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HYDRAULIC CONDUCTIVITY ESTIMATION THROUGH THE USE OF TRACERS TESTS AND GEOMECHANICAL SURVEY: PRELIMINARY OUTCOMES FROM THE MONTAGNA DEI FIORI CARBONATE AQUIFER (CENTRAL ITALY)

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EXTENDED ABSTRACT

Le acque sotterranee sono tra le risorse più sfruttate del nostro pianeta. Considerato l'impatto crescente che i cambiamenti climatici hanno sulla disponibilità idrica, uniti alla continua crescita demografica, gli enti gestori e le aziende che operano nel settore idrico sono spesso alla ricerca di risorse integrative. Pertanto, la loro caratterizzazione quali-quantitativa è una delle principali questioni che la comunità scientifica è chiamata ad affrontare. In questo scenario una valida risorsa è rappresentata dagli acquiferi montani, dove gli alti tassi di ricarica sono generalmente legati ad un'elevata qualità idrochimica. In particolare, gli acquiferi carbonatici forniscono acqua potabile a circa un quarto della popolazione mondiale, ma al contempo sono altamente vulnerabili all'inquinamento poiché caratterizzati da eterogeneità ed anisotropie che favoriscono percorsi preferenziali e condizioni di flusso rapido.

L'indagine, l'analisi e l'interpretazione dei sistemi di fratturazione in questi contesti risulta essere fondamentale, in quanto la tipologia, la distribuzione e l'apertura delle discontinuità governano le quantità e i movimenti dell'acqua all'interno dell'ammasso roccioso. A questo riguardo, numerose ricerche hanno evidenziato criticità nello studio della circolazione delle acque sotterranee degli acquiferi carbonatici, rendendo la protezione e la gestione delle acque sotterranee un compito particolarmente difficile. Con questa premessa, lo studio in esame mira a investigare e valutare l'idrodinamica dell'acquifero carbonatico della Montagna dei Fiori (Italia centrale), nel quale l'azienda idrica locale ha realizzato quattro pozzi profondi (tre pozzi tra i 260 e i 300 m ed uno di 500 m di profondità) allo scopo di implementare l'attuale sistema acquedottistico utilizzando risorse idriche integrative nei periodi di emergenza legati alla siccità.

Data l'importanza che hanno gli acquiferi in questi contesti, è stato impostato un approccio metodologico multidisciplinare con l'obiettivo di ottenere un quadro preliminare riguardo le potenzialità idriche dell'idrostruttura. Il metodo utilizzato consiste nel combinare prove con traccianti artificiali con le tradizionali prove geomeccaniche. Grazie all'utilizzo di traccianti artificiali è stato possibile quantificare la potenzialità dell'acquifero in termini di conducibilità idraulica, approfondire l'interazione tra i pozzi in fase di pompaggio, e individuare all'interno dei pozzi i tratti più produttivi.

Il rilievo geomeccanico, (scanline 1-D), ha permesso di ricostruire l'assetto geometrico dei principali sistemi di discontinuità e di stimare la conducibilità idraulica dell'acquifero in superficie. Così facendo è stato possibile esaminare l'idrostruttura, dal campo pozzi fino alle zone di ricarica dell'acquifero. Sono stati quindi confrontati i valori di conducibilità idraulica estratti dalle prove con traccianti e dall'indagine geomeccanica, osservando una lieve discrepanza, verosimilmente dovuta alla chiusura delle fratture all'interno dell'ammasso roccioso andando dalle zone superficiali a quelle in profondità. La validazione del metodo proposto fornisce utili indicazioni sulla circolazione idrica.

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ABSTRACT

Nowadays, groundwater is the most important resource on our planet. However, due to population growth, urbanisation, and climate change, this resource is often overexploited or contaminated. In this context, carbonate aquifers provide drinking water to approximately 25% of the global population. Due to aquifers heterogeneities and anisotropic fracture systems, they can be affected by potential contamination and their optimal exploitation represents a challenge aspect. In this particular scenario, carbonate mountain aquifers encompass valuable groundwater resources due to their high recharge rates and excellent water quality; therefore, the understanding of their hydrogeological characteristics are vital for aquifers protection and water management. A valid solution to explore water movement within such aquifers and to quantify the groundwater amount can be offered using artificial tracers.

At the same time, the geomechanical surveys can deep the knowledge on fracture density and orientation, providing valuable insights about fracture connection and conductivity. This study combines the advantages of six artificial tracer tests performed in four deep wells (260-500 m b.g.l.) and a geomechanical survey used, among other, to estimate hydraulic conductivity of a mountainous carbonate aquifer located in Central Italy. The results obtained by different methods highlighted the presence of multiple layers with higher conductivity values, able to sustain the groundwater flow without significant piezometric level drawdown during water pumping operations. This approach provides an effective support to the water management company operating

Keywords: *carbonate aquifers, hydraulic conductivity, groundwater management, tracers, scanlines, central Italy*

INTRODUCTION

The hydraulic conductivity of rock discontinuities is a fundamental parameter for hydrogeological studies, at both local and regional scales, controlling the flow transport and leads to the exploitation of geofluids (groundwater, hydrocarbons, geothermal reservoirs, etc.). In this framework, aquifer characterisation is essential for optimizing the groundwater management and protection, especially in overexploited areas. The aquifer characterisation approaches can be categorised into five main groups: a) core methods; b) hydrological (pressure-based) methods; c) tracer-based methods; d) geophysical methods; e) combination of the previous methods (Cardiff, 2012). Pumping or injection tests are commonly adopted to determine hydraulic conductivity (Huang *et alii*, 2016, 2019; D’oria *et alii*, 2018; Sun, 2018; Ostad-Ali-Askari *et alii*, 2020). However, as reported by Ostad-Ali-Askari *et alii* (2017), only an average hydraulic conductivity is determined using pumping/injection tests, which limits the description of the spatial heterogeneity of hydraulic conductivity. In contrast, tracer tests are a valid, low-cost method for determining groundwater flow rates and heterogeneities in hydraulic conductivity, by employing salt tracers, artificial radioactive components, or fluorescent dye tracers (Goldscheider *et alii*, 2008), in single or multiple wells. Tracer tests have been widely used in geoscience, from the petroleum industry (Patidar *et alii*, 2022) to hydrogeological regional studies (Barberà *et alii*, 2018; Fronzi *et alii*, 2021; Cambi *et alii*, 2022; Mammoliti *et alii*, 2022; Lorenzi *et alii*, 2024) or even for rock slope stability, giving important information about flow dynamics (Mammoliti *et alii,* 2023). On the contrary it must be highlighted that this kind of tests are often time-expensive and difficult to perform in deep wells. For this reason, the estimation of hydraulic conductivity through geomechanical surveys (scanline) is a commonly used method. In our approach, we combine deep wells tracer tests and geo-mechanical survey to characterize the hydraulic conductivity features along the Montagna dei Fiori carbonate aquifer and we delve into a comparison between the applied methods.

MATERIALS AND METHODS

Study Site

The tested site is in the Montagna Dei Fiori area (Marche-Abruzzo Regions, central Italy), where the external portion of the Central Apennines foreland thrust belt of Italy crops out (Fig. 1a) through a fault-related overturned anticline. The Montagna Dei Fiori anticline developed during Early Pliocene time involving the Umbria-Marche pelagic carbonate succession (Jurassic–Miocene age) and the foredeep siliciclastic deposits of the Laga Formation (Messinian Age) (Mattei, 1987; Calamita *et alii*, 1998; Scisciani *et alii*, 2002; Scisciani & Montefalcone, 2006; Di Francesco *et alii*, 2010; Storti *et alii*, 2016; Francioni *et alii*, 2019). The anticline has NNW–SSE axial trend and a marked NNW plunge (30-40° dip) and is characterized by a blind thrust with a tip line in the Cretaceous–Tertiary limestones. A regional SW-dipping normal fault affects the backlimb of anticline, juxtaposing the Jurassic–Cretaceous carbonate sequence and the Miocene hemipelagic succession (Calamita *et alii*, 1998). From a hydrogeological point of view, five hydrostratigraphic units were identified following Tazioli *et alii*, (2020): (*i*) the marly-calcareous complex, formed by Scaglia Bianca, Scaglia Rossa and Scaglia Variegata Formations (Fms.) (from now referring as Scaglia Fms.), which act as an aquifer (*ii*) the Marne a Fucoidi Fm. marly complex, acting as aquitard, (*iii*) the Maiolica Fm. calcareous complex which displays a good hydraulic conductivity due to fracturing, (*iv*) the Jurassic siliceous calcareous complex acting as an aquiclude and (*v*) the Calcare Massiccio Fm. calcareous complex, which is characterized by a high hydraulic conductivity due to fracturing. In this area, the recharge rate is enhanced by the high permeability of the soils, although elevated surface runoff can be observed due to the high terrain slope.

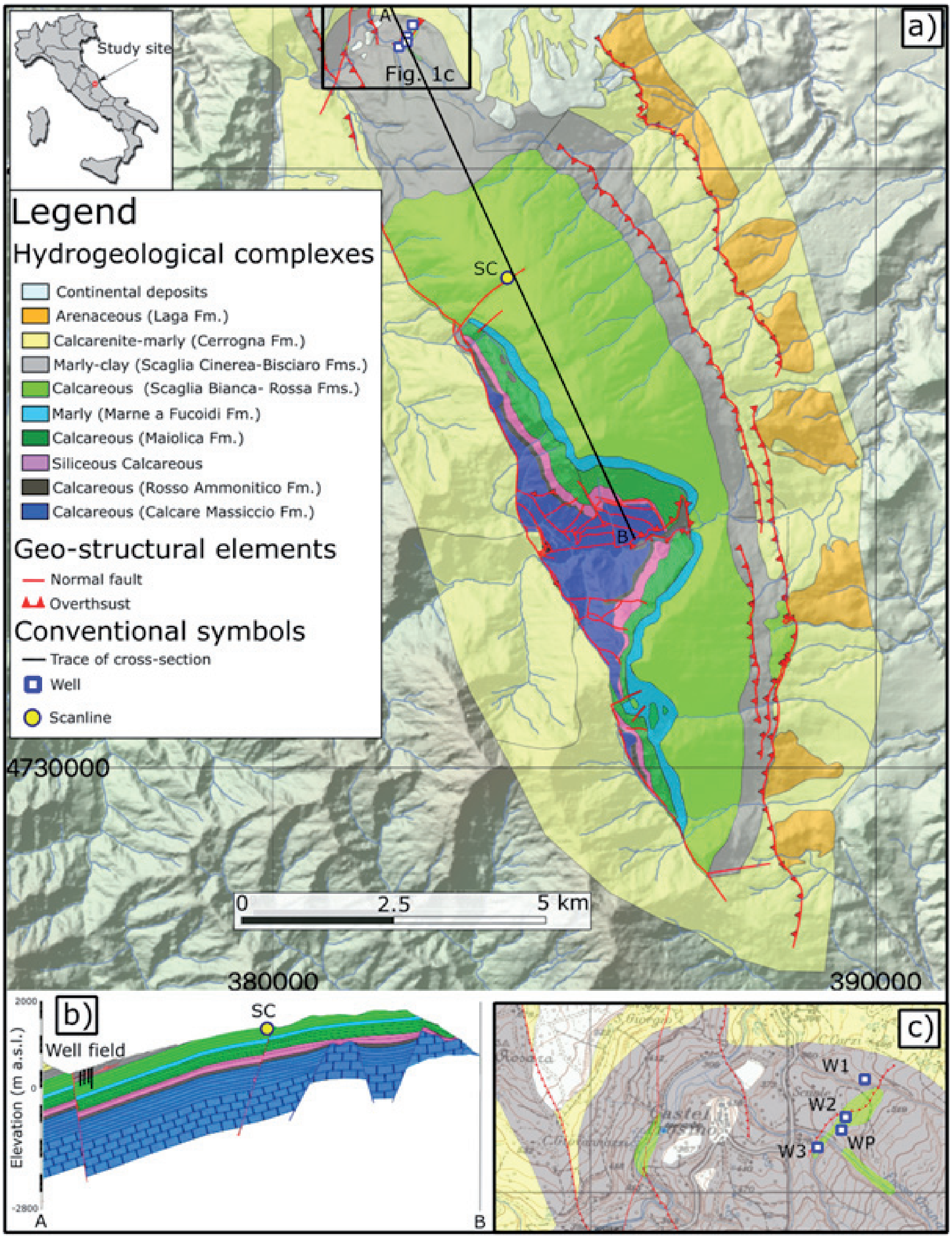

Fig. 1 - Location of the study site with a) hydrogeological map of the Montagna dei Fiori hydrostructure, with indication of wells (blue squares) and the geomechanical scanline (yellow circle, SC); b) hydrogeological cross-section (trace reported in Fig. 1a), and c) magnification of Fig. 1a for the well field area modified from Tazioli *et alii, 2020*

The upper limit of the recharge rate is about 600 mm/y (Boni *et alii*, 1993; Mastrorillo *et alii*, 2010). The study is based on four wells (Fig. 2), drilled by the CIIP Water Company for drinking water supplies in case of extreme droughts. Wells W1 and W3 were drilled reaching a depth of 300 m below ground level (b.g.l.), the W2 well was drilled until 263 m b.g.l., while WP reach about 500 m b.g.l. W1 was drilled by air and water roto percussion method with a diameter of 500 mm. During the drilling operation, the groundwater level was measured at 150 m b.g.l., and it equilibrated at 134 m b.g.l. just after a few hours. The borehole was then lined with stainless-steel filter pipe from 300 m to 150 m, while the remaining part was lined with blind pipe both with a nominal diameter of 400 mm. W2 was drilled by direct-circulation drilling of bentonite mud up to approximately 150 m depth, with roto percussion method with air and water insufflation from 150 m b.g.l. to 237 m b.g.l. and with Elmex Symmetrix technology until 263 m b.g.l. During the drilling phase, the groundwater level was approximately 148 m b.g.l., then it increased to 115 m b.g.l. The borehole is not lined from 263 to 237 m b.g.l. The lining starts at 237 m b.g.l. with a carbon steel filter pipe until 143.5 m b.g.l., moving up a carbon steel blind pipe to the borehole until the ground level, both the pipe has 400 mm of nominal diameter. W3 was drilled by a roto percussion method until a depth of 300 m b.g.l. with a diameter of 305 mm. The borehole was lined by a stainless-steel filter pipe from 300 m to 108 m b.g.l. and with a stainless-steel blind pipe from 108 m to the ground level. The pumps are placed within the boreholes at 162 m, 150 m, and 126 m b.g.l. in W1, W2, and W3 respectively. Unfortunately, no information about the drilling operations and the constructive techniques for the WP are available to the authors. All the boreholes involve the Scaglia Fms. Calcareous complex (Fig. 1b), an alternation of limestone, micritic limestone and marly limestone, with a high fracturing rate due to the tectonic deformation (Fronzi *et alii*, 2020).

Tracer tests

Six artificial tracer tests, namely TEST1, TEST2, TEST3, TEST4, TEST5, TEST6, were performed to experimentally obtain the hydrodynamic parameters of the investigated aquifer.

The first test (TEST1) was performed on 17th July 2017, by injecting 20 mL of dye tracer between 270-280 m below ground level (b.g.l.) in WP. The fluorometric probe was positioned immediately below the injection point and the tracer concentration was continuously measured every five-seconds.

During the second test (TEST2), performed on 18th July 2017, 50 mL of dye tracer were release in WP at the same depth as the previous test (between 270 and 280 m b.g.l.). Then, six vertical logs were performed at 256, 1409, 1465, 2795, 10151, and 12929 minutes after the injection along the well by using the fluorometric probe.

On 25th July 2017 the third test (TEST3) was characterized by the injection of 12 mL of dye tracer in W2 at a depth of 194 m b.g.l. Then, three vertical logs were performed at 237, 2679, and 2829 minutes after the injection along the well by using the fluorometric probe. At the same time, another fluorometric probe was positioned immediately below the injection point and the tracer concentration was continuously measured every five-seconds.

TEST1, TEST2, TEST3 were carried under static conditions (*i.e.*, without pumping), and the vertical logs performed in TEST2 and TEST3 were used to measure the tracer concentration at different depths.

The fourth test (TEST4) was conducted on 7th November 2017, by injecting 2,000 mL of dye tracer into W2 at 194 m b.g.l. Three hours before the tracer injection, pumping operations started in W1 (located approximately 125 m far from W2), with a constant pumping flowrate of 75 L/s. The tracer concentration of the extracted groundwater was monitored by the fluorometric probe placed at the outlet of W1. The tracer concentration was continuous monitored along the test every 10 minutes until the morning of 10th November 2017, when the pumping operations were concluded.

On 12th December 2017 the fifth test (TEST5) was conducted by injecting 4000 mL of dye tracer into W2, while in W3 pumping operations started about two hours before the injection with constant pumping flowrate of 105 L/s. The possible tracer arrivals were monitored by using the fluorometric probe placed at the outlet of W3 to monitor the tracer concentration of the extracted groundwater every 10 minutes for about three days.

The last test (TEST6) was carried out on 20th February 2018. In this case 3700 mL of dye tracer was injected into WP, while the fluorometric probe was placed within W2 to monitor possible tracer arrivals. This test was characterized by a constant pumping flowrate of 120 L/s in W2 until the end of the test, concluded after 80 minutes from the injection.

During all the tests Na-Fluorescein ($C_{20}H_{10}Na_2O_5$) 30% vol./vol solution in liquid form was used as a dye tracer, while two kinds of continuous fluorometric probe were used to detect the tracer concentration in the monitoring points. TEST1, TEST2, TEST3 and TEST6 were performed using a PME Cyclops-7 Logger (PME Inc. USA), while TEST4 and TEST5 were performed using the Albilia GGUN FL-24. Each probe contains the optic for tracer concentration detection (measured after calibration at 0 and 100 ppb), a standalone power supply, and a data logger for storing the measured data.

The graphical data for all the tests were processed using MS Excel while the free software QTracer2 (EPA 2002, USA) was used for the quantitative evaluation of tracer tests. Qtracer2 is a program developed to calculate total tracer mass recovery, hydraulic and geometric parameters from groundwater tracer tests in various hydrologic system, especially in those characterised by karstic and fractured aquifers (EPA 2002, USA). The tracer mass recovery (Mr) has been determined for TEST4, TEST5, and TEST6 starting from the monitored tracer concentration (c) and the pumping flowrate (Q) over time (t) as follows:

$$M_r = \int_{t=0}^{\infty} (Q \cdot c)\, dt \quad (1)$$

Where possible the hydraulic conductivity of the investigated aquifer (*k*) was determined by using the Darcy law following the equation below:

$$k = v/i \quad (2)$$

where *v* is the computed groundwater velocity from the tracer tests, while i is the hydraulic gradient taken from Tazioli *et alii,* 2020.

Table 1 summarizes the characteristics of each performed artificial tracer test.

Test ID	Test type	Involved well/s	Tracer injected quantity (mL)	Injection depth (m b.g.l.)	Pumping flowrate (L/s)
TEST1	Single well	WP	20	270-280	0
TEST2	Single well	WP	50	270-280	0
TEST3	Single well	W2	12	194	0
TEST4	Multiple wells	W2/W1	2000	194	75
TEST5	Multiple wells	W2 / W3	4000	n.a.	105
TEST6	Multiple wells	WP / W2	3700	n.a.	120

Tab. 1 - Specification about the artificial tracer tests performed in the study site. "n.a.": information not available

Geomechanical survey

With the aim to identify the discontinuity characteristics of the exploited aquifer, one mono-dimensional (1-D) scanline was performed on subsurface outcrop of the calcareous complex of Scaglia Rossa Fms. (SC in Fig. 1). The location of the scanline SC has been decided considering the structural and morphological framework of the area, for which the aquifer recharge area is identified. In detail, the scanline is in a barycentric position of the aquifer recharge area, as reported by Tazioli *et alii* (2020), where the Scaglia Fm. is outcropping. As evidenced in the geological cross section in Fig. 1b, the scanline and the well field are thus located in the same geological formation. The scanline length was set considering the average spacing of each set, trying to cover at least 10-12 m of length. The information identified for each discontinuity (joints, faults, bedding planes) crossing the graduated rule includes: (*i*) dip/dip direction, (*ii*) aperture (mm), (*iii*) average spacing (m), (*iv*) fill material, (*v*) fill consistency, (*vi*) presence of water, (*vii*) alteration, (*viii*) Joint Roughness Coefficient (JRC). A geological compass was used to measure the discontinuities orientation, while a discontinuity profilometer was used to measure the joint roughness. The aperture has been measured in the field using the JRC profile-aperture comparator (Barton & Choubey, 1977). The JRC has been estimated by visually comparing the fractures with standard set of roughness profiles.

RESULTS AND DISCUSSIONS

Tracer tests

The results of TEST1 are shown in Fig. 2a. A peak in the tracer concentration (about 2200 ppb) is observed after 15 minutes from the injection. This phase is followed by multiple tracer arrivals in the order of 500 to 1500 ppb occurring for the next 24 hours. The sharp increase and decrease of tracer concentration recorded between 270 and 280 m b.g.l. in WP indicates the presence of strong vertical currents within the aquifer, able to remobilize the injected tracer by shifting its peak concentration to different depths within the well. The data depicted from TEST1 only allowed for a raw estimation of a maximum vertical velocity of

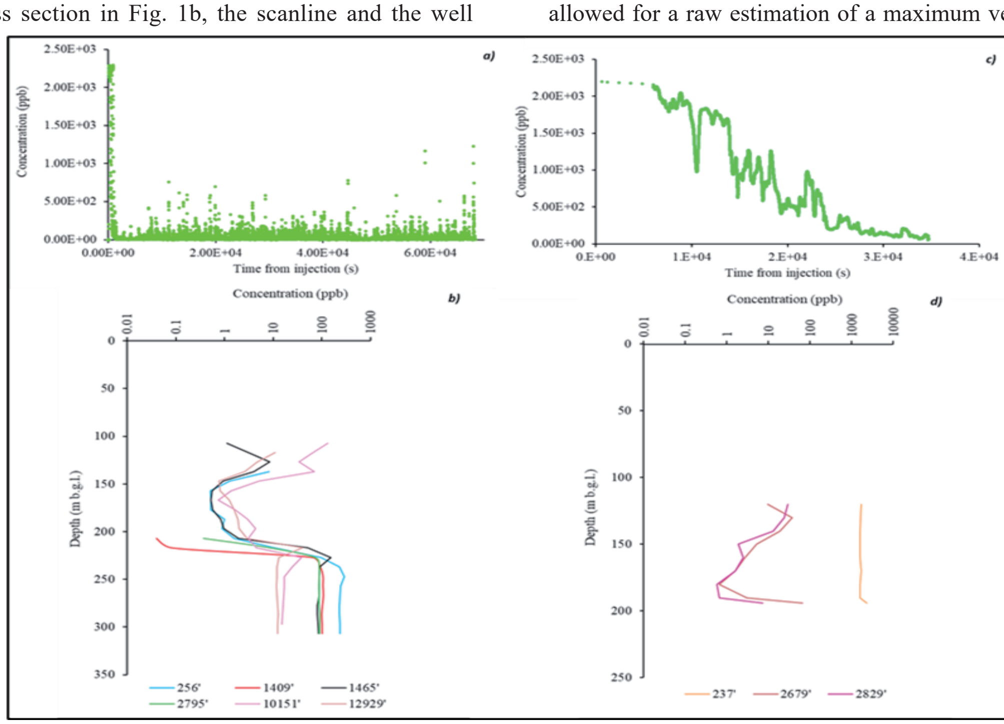

Fig. 2 - a) BTC for the TEST1; b) vertical logs for TEST2; c) BTC for the TEST3 and d) vertical logs during TEST3

approximately 9.2×10^{-6} m/s, as it was considered a pilot test for the investigated area. Fig. 2b shows the results of the six vertical logs performed in TEST2. The most significant tracer dilution is observed at about 230 m b.g.l. if considering the differences between the log performed after 256 minutes from the injection and the one conducted after 1409 minutes.

Indeed, a decreasing of almost two orders of magnitude in the initial tracer concentration is recorded. Further logs highlight vertical flow component that bring the traced groundwater up to the static level (about 110 m b.g.l.). The TEST2 permits to calculate the horizontal velocity ranging from 1.7 up to 2×10^{-6} m/s. These values are greatly influenced by the presence of vertical currents inside the aquifer, as observed also in TEST1. However, the obtained results permit to identify a layer with a higher hydraulic conductivity at about 230 m b.g.l. with respect to the other depths involving WP. The Fig. 2c and 2d show the graphical results of TEST3. The breakthrough curve (BTC) for TEST3 (Fig. 2c) display the occurrence of different concentration peaks confirming the presence of vertical velocity components within the aquifer. The tracer at this depth reaches a value of about 1-2 ppb approximately 10 hours after the injection. The tracer dilution resulted in low horizontal velocity values, approximately 3.82×10^{-6} m/s. The vertical logs performed in W2 (Fig. 2d) show that the tracer disappears at a depth of around 190-195 m almost completely, indicating the higher horizontal flow condition along the well at this depth, if compared to the other layers. This evidence highlights the possible presence of active fractures that allow for significant water circulation. This result, apparently in contrast to the calculated low groundwater velocities can be justified by the presence of vertical groundwater components that affect the tracer concentration within the wells maintaining high tracer concentration value for prolonged periods at the monitored depth. Therefore, the obtained aquifer velocities were not used to compute the hydraulic conductivity values. On the other hand, is important to notice that the results of TEST1, TEST2, and TEST3 were useful to explore the presence of vertical groundwater movements and high fractured layers within the aquifer. For this reason, it is important to remark that this kind of tests, if performed in aquifers characterized by strong vertical flow component, should be performed by using hydraulic packers capable of confining the well to discrete depths and monitoring the tracer concentration at single levels.

Two main tracer concentration peaks can be observed by analysing the BTC for TEST4 (Fig. 3a). The main peaks occur at 3 and 28 hours after injection, while a secondary peak is recorded after 4.5 hours from the injection. The BTC shape is marked by both impulsive and dispersive tracer arrivals suggesting the presence of two hydrodynamic components, the one in which the groundwater circulation is more controlled by single fractures crossing the aquifer, thus generating distinct flow paths, and the one occurring within interconnected fractures resulting in a hydro dispersive tracer migration. Unfortunately, in this test, the tracer mass recovery was approximately only 5 % of the injected tracer quantity. As a result, the traced aquifer volume may be underestimated (approximately 550 m^3). Fig 3b shows the BTC for W3 during TEST5. In this case the curve is marked by several concentration peaks indicating impulsive behaviour due to single fractures between W2 and

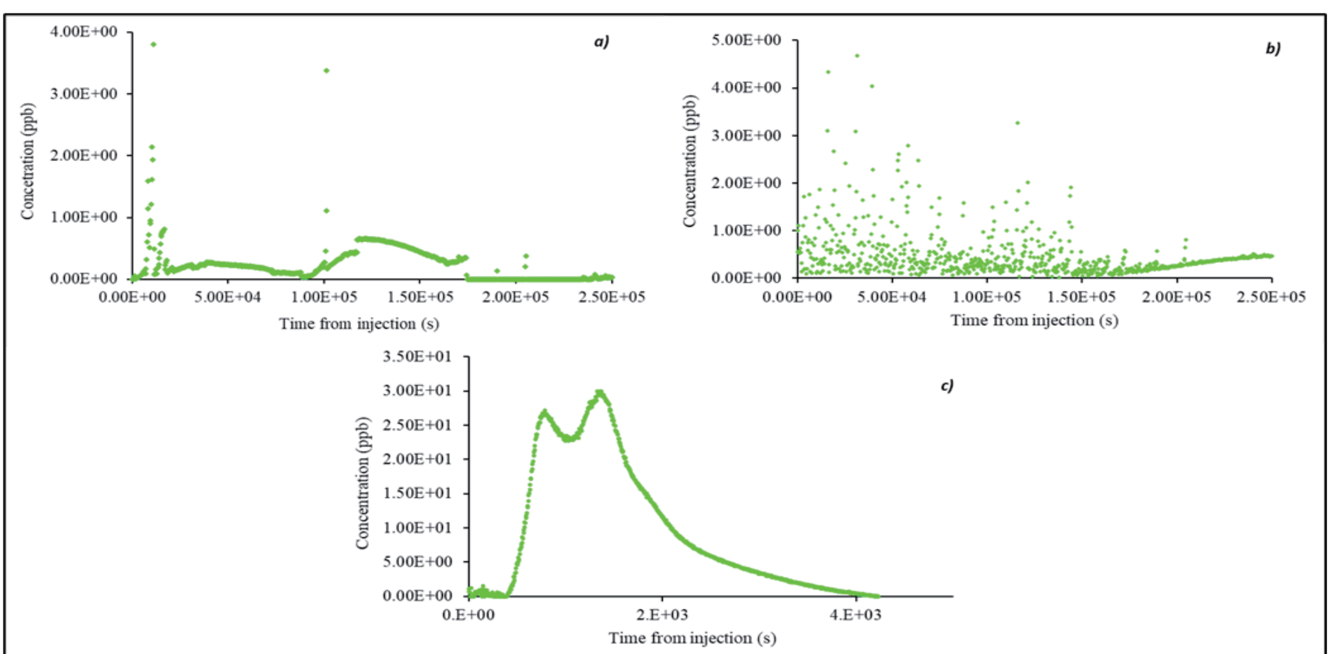

Fig. 3 - a) BTC for the TEST4; b) BTC for the TEST5 and c) BTC for the TEST6

W3. The computed volume of the traced aquifer volume was approximately 17,000 m^3. In this case the tracer mass recovery is approximately 7% of the total injected tracer mass. Fig. 3c displays the BTC for TEST6. The curve shape is defined by an asymmetric Gaussian curve marked by two consecutive peaks recorded 14 and 23 minutes after the tracer injection. The first tracer arrival is observed approximately 6 minutes after the injection, and it disappeared after 72 minutes. The computed tracer mass recovery is approximately 50%, thus enabling accurate determination of the aquifer's effective porosity (3.7×10^{-2}), and an overall traced aquifer volume of about 47,000 m^3.

Considering the low tracer mass recovery characterising TEST4 and TEST5, they were not used to compute the groundwater velocity, while TEST6, characterized by a good percentage of recovery mass has been used to evaluate the aquifer velocity and consequently the hydraulic conductivity by using equation 2. Nevertheless, TEST4 and TEST5 were pivotal to stress the wells interactions during the pumping phases.

In Table 2 the computed results obtained by QTracer 2 are reported for the multiple wells tracer tests, together with piezometric level drawdown recorded during pumping operation, if available. The obtained hydraulic conductivity value (10^{-5} m/s) is typical of similar fractured carbonate aquifers (Amoruso *et alii*, 2013; Medici *et alii*, 2019). This evidence suggests a moderate hydraulic conductivity for the investigated aquifer and is full in line with the observed minimal decrease in piezometric level during pumping.

Involved well	Hydraulic conductivity (m/s)	Traced volume (m^3)	Effective porosity	Pumped volume (m^3)	Piezometric lowering (m)
TEST4	n.a.	550	1.33×10^{-4}	19000	0.29
TEST5	n.a.	17000	1.42×10^{-3}	25350	n.a.
TEST6	1.02×10^{-5}	47300	3.7×10^{-2}	30420	0.71

Tab. 2 - Specification about the multiple wells tracer tests results. "n.a.": information not available

GEOMECHANICAL SURVEY

From the geomechanical scanline method survey, the stereographic projections were extracted, using the RocScience software DIPS (RocScience. DIPS,. 2018. Available online: http://www.rocscience.com. Accessed on 11 May 2018). From the stereographic projections, two main joint sets, named J1 and J2, and the bedding (S0) were identified (Fig. 4a and 4b). The results of the survey were reported in Table 3, highlighting the average orientation of the joint sets (dip angle/dip direction), the aperture (mm), the average spacing (m), the fill material, the fill consistency, the presence of water, the alteration, the JRC and the Fisher value (K). The aperture values for each joint set and the absence of fill material and water inside the fractures are clear indicators of important infiltration features characterizing the aquifer recharge area. Furthermore, from the geomechanical survey, using the Snow method (Snow, 1969), a hydraulic conductivity value of 3.0×10^{-4} m/s was calculated. A comparison of the hydraulic conductivity values obtained from the tracer test (TEST6) and the geomechanical survey (Table 4) revealed a discrepancy of one order of magnitude, i.e. the value of hydraulic conductivity from scanline is larger. It is important to note that the hydraulic conductivity value obtained at the surface may be overestimated when compared to the values extracted from the tracer tests. As reported by several authors (Carlsson & Olsson, 1977, 1993; Lee & Farmer, 1993; Zhao, 1998; Meng *et alii*, 2011; Zhang, 2013), decreased rock mass permeability with depth is to be expected due to associated increased of the confining pressure.

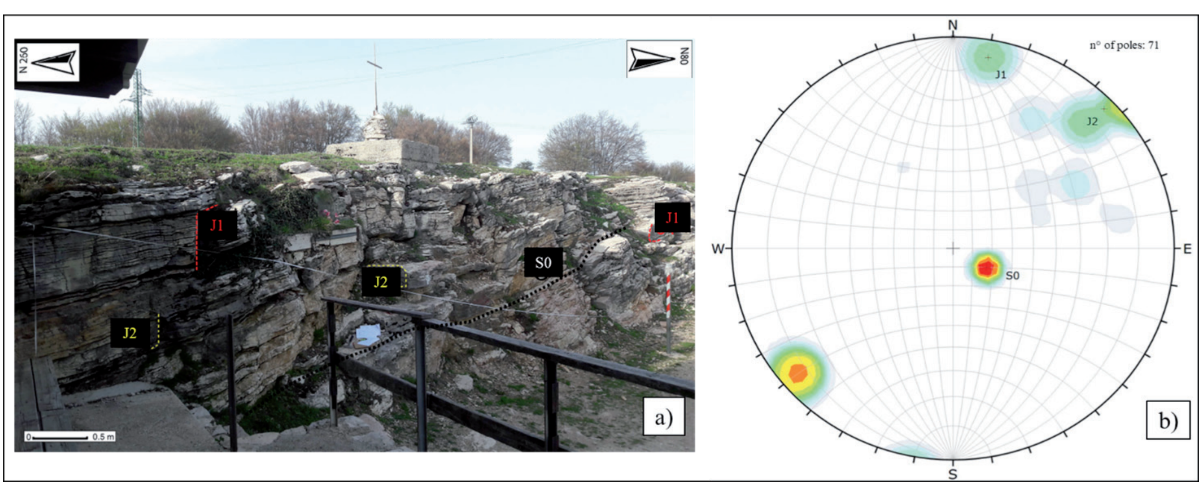

Fig. 4 - a) Field-based geomechanical scanline and identification of bedding plane (S0) and joint sets (J1, J2); b) Stereographic projection derived from the scanline survey (equal area projection, lower hemisphere)

Joint Set	Dip (°) /Dip Direction (°)	Aperture (mm)	Average Spacing (m)	Fill Material	Consistency of the Fill	Water	Alteration	JRC	Fisher K values
J1	85/190	2.3	0.33	/	/	/	II	8	45
J2	87/226	2.44	0.74	/	/	/	II	8	40
S0	20/301	2.16	0.22	/	/	/	II	8	38

Tab. 3 - Field-based geomechanical scanline results

Survey	Hydraulic Conductivity [m/s]
Scanline	3.0×10^{-4}
Tracer Test	1.02×10^{-5}

Tab. 4 - Hydraulic conductivity value from scanline and multiple wells tracer test (TEST6)

CONCLUSIONS

The approach used in this study, which combined tracer tests with traditional geomechanical analysis (1-D scanline), has been proved useful in determining the geometric structure of the main fracture systems characterizing the Montagna dei Fiori system and quantify the aquifer potential by estimating the hydraulic conductivity value. Six artificial tracer tests were conducted inside the four deep wells to experimentally extract the hydrodynamic parameters of the investigated aquifer; furthermore, a field-based geomechanical scanline was performed to identify the discontinuity characteristics and sets, defining the hydraulic conductivity in a barycentric position of the aquifer recharge area.

The hydraulic conductivity values determined from the two methods differ in one order of magnitude. This discrepancy has been attributed to the decreasing of fracture aperture moving from the aquifer surface (*i.e.*, recharge area) towards the deepest portion (*i.e.* well's capture zone). However, thanks to the tracer tests several highly fractured layers within the wells have been observed. These levels, which represent preferential flow paths, may be also the vectors of potential contamination to be monitored by the local water company to safeguard drinking water wells. Moreover, the interaction between the wells, monitored in terms of tracer recovery mass, has been proved useful in guiding the company in groundwater management operations: optimizing pumping rates, ensuring sustainable groundwater extraction, preventing the propagation of possible contaminants within the aquifer in the well's capture zone, reducing their vulnerability.

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