeological contexts with limited data availability.

The analysis carried out in this study could be useful to define strategic sustainable management actions for the supply processes in relation to the water availability and demand, and to preserve the groundwater quality. The findings indicate that effort should be directed towards future studies involving specific hydrogeological investigations in order to understand primarily the impact of climate change on groundwater resources.

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