


Different groundwater behaviour in deep karst boreholes: the case of Jadro spring basin (Dinaric karst, Croatia)

Diverso comportamento delle acque sotterranee in pozzi carsici profondi: il caso del bacino della sorgente Jadro (Carso Dinarico, Croazia)

Ognjen BONACCI^a, Tanja ROJE-BONACCI^a, Adrijana VRŠALOVIĆ^a 

^a University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice hrvatske 15, 21000 Split, Croatia
e-mail: obonacci@gradst.hr (O.B.), bonacci@gradst.hr (T.R.B.), e-mail  : avrshalovic@gradst.hr (A.V.)

ARTICLE INFO

Ricevuto/Received: 2 June 2023
Accettato/Accepted: 28 August 2023
Pubblicato online/Published online:
07 November 2023

Handling Editor:
Emma Petrella

Citation:

Bonacci, O., Roje-Bonacci, T., Vrsalović, A., (2023). Different groundwater behaviour in deep karst boreholes: the case of Jadro spring basin (Dinaric karst, Croatia) *Acque Sotteranee - Italian Journal of Groundwater*, 12(4), 59 - 69
<https://doi.org/10.7343/as-2023-682>

Correspondence to:

Adrijana Vrsalović 
avrshalovic@gradst.hr

Keywords: Karst, deep piezometer, water temperature, electrical conductivity, Jadro spring basin.

Parole chiave: Carso, piezometro profondo, temperatura dell'acqua, conducibilità elettrica, Bacino sorgivo carsico di Jadro.

Copyright: © 2023 by the authors. License Associazione Acque Sotteranee. This is an open access article under the CC BY-NC-ND license: <http://creativecommons.org/licenses/by-nc-nd/4.0/>

Riassunto

Il presente articolo analizza i dati relativi al monitoraggio in continuo dei livelli di falda (GWL), della temperatura (TW) e della conducibilità elettrica (EC) in tre piezometri profondi (B1, B2, B3) nel bacino della sorgente Jadro, acquisiti da ottobre 2010 a dicembre 2021. La variazione di questi parametri viene analizzata su diverse scale temporali: annuale, mensile, giornaliera (24 ore) e oraria. Questi dati vengono confrontati con quelli degli stessi parametri misurati alla Sorgente Jadro. L'analisi dei tassi massimi di aumento e diminuzione osservati del GWL ha mostrato che i piezometri sono stati perforati in ambienti carsici molto diversi. Il piezometro B1 si trova in una matrice carsica dove l'acqua scorre prevalentemente in regime laminare diffuso (a flusso lento). I piezometri B2 e B3 si trovano in corrispondenza di una zona di faglia dove sono presenti numerosi ed estesi fenomeni carsici ipogei e il flusso è rapido e turbolento. Le portate medie annue della sorgente di Jadro dipendono fortemente dalla variazione dei livelli piezometrici medi annui in ciascuno dei piezometri. Durante gran parte dell'anno (circa il 99%), in tutti e tre i piezometri la falda si trova a più di 210 m sotto la superficie del suolo. Poiché i sensori di misurazione si trovano vicino al fondo dei piezometri, la temperatura rilevata si riferisce a quella dell'acquifero profondo e sono quindi piuttosto omogenee. Questa si attesta sempre a 12.5 °C nel piezometro B1 e si comporta in modo quasi identico nel piezometro B3. La temperatura dell'acqua è più alta nel piezometro B2 e si aggira intorno al valore medio di 13.5 °C. Alla sorgente Jadro, la temperatura media dell'acqua è di 12.95 °C. I valori di conducibilità elettrica sono i più elevati nei piezometri B2 e B3, con una media di circa 0.500 mS/cm. Sono inferiori nel piezometro B1, dove oscillano intorno a un valore medio di 0.465 mS/cm, mentre alla Sorgente Jadro variano da 0.400 mS/cm a 0.480 mS/cm, con un valore medio di 0.440 mS/cm. In tutti i piezometri è evidente una variazione stagionale dei livelli di falda. Tuttavia, non si osserva alcun trend in un aumento o in diminuzione del carico idraulico.

Abstract

The paper analyzes the data of groundwater level (GWL), groundwater temperature (TW), and electrical conductivity (EC) measurements in three deep piezometers (B1, B2, B3) in the Jadro spring basin, taken from October 2010 to December 2021. The variation of these parameters is analyzed at different time scales: annually, monthly, daily (24 hours), and hourly. They are compared with the data of the same parameters measured at the Jadro Spring. The analysis of the maximum observed rise and fall rates of the GWL showed that the piezometers were drilled in very different karst environments. Piezometer B1 is located in a karst matrix where the water flows predominantly in a diffuse laminar (slow-flow) regime. Piezometers B2 and B3 are located in a fault line where numerous large karst underground formations occur and rapid turbulent water flow takes place. The mean annual flows of the Jadro Spring strongly depend on the mean annual GWL-s in each of the piezometers. For much of the year (about 99%), the GWL in all three piezometers is more than 210 m below the ground surface. As the measuring sensors are located near the bottom of the piezometers, the groundwater temperature is almost stagnant. It is always at 12.5 °C in piezometer B1 and behaves almost identically in piezometer B3. Water temperature is the highest in piezometer B2 and hovers around the average value of 13.5 °C. At the Jadro Spring, the average water temperature is 12.95 °C. The electrical conductivity values are the highest in piezometers B2 and B3, with an average of around 0.5 mS/cm. They are lower in piezometer B1, where they range around an average value of 0.465 mS/cm, while at the Jadro Spring, they vary from 0.40 mS/cm to 0.48 mS/cm, with an average value of 0.44 mS/cm. A distinct seasonal pattern in groundwater level behavior is evident across all piezometers. However, no discernible upward or downward trend is observed.

Introduction

Each karst aquifer is unique, and the geometry of its different parts can be rather complex (Zwahlen, 2003). Due to this fact it is habitually to have different groundwater behavior in its very close proximity (Chalikakis et al., 2011). Geophysical measurements performed in deep piezometers provide information essential for understanding the processes taking place in the underground. This information is particularly important in karst aquifers characterized by strong heterogeneity due to the presence of numerous underground karst forms, above all cracks and conduits of the most diverse dimensions, and by unknown and variable interconnections between them over time and space (e.g., Drogue, 1985; Bonacci, 1988, 1995; Paillet, 1998; Bonacci and Roje-Bonacci, 2000; Chalikakis et al., 2011). Data on different hydrogeologic and geologic parameters collected in deep piezometers offer an insight into the vertical structure of variations in the geophysical, chemical, and lithological properties of the rock mass. They can also be used to monitor ecological and biological processes underground.

Karst is a complex four-dimensional environment in which various complicated processes take place. With three spatial components x , y , z , and an additional temporal dimension, karst dynamics are shaped by the restructuring of runoff processes due to a combination of natural events, such as earthquakes and valley collapses, as well as human activities. Inside the expanse of karst, numerous karst formations with different ecosystems can be found. They all intertwine through a series of feedback loops, mutually influencing development and function within this highly vulnerable space. Piezometers offer a complete insight into the underground karst structure, enabling the understanding, monitoring, and control of the processes that take place there. Since karst aquifers on a planetary level are frequently exposed to uncontrolled and mostly very dangerous anthropogenic influences, the information that can be obtained is of great importance for ensuring the sustainable development of these vulnerable and extremely valuable areas (Lv et al., 2021).

Modern technological achievements enable the continuous measurement of various hydrological, hydrogeological, chemical, and biological parameters that are important for defining the properties of karst aquifers and the processes that take place within them. At the same time, to define karst aquifers and their processes, a significantly larger number of piezometers is required than in aquifers formed in homogeneous media. Experimental research conducted by Drogue (1985) in the karst area of southern France supports the previously stated position. On about 600 m² area, nineteen 60-meter deep piezometers were drilled. They were about 5 m apart, on average. In this small strongly karstified area, very different values of water temperature, water flow rate, and temperature gradients in space and height were observed in narrow boreholes. For example, in the nearby piezometers, the geothermal gradients varied significantly from 0.01 °C/m to 0.03 °C/m.

In fact, two types of flow exist and occur simultaneously in the karst medium: (1) fast turbulent flow through karst conduits of larger dimensions; (2) slow laminar flow through the karst matrix (Atkinson, 1977). Some parts of the karst aquifer respond differently to the filling that occurs as a result of precipitation falling on the watershed (Vigna & Banzato, 2015). Analyzing factors affecting hydrochemistry of karst springs and their relationship to karst aquifer development in Jonggrangan Karst, Java Island, Indonesia, According to Pratama et al. (2021), during the dry season, slow-flow leads to the primary process of carbonate mineral dissolution-precipitation, while in flood events, quick-flow primarily triggers carbonate mineral dissolution through precipitation-induced dilution. Secondary factors encompass rainwater mixing, water infiltration from unsaturated zones, and interaction with clastic rock.

By measuring the speed of water flow along the height of a piezometer, it is possible to determine the exact position and dimension of the underground karst conduits (Goldscheider & Drew, 2007). The filling and flow of water in large karst conduits take place in a fast-turbulent regime, while small cracks in the karst matrix are filled much more slowly in a laminar or transitional flow regime. The physical and chemical characteristics measured in an individual piezometer will depend on the environment in which the individual piezometer was drilled.

Paillet (2001) lists the information on the properties and functioning of heterogeneous karst aquifers that can be obtained from various measurements in deep piezometers: (1) locations and dimensions of hydraulically active zones intersected by borehole; (2) geometrical correlation between individual boreholes, showing the connection between each piezometer and therefore the internal structure of the aquifer; (3) data on groundwater levels GWL-s and physical-chemical characteristics of the water in the well, which enable the identification of groundwater flows; (4) the possibility of establishing hydraulic connections between surface and underground karst formations and conduits in the watershed through tracer tests; (5) possibility of establishing the properties of hydraulic conductivity of local, medium and wide areas within the aquifer, using geophysical measurements.

The paper analyzes groundwater level (GWL), groundwater temperature (TW), and electrical conductivity (EC) measurements from three deep piezometers (B1, B2, B3) located within the Jadro spring basin. The data covers from October 2010 to December 2021, with the goal of improving the understanding of the processes taking place in the karst aquifer of the Jadro Spring. Based on this knowledge it will be possible to organize a more reliable protection of the water resources of this extremely important karst spring. It is second largest karst spring in the eastern coast of the Adriatic Sea. The Jadro Spring has been supplying high-quality drinking water numerous settlements for more than two millennia, from the largest Roman city Salona to the present-day city of Split. It is necessary to point out that this is the first such analysis performed in the Jadro spring basin.

Materials and methods

Jadro Spring and piezometers

The Jadro Spring is located on the western slope of the Mosor Mountain, in the village of Majdan, at an altitude of 35 m a.s.l. (Fig. 1). The geographical coordinates of the spring are 43°32'34" N and 16°31'19" E. Until now, its catchment area has not been defined, and its surface is not precisely determined. Numerous authors have tried to define the area of the basin using different methods. Results ranged from 396 km² (Jukić and Denić-Jukić, 2009), over 450 km² (Denić-Jukić and Jukić, 2003), to 502.5 km² (Bonacci, 2015). It should be noted that neither the hydrogeological nor the hydrological connection between the Jadro and Žrnovnica spring basins has been clarified (Fig. 1). Although the Žrnovnica spring is only 4.2 km away from Jadro in terms of air distance, it exhibits similar precipitation regimes and nearly identical geological characteristics (Bonacci & Andric, 2015). Bonacci (2015) believes that during the high-water periods, water overflows from the Jadro basin into the Žrnovnica basin in an average annual rate of about 1 m³/s. However, this hypothesis has yet to be verified, first by measuring the GWL in piezometers located in such a way as to provide a reliable answer to this relevant question.

Caving expeditions into the cave system of the Jadro Spring have been carried out on three occasions so far: (1) February 9, 2016; (2) August 12, 2016; (3) August 16, 2017. The length of the currently explored parts is only 75 meters, while its greatest depth is 22 m (Jalžić and Kovač-Konrad, 2019).

During the period from 1995 to 2021, when reliable measurements of the spring's flow are available, it was determined that its average annual flow is 9.76 m³/s. The

mean annual flow ranged from a minimum value of 6.8 m³/s measured in 2017 to a maximum of 13.7 m³/s measured in 2010. The minimum and maximum mean daily flows are 3.65 m³/s and 70.1 m³/s respectively. All the above values confirm the torrential character of the spring hydrological regime. The Jadro Spring is a typical karst spring with a limited capacity of maximum discharge (Bonacci, 2001). It is important to emphasize that in the recent 27 years (1995-2021), no trend of either decrease or increase in annual or monthly flows was observed (Bonacci and Roje-Bonacci, 2023).

Tab. 1 - Basic data on piezometers.

Tab. 1 - Caratteristiche tecniche dei piezometri.

	B1	B2	B3
latitude	43°34'52.84" N	43°35'43.06" N	43°38'43 62" N
longitude	16°34'55.80" E	16°30'35.42" E	16°29'7.51" E
H1 (m a. s. l.)	278.73	340.412	356.565
H2 (m a.s.l.)	44.28	98.23	140.8
ΔH=H1-H2 (m)	234.42	242.182	215.765

H1= Reference datum plane; H2= Sensor elevation

On the basis of the geological characteristics of the area and the results of tracing underground flows in the basin of the Jadro and Žrnovnica Springs, four locations of deep exploratory and observational piezometers were selected, as shown in Figure 1. An exploratory and observational borehole (B-1, Dugopolje), 300 m deep, was located in the area where the anthropogenic impact on groundwater was expected. The piezometer was drilled in the second zone of sanitary protection in the

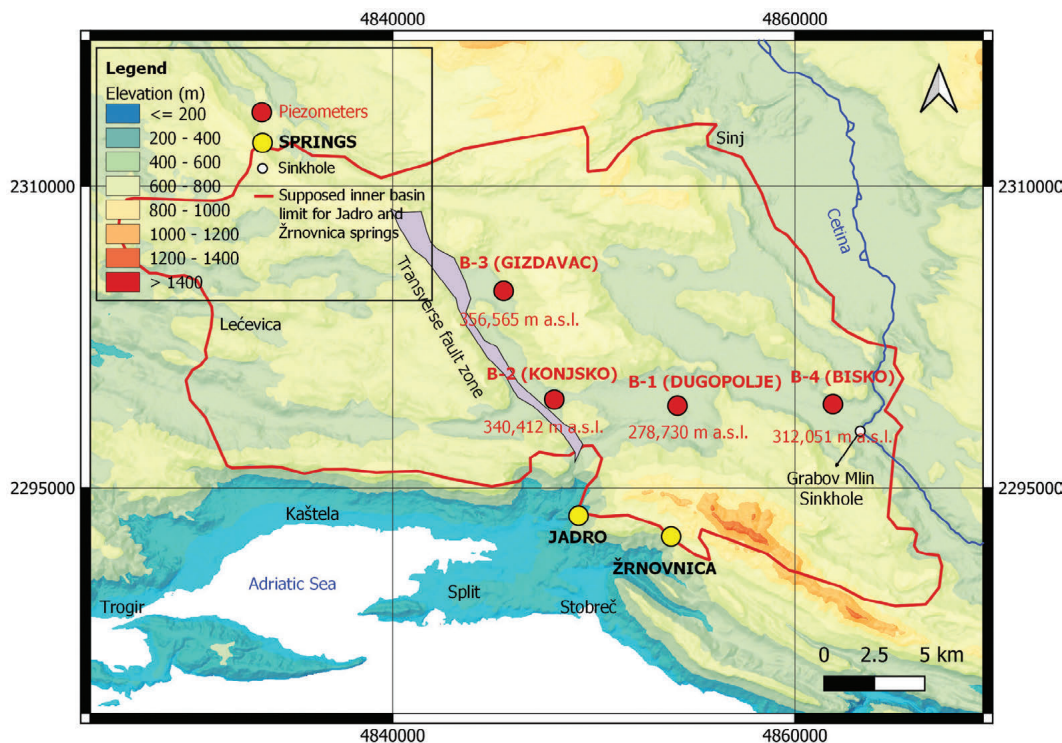


Fig. 1 - Map of the analyzed area with the positions of piezometers, Jadro and Žrnovnica Springs, and the supposed inner basin limit of Jadro and Žrnovnica according to Kapelj et al., 2008.

Fig. 1 - Carta dell'area analizzata con le posizioni dei piezometri delle sorgenti Jadro e Žrnovnica e il presunto limite interno del bacino di Jadro e Žrnovnica secondo Kapelj et al., 2008.

area of sudden urbanization. The locations of the other two boreholes, Gizdavac (B-3), 350 m deep, and Konjsko (B-2), 300 m deep, were selected along the transverse fault zone Muć – Gizdavac – Prugovo – Konjsko – Klis (Kapelj et al., 2012; Loborec, 2013). In these three piezometers, equipment for measuring GWL, groundwater temperature, and electrical conductivity was installed, but it was not installed in the fourth borehole Bisko (B-4). Table 1 lists the basic data on the three piezometers where measurements were taken and whose data are processed in this paper. Table 2 lists the values of air distances between the piezometers and the Jadro Spring

Tab. 2 - Areal distance, L, between the piezometers and the spring.

Tab. 2 - Distanza areale, L, tra i piezometri e il sorgente.

L (km)	B1	B2	B3	spring
B1	-	5.11	10.32	8.72
B2		-	6.07	8.09
B3			-	15.46
spring				-

Available data

In each of the three active piezometers (B1, B2, B3), continuous (hourly) measurements of GWL, groundwater temperature (TW), and electrical conductivity of groundwater (EC), were acquired. In the paper, the hourly data of these three parameters were processed. Hourly measurements of water temperature and electrical conductivity of the Jadro Spring were also available. In addition, the data of mean daily, monthly, and annual flow (Q) of the Jadro Spring, and daily precipitation measured at the climatological station Sinj were also used in the paper. Table 3 lists the time periods in which measurements of hydrological, hydrogeological, and geophysical characteristics were available.

Methods used

The linear regression method was used to analyze the relationship between t Q values of the Jadro Spring and the GWL in B1, B2, and B3 on both a monthly and annual

basis. For each pair of parameters, the squared values of the coefficients of determination, R², were calculated. Due to the shortness of the time series and interruptions in the observations, it was useless to calculate the lines of linear regression that would determine the trends of the time series of each parameter.

Results and discussion

Year as a time unit of analysis

Figure 2 shows minimum, mean, and maximum annual groundwater levels measured in piezometers B1, B2, and B3 during the period of 2011 to 2021. Due to the shortness of the series and the fact that we do not have equally long time series, it is not possible to draw more precise conclusions. What can be determined is that the mean annual GWL-s are the highest in piezometer B3, which is the farthest from the spring (15.46 km), while in the other two piezometers, B1 (8.72 km distant) and B2 (8.09 km distant), the GWL are similar.

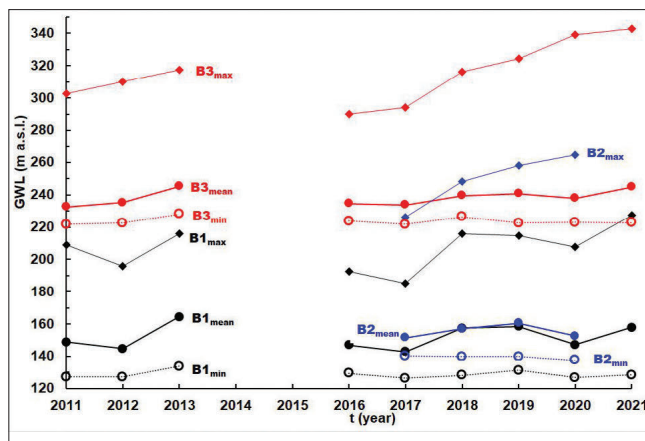


Fig. 2 - Annual variation of the minimum, mean and maximum groundwater level measured in piezometers B1, B2, and B3.

Fig. 2 - Variazione annuale dei livelli minimi medi e massimi misurati nei piezometri B1, B2 e B3.

Tab. 3 - Overview of periods for which measured data of GWL, groundwater temperature, TW, the electrical conductivity, EC, in piezometers and at the spring are available.

Tab. 3 - Panoramica dei periodi per i quali sono disponibili i dati misurati di GWL, temperatura dell'acqua di falda, TW, conducibilità elettrica, EC, in piezometri e alla sorgente.

	B1	B2	B3	SPRING
GWL (m a.s.l.)	VIII. 2010-XII. 2021 Missing: IV.- XII.2014; X.- XII.2015	I. 2017-IX.2021 Missing: I.-VI.2021	VIII. 2010-XII. 2021 Missing: IV.-XII.2014; X.-XII.2015	Q (m ³ /s) I. 2011-XII. 2021
TW (°C)	I. 2011-XII. 2021	I. 2017.-XII. 2021. Missing: VIII.-XII.2018; IX.-XI.2019	I. 2011-XII. 2021	I. 2011-XII. 2021
EC (mS/cm)	I. 2011-XII. 2021 Missing: VIII.- XII.2016; I.2017	I. 2017.-XII. 2021 Missing:V.-X.2017; VIII.-X.2018; IX.2019- X.2021	I. 2011-XII. 2021 Missing: VI-VIII.2016	I. 2011-XII. 2021

Tab. 4 - Characteristic (minimum, average, and maximum) annual values of groundwater table depth (GTD) in three piezometers.

Tab. 4 - Valori caratteristici (minimi, medi e massimi) annuali della profondità della falda (GTD) nei tre piezometri.

(m)	Minimum GTD			Average GTD			Maximum GTD		
	B1	B2	B3	B1	B2	B3	B1	B2	B3
2011	151.46		134.88	129.85		123.95	69.58		53.86
2012	151.65		134.06	133.97		121.21	82.69		46.52
2013	145.09		128.48	114.25		111.35	62.63		39.06
2016	149.24		132.68	131.77		121.84	86.21		66.54
2017	152.29	200.20	134.80	135.69	188.87	122.74	93.44	114.34	62.62
2018	150.46	200.57	130.16	121.33	183.44	117.05	62.65	92.32	40.54
2019	147.54	200.58	134.06	120.33	179.87	115.78	64.22	82.36	32.26
2020	152.01	202.87	133.58	131.48	187.82	118.75	71.04	75.97	17.60
2021	150.29		133.58	120.89		111.66	51.43		13.80
average	150.00	201.06	132.96	126.62	185.00	118.26	71.54	91.25	41.43

Table 4 shows the characteristic (minimum, average, and maximum) annual values of groundwater table depth (GTD) in three piezometers. It is possible to read that the GTD at all three piezometers is more than 118 m below the terrain surface on average. The deepest deposit is at piezometer B2 and the shallowest at piezometer B3. For a very short period that lasts only a few hours a year after intense short-term precipitation, the GTD in piezometer B3 is less than 20 m below the terrain surface.

Figure 3 shows the ratios of the average annual flows of the Jadro Spring (Q) depending on the average annual GWL measured in piezometers B1, B2, and B3, for the years when complete annual observations of the GWL were available in each of the three piezometers. Although it is a relatively small number of years (9 for piezometers B1 and B3 and only 4 for piezometer B2), the strong influence of the GWL in any of the three piezometers on the flow of the Jadro Spring is clearly visible. The values of the coefficients of determination are extremely high and range from $R^2=0.8384$ at piezometer B1 to $R^2=0.9346$ at piezometer B2. It should be noted that the coefficients of determination for piezometers B2 and B3 are

almost identical and considerably higher than for piezometer B1. This indicates a stronger influence of groundwater inflow from the northwest direction, formed by the junction of piezometers B2-B3, than from the northeast where piezometer B1 is located.

Figure 4 shows the series of mean annual groundwater temperatures, measured in piezometers B1, B2, and B3 and at the Jadro Spring in the period 2011-2021, for the years in which complete measurements were available at each location. It is important to note that the temperature values in piezometers B1 and B3 are almost identical and change very little during the analyzed period. Groundwater temperatures in piezometer B2 are significantly higher. The temperature of the groundwater flowing out at the Jadro Spring is higher than that measured in piezometers B1 and B3 but lower than that measured in piezometer B2. Based on these data, it is not possible to draw reliable conclusions. The main reason is that the measuring devices are located deep below the terrain surface, more than 210 m (see the last line in Table 1). Considering that GTD can be less than 20 m below the terrain surface (Table 4), alongside the analyzed

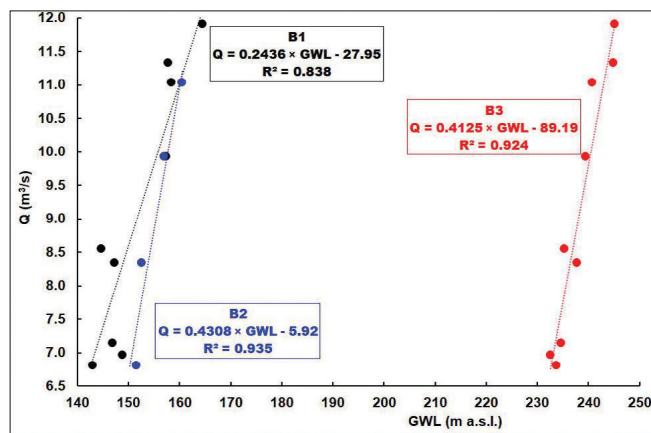


Fig. 3 - The relationship between the mean annual discharges of the Jadro Spring, Q, and the mean annual GWL, measured in piezometers B1, B2, and B3.
Fig. 3 - Rapporto tra le portate medie annue della Sorgente Jadro, Q, e il GWL medio annuo, misurato nei piezometri B1, B2 e B3.

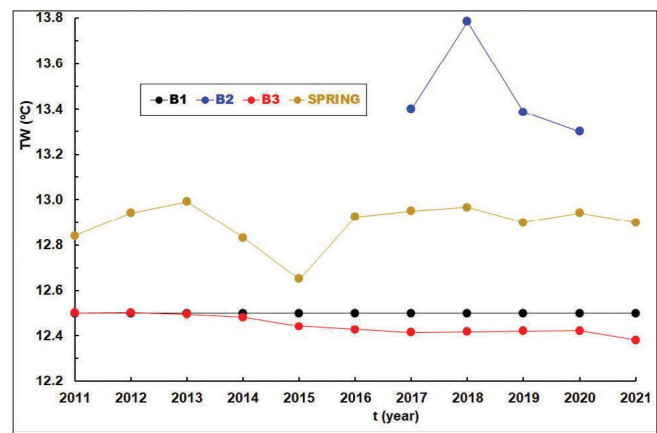


Fig. 4 - Series of the mean annual groundwater temperatures, TW, measured in piezometers B1, B2, and B3 and at the Jadro Spring.
Fig. 4 - Variazione delle temperature medie annue delle acque sotterranee, TW, misurate nei piezometri B1, B2, B3 e alla Sorgente Jadro.

temperature fluctuations, it can be inferred that air temperature cannot dominantly and directly affect the water temperature measured by the instruments positioned in the three analyzed piezometers deep below the terrain surface.

Series of mean annual values of electrical conductivity of groundwater measured in piezometers B1, B2, and B3 and at the Jadro Spring in the period 2011-2021, for the years in which complete measurements were available at each location, are shown in Figure 5. For this parameter, the values measured in piezometers B2 and B3 are similar and higher than the two other analyzed locations. At piezometer B1, they are slightly higher than at the Jadro Spring. This behavior of mean annual electrical conductivity values is primarily influenced by the characteristics of the rock mass in which the piezometers are drilled.

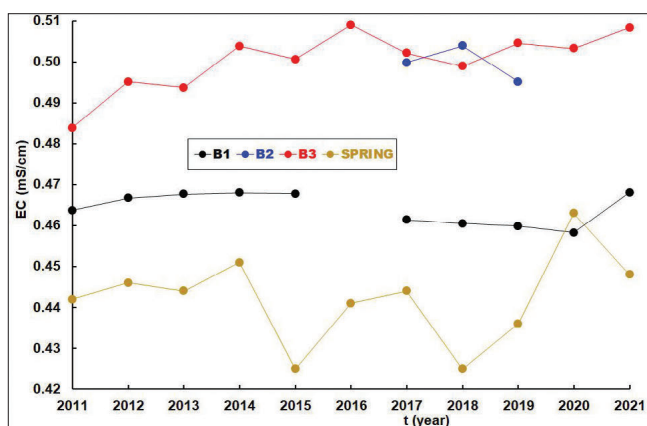


Fig. 5 - Series of the mean annual electrical conductivity, EC, measured in piezometers B1, B2, and B3 and at the Jadro Spring.

Fig. 5 - Variazione della conducibilità elettrica media annua, EC, misurata nei piezometri B1, B2 e B3 e alla Sorgente di Jadro.

The month as a time unit of analysis

The series of the mean annual GWL measured at three piezometers are shown in Figure 6. A strong seasonal character of groundwater level behavior is noticeable in all piezometers. There is neither an increasing nor decreasing trend.

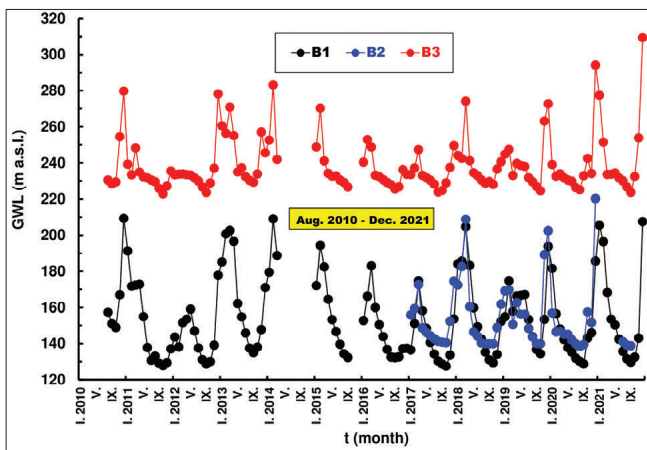


Fig. 6 - Series of the mean monthly GWL, measured in piezometers B1, B2, and B3.

Fig. 6 - Serie del GWL mensile medio, misurato nei piezometri B1, B2 e B3.

Figure 7 presents the average characteristic (minimum, average, and maximum) values of monthly GWL, measured in piezometers B1, B2, and B3 during 48 months of joint measurement (January 2017-November 2020). Even with the monthly values, a great similarity can be observed in the behavior of the characteristic GWL between piezometers B1 and B3, as well as in the case of annual values. In all three piezometers, the minimum values occur from August to even October, depending on when abundant autumn precipitation occurred during the four analyzed years. Maximum GWL occurs in December.

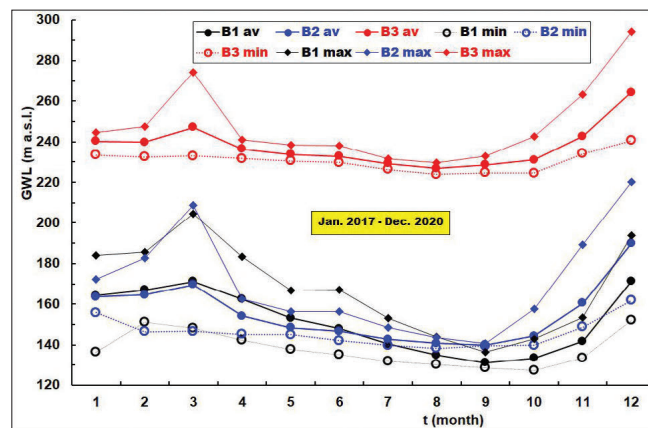


Fig. 7 - Average characteristic (minimum, mean, and maximum) values of monthly GWL, measured in piezometers B1, B2, and B3 during 48 months of joint measurement (January 2017- November 2020).

Fig. 7 - Valori caratteristici medi (minimo, medio e massimo) del GWL mensile, misurati nei piezometri B1, B2 e B3 durante 48 mesi di acquisizione congiunta (gennaio 2017-novembre 2020).

In Table 5, the values of the coefficients of determination, R^2 , between the average monthly GWL measured in three piezometers are entered. The number of pairs of values used to calculate the coefficients of determination are listed in parentheses. The monthly values also showed a similarly significant correlation as the annual values. The relationship between the GWL of piezometers B2 and B3 ($R^2=0.9357$) is much tighter than with piezometer B1 and in both cases, it is around the value of $R^2=0.65$.

Tab. 5 - Coefficients of determination, R^2 , between the mean monthly GWL measured in three piezometers. The number of pairs of values used to calculate the coefficients of determination are listed in parentheses.

Tab. 5 - Coefficienti di determinazione, R^2 , tra il GWL mensile medio misurato nei tre piezometri. Il numero di coppie di valori utilizzate per calcolare i coefficienti di determinazione è riportato tra parentesi.

R^2	GWL _{B1}	GWL _{B2}	GWL _{B3}
GWL _{B1}	1	0.6586 (51)	0.6311 (126)
GWL _{B2}		1	0.9357 (51)
GWL _{B3}			1

Figure 8 shows the average monthly values of mean monthly GWL, measured in piezometers B1 and B3 during the months of joint measurement (August 2010-November 2021; missing data for the period July-November 2014 and October-November 2015). The histogram shows the

differences, $\Delta GWL_i = GWL_{B3i} - GWL_{B1i}$, between the average values for each month, i . The aim of this analysis is to determine how the GWL behave during the 12 months of the year in two piezometers for which longer series of observations were available. The average multi-year difference in the GWL between the two piezometers was 86.2 m. During the year, this value ranged from a minimum of 69.9 m in March to a maximum of 102.0 m in November. The observed behavior, as depicted in the histogram in Figure 8, is attributed to the distinct environments in which the piezometers were drilled, each characterized by unique hydraulic conductivity traits. Specifically, piezometer B1 was positioned within a karst matrix where a prevailing slow diffuse laminar flow is dominant. In contrast, piezometer B3 was drilled in a section of the karst aquifer known for hosting numerous large conduits that facilitate a fast-turbulent flow. This interpretation aims to shed light on the observed disparities in behavior. To clarify, the authors hypothesize that the differences in drilling environments may underlie the observed variations in behavior.

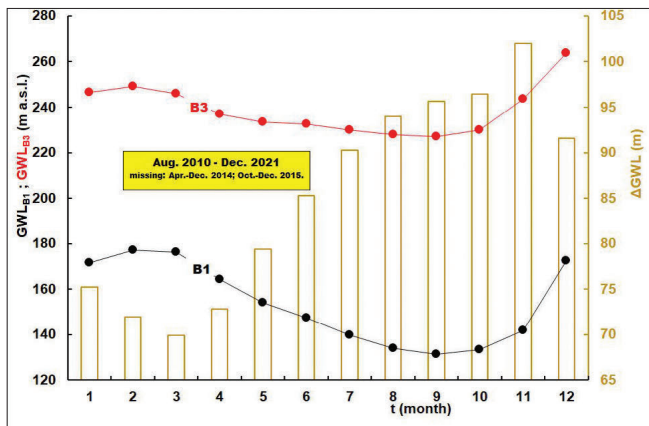


Fig. 8 - Average values of the mean monthly GWL, measured in piezometers B1 and B3 during the months of joint measurement (August 2010- November 2021; missing data for the period July- November 2014 and October- November 2015). The histogram shows the differences, $\Delta GWL_i = GWL_{B3i} - GWL_{B1i}$, between the average values for each month, i .

Fig. 8 - Variazione media mensile del GWL, misurato nei piezometri B1 e B3 nei mesi di acquisizione congiunta (agosto 2010-novembre 2021; dati mancanti per il periodo luglio-novembre 2014 e ottobre- novembre 2015). L'istogramma mostra le differenze, $\Delta GWL_i = GWL_{B3i} - GWL_{B1i}$, tra i valori medi per ogni mese, i .

Figure 9 shows the series of mean monthly groundwater temperatures, TW, measured in piezometers B1, B2, and B3, and at the Jadro Spring. While the seasonal character of variations in underground water temperatures can be clearly observed at the Jadro Spring, it cannot be established in piezometers. The reason is most likely that the measuring devices are placed very deep in the boreholes, as previously discussed.

Figure 10 shows the series of average monthly electrical conductivities, EC, measured in piezometers B1, B2, and B3 and at the Jadro Spring. With this parameter, the seasonal character of variations in the electrical conductivity of

groundwater can be clearly observed in all four locations. The largest range of values was measured at the spring, while the smallest range was observed in piezometer B1. This behavior of electrical conductivity at various locations in the Jadro spring basin can be explained by the different characteristics of minerals in the rocks but also by the collision of parts of the aquifer within which a particular piezometer is located. At the Jadro Spring, the electrical conductivity value is the result of the influence of water flowing from all parts of its vast basin, whose surface and watersheds are unfortunately still unknown.

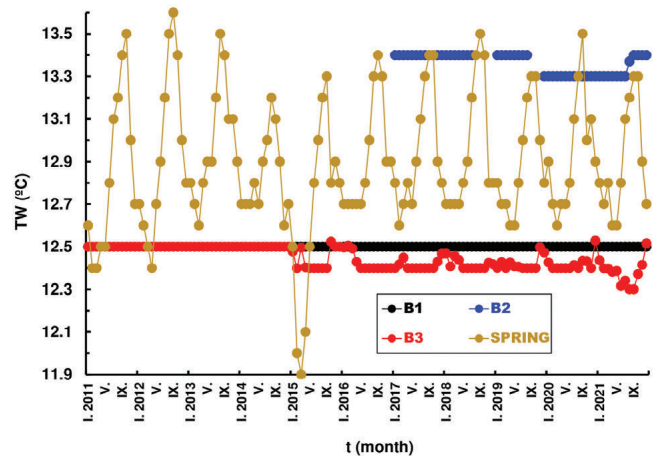


Fig. 9 - Series of mean monthly groundwater temperatures, TW, measured in piezometers B1, B2, and B3 and at the Jadro Spring.

Fig. 9 - Variazione media mensile della temperatura delle acque sotterranee, TW, misurate nei piezometri B1, B2 e B3 e alla Sorgente Jadro.

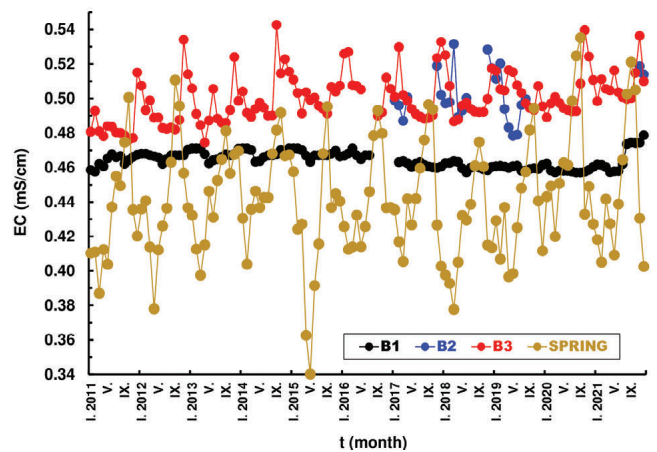


Fig. 10 - Series of the mean monthly electrical conductivities, EC, measured in piezometers B1, B2, and B3 and at the Jadro Spring.

Fig. 10 - Variazione media mensile della conducibilità elettrica, EC, misurate nei piezometri B1, B2 e B3 e alla Fonte Jadro.

Time series of the average monthly values of electrical conductivity, EC, measured at piezometers B1, B3 and at the Jadro Spring during the Jan. 2011- Dec. 2021 period are presented in Figure 11. Variation of EC during the year is the most pronounced at the spring. In case of the B1 piezometers variations are slight what is very probably caused by the position of sensor which is located at the bottom of the deep borehole.

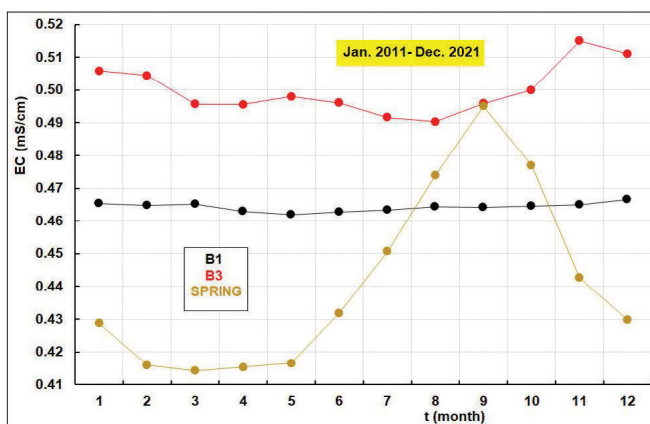


Fig. 11 - Average monthly values of electrical conductivity, EC, measured at piezometers B1, B3 and at the Jadro Spring during the Jan. 2011- Dec. 2021 period.
 Fig. 11 - Valori medi mensili della conducibilità elettrica, EC, misurati nei piezometri B1, B3 e alla Sorgente Jadro nel periodo gennaio 2011- dicembre 2021.

Day as the time unit of analysis

Time series of mean daily GWL, of three piezometers, B1, B2, and B3, and the flow hydrograph of the Jadro spring, Q, measured during 2017, are shown in Figure 12. On the time scale of a day (24 hours), a difference in response in GWL in three piezometers can be observed. While in piezometers B2 and B3, the level increase is followed by the increase in discharge at the Jadro Spring, this increase is much slower in piezometer B1 drilled in the karst matrix.

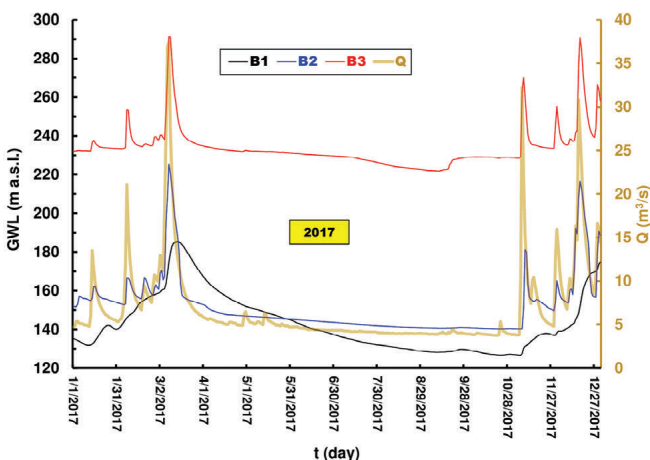


Fig. 12 - Time series of the mean daily GWL, of three piezometers, B1, B2, and B3, and the discharge hydrograph of the Jadro Spring, Q, measured during 2017.
 Fig. 12 - Serie storiche del GWL medio giornaliero, nei tre piezometri, B1, B2 e B3, e dell'idrogramma di portata della Sorgente Jadro, Q, misurati nel corso del 2017.

Differences in the response of GWL and the discharge hydrograph to daily precipitation in the basin (measured at the meteorological station Sinj) can be seen in Figure 13. Heavy precipitation that fell on October 23 (28.8 mm) after a long dry period that started in April of the same year (see Fig. 12) did not affect the rise of the GWL in any of the three piezometers. The rise in the GWL was observed in all piezometers only as a result of a long-lasting rainfall episode

that started on October 4 and lasted for five days till October 8. In piezometers B2 and B3, it caused a sudden increase and then a slight decrease in the GWL. At the same time, the level in piezometer B1 reacted with only a slight increase as a consequence of the long-term and slow filling of the matrix.

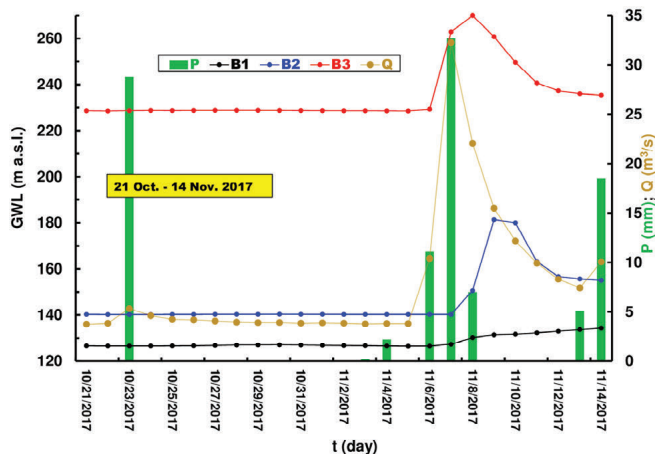


Fig. 13 - Time series of the mean daily GWL, of three piezometers, B1, B2, and B3, and the discharge hydrograph of the Jadro Spring, Q, measured during the period 21 October - 14 November 2017. The values of daily precipitation P, observed at the station Sinj, are plotted in the form of a histogram.

Fig. 13 - Serie storiche del GWL medio giornaliero, nei tre piezometri, B1, B2 e B3, e dell'idrogramma di portata della Sorgente Jadro, Q, misurati nel periodo 21 ottobre - 14 novembre 2017. I valori di precipitazione giornaliera P, osservati alla stazione Sinj, sono rappresentati sotto forma di istogramma.

The hour as a time unit of analysis

Table 6 lists the values of the maximum annual fall and rise rate of the GWL in three piezometers during the period 2011-2021, expressed in centimeters per hour (cm/h). The differences in behavior from piezometer to piezometer are very clear. The falling rate is on the average two times slower than the rising rate in piezometer B1, four times in piezometer B3 and almost 10 times in piezometer B2. The maximum annual values of the falling rate in piezometer B1 are 10 to 55 times slower than in piezometers B2 and B3. The maximum annual values of the rising rate in piezometer B1 are 30 to 50 times slower than in piezometers B3 and B2. The differences in the values of the rising and falling rates of the GWL in the three piezometers clearly shows how they were drilled in the environments that are karstified differently, which further supports the hypotheses presented previously in this paper

For the sake of comparison, it is stated that in five deep piezometers in the basin of the Omble karst spring, in a period of two years (1988-1989), the maximum GWL rising rate of 2920 cm/h was observed (Bonacci, 1995).

Figure 14 shows the series of hourly values of electrical conductivity, EC, measured in three piezometers, B1, B2, and B3, and at the Jadro Spring during 2017 (Fig. 14), 2018 (Fig. 15) and 2019 (Fig. 16). Very different behavior of the sets between each piezometer indicates different characteristics of the environments in which they were drilled. It is impossible to give more precise conclusions without more detailed knowledge of the various parameters of the aquifer space in

Tab. 6 - Maximum annual rates, *i*, of rise and fall of GWL observed in three piezometers.

Tab. 6 - Tassi massimi annui, *i*, di aumento e diminuzione del GWL osservati nei tre piezometri.

i (cm/h)	fall			rise		
	B1	B2	B3	B1	B2	B3
2011	15		437	29		
2012	14		108	38		
2013	18		349	46		
2016	10		167	22		
2017	12	188	125	29	1001	656
2018	18	176	178	40	1253	1013
2019	17	151	234	28	2159	1484
2010	17	153	335	31	1943	1478
2021	19		150	30		1006
average	15.6	167	231	32.6	1598	940

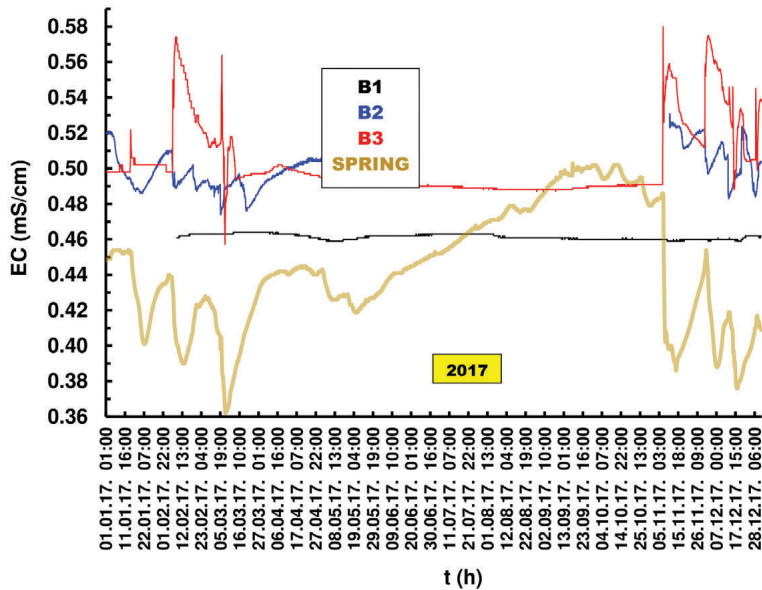


Fig. 14 - Graphical representations of series of hourly values of electrical conductivity, EC, measured in three piezometers, B1, B2, and B3, and at the Jadro Spring during 2017.

Fig. 14 - Variazione oraria della conducibilità elettrica, EC, misurata nei tre piezometri, B1, B2 e B3, e alla Sorgente Jadro nel corso del 2017.

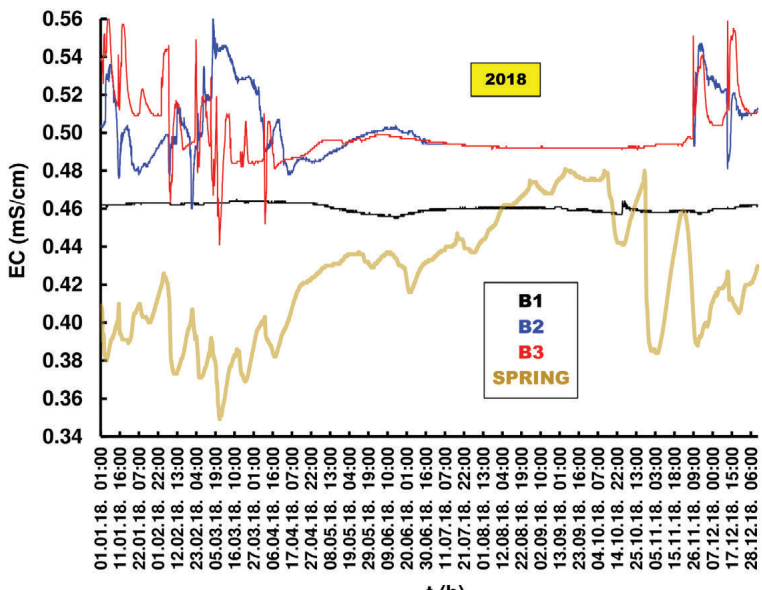


Fig. 15 - Graphical representations of series of hourly values of electrical conductivity, EC, measured in three piezometers, B1, B2, and B3, and at the Jadro Spring during 2018.

Fig. 15 - Variazione oraria della conducibilità elettrica, EC, misurata nei tre piezometri, B1, B2 e B3, e alla Sorgente Jadro nel corso del 2018.

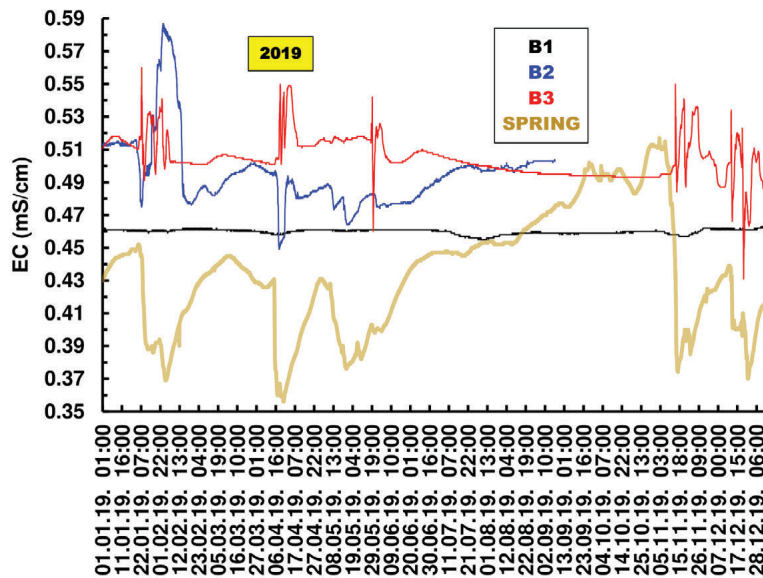


Fig. 16 - Graphical representations of series of hourly values of electrical conductivity, EC, measured in three piezometers, B1, B2, and B3, and at the Jadro Spring during 2019.

Fig. 16 - Variazione oraria della conducibilità elettrica, EC, misurata nei tre piezometri, B1, B2 e B3, e alla Sorgente Jadro nel corso del 2019.

which they are located. However, these representations clearly point to a direction the research should be heading in the near future.

Conclusions and guidelines for further work

The parameters analyzed in the paper showed variations in the three piezometers because of different discharge fluctuations controlled by the karst aquifer geological and hydrogeological characteristics in releasing its groundwater storage. Based on existing measurements, it can be reliably concluded that the parameters measured in piezometers B2 and B3, located in the fault zone are strongly influenced by the movement of groundwater in large karst conduits. On the other hand, piezometer B1 appears to be located in a karst matrix where the processes take place primarily by diffuse laminar flow (slow-flow). More detailed measurements will allow many other conclusions that are essential for the optimal management of water resources of this valuable source and its basin.

Analyzing the state of underground water reserves during the last decades in the aquifers of a number of karst springs on the eastern coast of the Adriatic Sea, Lukač-Reberski et al. (2020) determined the existence of worrying trends in the GWL declines, caused partly by increased pumping, but also by weaker replenishment of aquifers as a result of global climate changes. Fortunately, no trend of decrease in flow was observed at the Jadro Spring in the period 1995-2011 and there has been a significant reduction in the removal of water from the spring for water supply needs in the last 12 years (2010-2021) (Bonacci and Roje- Bonacci, 2023).

Regardless of these positive facts, the water of the Jadro Spring demands more care than nowadays received. Better management of its water quality must be based on much denser and more sophisticated monitoring of various parameters than is currently available. Deep exploratory and observational piezometers play a key role in this process. The number of piezometers and their location should help define

reliable watershed boundaries. Therefore, it is crucial to drill a set of deep piezometers in three locations. The first of them should be related to the control of groundwater transport from the Lečevica location, where the construction of a large regional waste disposal site is planned. The second location should be chosen in order to establish how and whether the water that comes out at the Jadro Spring is connected with the water from the basin and the Cetina River. It is of crucial importance to clarify in more detail the connection between the Grabov Mlin Sinkhole and the water that comes to the surface through the Jadro Spring. The third location of the group of deep piezometers should provide an answer to the question of the relationship between the aquifers of the Jadro and Žrnovnica basins. In addition to measuring the GWL, groundwater temperature, and electrical conductivity, it will be necessary to measure a number of chemical and ecological-biological parameters.

Today's measurements with sensors that are constantly located at the same depth cannot provide answers to numerous questions, above all the height position and dimensions of large karst conduits. In the existing three piezometers, it is necessary to immediately organize measurements of water temperatures, water velocity, and electrical conductivity at depth and under different hydrological-hydrogeological conditions, i.e., during high water levels in winter conditions as well as during low water levels in long rainless periods.

Funding source

This research was partially co-financed through project KK.01.1.1.02.0027, which was co-financed by the Government of the Republic of Croatia and the European Union through the "European Regional Development Fund - the Competitiveness and Cohesion Operational Programme".

Additional funding was provided through the project "VODIME - Vode Imotske krajine" (KK.05.1.1.02.0024), by the Government of the Republic of Croatia and the European Union through the European Structural Funds, as part of the tender "Shema za jačanje primijenjenih istraživanja za mjere prilagodbe klimatskim promjenama (Scheme for strengthening of applied research for adaptation to climate change)" (KK.05.1.1.02.).

Competing interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, data curation, formal analysis, investigation and writing of the original draft, O.B.; supervision and review and editing, T.R.-B; review and editing, A.V.

All authors have read and agreed to the final version of the manuscript.

Additional information

Supplementary information is available for this paper at

<https://doi.org/10.7343/as-2023-682>

Reprint and permission information are available writing to acquessotterranee@anipapozzi.it

Publisher's note Associazione Acque Sotterranee remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

- Atkinson, T.C. (1977). Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). *Journal of Hydrology* 35(1):93–110. [https://doi.org/10.1016/0022-1694\(77\)90079-8](https://doi.org/10.1016/0022-1694(77)90079-8)
- Bonacci, O. (1988). Piezometer – the main source of hydrologic information in the karst. *Vodoprivreda* 20(115):265–278
- Bonacci, O. (1995) Ground water behaviour in karst: example of the Ombla Spring (Croatia). *Journal of Hydrology* 165(1-4):113–134. [https://doi.org/10.1016/0022-1694\(94\)02577-X](https://doi.org/10.1016/0022-1694(94)02577-X)
- Bonacci, O. (2001). Analysis of the maximum discharge of karst springs. *Hydrogeology Journal* 9(4):328–338. <https://doi.org/10.1007/s100400100142>
- Bonacci, O. (2015). Karst hydrogeology/hydrology of Dinaric chain and Isles. *Environmental Earth Sciences* 74(1):37–55. <https://doi.org/10.1007/s12665-014-3677-8>
- Bonacci, O., Andric, I. (2015). Hidrološka analiza krškog izvora Žrnovnice kod Splita "Hydrological analysis of the karst spring Žrnovnica near Split". *Hrvatske Vode*, 23(94).
- Bonacci, O., Roje-Bonacci, T. (2000). Interpretation of groundwater level monitoring results in karst aquifers: examples from the Dinaric karst. *Hydrological Processes* 14(14):2423–2438. [https://doi.org/10.1002/1099-1085\(20001015\)14:14<2423::AID-HYP104>3.0.CO;2-2](https://doi.org/10.1002/1099-1085(20001015)14:14<2423::AID-HYP104>3.0.CO;2-2)
- Bonacci, O., Roje-Bonacci, T. (2023). Analiza oduzimanja vode iz izvora Jadro u razdoblju 2010.-2021 "Analysis of water withdrawal from the Jadro spring in the period 2010-2021". *Hrvatske Vode* 31(123):1-9
- Chalikakis, K., Plagnes, V., Guérin, R., Valois, R., Bosch, F.P. (2011). Contribution of geophysical methods to karst-system exploration: An overview. *Hydrogeology Journal* 19(6):1169–1180. <https://doi.org/10.1007/s10040-011-0746-x>
- Denić-Jukić, V., Jukić, D. (2003). Composite transfer function for karst aquifers. *Journal of Hydrology* 274(1-4):80–94. [https://doi.org/10.1016/S0022-1694\(02\)00393-1](https://doi.org/10.1016/S0022-1694(02)00393-1)
- Drogue, C. (1985). Geothermal gradients and ground water circulation in fissured and karstic rocks: The role played by the structure of the permeable network. *Journal of Geodynamics* 4(1-4):219–231. [https://doi.org/10.1016/0264-3707\(85\)90061-4](https://doi.org/10.1016/0264-3707(85)90061-4)
- Goldscheider, N., & Drew, D. (2007). *Methods in Karst Hydrogeology*: IAH: International Contributions to Hydrogeology, 26. In *Groundwater*.
- Jalžić, B., Kovač-Konrad, P. (2019). Izvor-špilja Jadro "Jadro spring-cave". *Subterranea Croatica* 17(1):26–33
- Jukić, D., Denić-Jukić, V. (2009). Groundwater balance estimation in karst by using a conceptual rainfall-runoff model. *Journal of Hydrology* 373(3-4):302–315. <https://doi.org/10.1016/j.jhydrol.2009.04.035>
- Kapelj, S.; Kapelj, J.; Jukić, D.; Denić-Jukić, V. (2008). Studija upravljanja vodama sliva Jadra i Žrnovnice. Druga faza studijsko-istraživačkih radova, Varaždin "Water management study of the Jadro and Žrnovnica basins. The second phase of study and research works, Varaždin". (Geotehnički fakultet, Fond stručne dokumentacije, br. 538/02).
- Kapelj, S., Kapelj, J., Švonja, M. (2012). Hidrogeološka obilježja sliva Jadro i Žrnovnice "Hydrogeological characteristics of the Jadro and Žrnovnica basins". *Tusculum*5(1):205–216
- Loborec, J. (2013). Procjena rizika od onečišćenja podzemnih voda u kršu na području sliva izvora Jadro i Žrnovnice. Rudarsko-geološko-naftni fakultet, Zagreb University, Zagreb "Assessment of the risk of groundwater pollution in the karst in the area of the Jadro and Žrnovnica springs. Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Zagreb"(Graduation's Dissertation). <https://urn.nsk.hr/urn:nbn:hr:169:812029>. Accessed 20 March 2023.
- Lukač-Reberski, J., Rubinić, J., Terzić, J., Radišić, M. (2020). Climate change impacts on groundwater resources in the coastal Karstic Adriatic area: a case study from the Dinaric Karst. *Natural Resources Research* 29(3):1975–1988. <https://doi.org/10.1007/s11053-019-09558-6>
- Ly, C., Ling, M., Wu, Z., Gu, P., Guo, X., Di, D. (2019). Analysis of groundwater variation in the Jinci Spring area, Shanxi Province (China), under the influence of human activity. *Environmental Geochemistry and Health* 41(2):921–928. <https://doi.org/10.1007/s10653-018-0189-6>
- Paillet, F.L. (1998). Flow modelling and permeability estimation using borehole flow logs in heterogeneous fractured formations. *Water Resources Research* 34(5):997–1010. <https://doi.org/10.1029/98WR00268>
- Paillet, F.L. (2001). Borehole geophysical applications in karst hydrogeology. US Geological Survey Karst Interest Group Proceedings. Water-Resources Investigations Report 01-4011:116–123
- Pratama, A.D., Dwiputra, D.S., Nurkholis, A., Haryono, E., Cahyadi, A., Agniy, R.F., Adji, T.N. (2021). Factors affecting hydrochemistry of karst springs and their relationship to aquifer development. *Environmental Processes* 8(4):1379–1413. <https://doi.org/10.1007/s40710-021-00547-7>
- Vigna, B., & Banzato, C. (2015). The hydrogeology of high-mountain carbonate areas: an example of some Alpine systems in southern Piedmont (Italy). *Environmental Earth Sciences*, 74(1), 267–280. <https://doi.org/10.1007/s12665-015-4308-8>
- Zwahlen, F. (2003). COST Action 620 Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers Final Report. In *Water*.