

# Comparative analysis of water temperatures variability from hourly to annual time scales in two large karst springs in the dinaric karst


## Analisi comparativa della variabilità della temperatura dell'acqua su scale temporali da orarie ad annuali in due grandi sorgenti carsiche nel carso dinarico

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### Abstract

*This study presents a comparative analysis of water temperatures from the Jadro and Ombla springs, two of the largest karst springs in the Dinaric Karst region of Croatia, situated 162.7 km apart. Both analyzed springs fall into the category of highly karstified systems. The analysis encompasses data recorded hourly from January 1, 2013, to December 31, 2021. During this period, comprehensive datasets of hourly water temperatures were available for both springs. The study examined four temporal scales: annual, monthly, daily, and hourly. Results revealed both similarities and distinctions in water temperature behavior within the coastal Dinaric Karst region. At Jadro and Ombla, the average annual water temperatures were 12.895 °C, and 12.875 °C respectively. The air temperature significantly influences the variations in water temperatures at both springs. At Jadro, the upward temperature trend was statistically insignificant, while at Ombla, the downward trend was similarly insignificant. The temperature range at Jadro (2.0 °C) was significantly smaller than that at Ombla (3.4 °C). From December to April, Jadro exhibited higher average monthly water temperatures than Ombla, while from June to September, temperatures at Jadro were lower than those at Ombla. The water temperatures at both springs were nearly identical during May, October, and November. The differences in water temperature ranges between the two springs are primarily shaped by the location, size, and natural characteristics of their catchments, including surface terrain, geological structure, hydrogeological properties, and the relative position of the water table to the ground surface.*

### Riassunto

Questo studio presenta un'analisi comparativa delle temperature dell'acqua delle sorgenti Jadro e Ombla, due delle più grandi sorgenti carsiche della regione carsica dinarica della Croazia, situate a 162,7 km di distanza l'una dall'altra. Entrambe le sorgenti analizzate rientrano nella categoria dei sistemi altamente carsificati. L'analisi comprende i dati registrati ogni ora dal 1° gennaio 2013 al 31 dicembre 2021. Durante questo periodo, sono stati disponibili set di dati completi sulle temperature dell'acqua registrate ogni ora per entrambe le sorgenti. Lo studio ha esaminato quattro scale temporali: annuale, mensile, giornaliera e oraria. I risultati hanno rivelato sia somiglianze sia differenze nel comportamento della temperatura dell'acqua nella regione costiera del carso dinarico. A Jadro e Ombla, le temperature medie annuali dell'acqua erano rispettivamente di 12,895 °C e 12,875 °C. La temperatura dell'aria influenza in modo significativo le variazioni della temperatura dell'acqua in entrambe le sorgenti. A Jadro, il trend di incremento della temperatura era statisticamente non significativo, mentre a Ombla il trend di diminuzione era altrettanto non significativo. L'escursione termica a Jadro (2,0 °C) era significativamente inferiore a quella di Ombla (3,4 °C). Da dicembre ad aprile, Jadro ha registrato temperature medie mensili dell'acqua più elevate rispetto a Ombla, mentre da giugno a settembre le temperature a Jadro sono state inferiori a quelle di Ombla. Le temperature dell'acqua in entrambe le sorgenti sono state quasi identiche nei mesi di maggio, ottobre e novembre. Le differenze nella temperatura dell'acqua tra le due sorgenti sono determinate principalmente dalla posizione, dalle dimensioni e dalle caratteristiche naturali dei loro bacini idrografici, tra cui il terreno superficiale, la struttura geologica, le proprietà idrogeologiche e la posizione relativa della superficie di falda rispetto alla superficie del terreno.

## Introduction

The Dinaric Karst is a unique and specific region extending from southwestern Slovenia (the Gulf of Trieste) in the north, through western and southern Croatia, western Bosnia and Herzegovina, all of Montenegro, and the Drim River basin in northern Albania in the south. Its eastern boundary lies in the Zapadna Morava valley in Serbia. Despite its broad geographical span, the precise area and boundaries of the Dinaric Karst are not universally defined, with estimates suggesting it covers approximately 60,000 km<sup>2</sup>. This karst region forms the westernmost segment of the world's largest karst chain, which stretches 6,400 km (Bakalowicz, 2015; Xanke et al., 2024). In Croatia, approximately 50% of the surface area is karst terrain. The Dinaric Karst is renowned as a classical karst region (*locus typicus*). It was the first karst system of this type studied worldwide and is an ideal example of karst, characterized by a full range of surface and subsurface karst features and as the birthplace of foundational theories on karst water circulation (Cvijić, 1893; Ford and Williams, 2007). It is globally recognized for its exceptional geological, hydrogeological, and biological diversity (Roglić, 1976; Bonacci, 1987, 2015; Kranjc, 2004).

Karst springs in the Dinaric Karst, which serve as discharge points for extensive karst aquifers, provide essential resources for human societies and ecosystems in this often-challenging

environment. The development of a flourishing civilization in these regions has been intricately tied to the presence and sustainable functioning of karst springs (Parise, 2018; Zwitter, 2024; Marasović & Margeta, 2017; McCormick et al., 2012; Ilakovac, 1982). This is particularly true for the coastal part of the Dinaric Karst, which extends along the entire eastern Adriatic coast. In this context, the Jadro and Ombla springs, among the most significant and water-rich springs in the region, have played and continue to play a vital role. Ombla, for example, has supplied the city of Dubrovnik and surrounding communities for centuries, illustrating the historical importance of freshwater availability and the management of hydraulic resources (Bonacci and Roje Bonacci, 2023; Margeta, 2023). More recent studies emphasize the interplay between climate hazards, water resource management, and cultural heritage in historic urban centers such as Dubrovnik and Kaštela Bay, where springs like Ombla have been central to social and economic development (Margeta, 2025; Bergheim, 2020). Furthermore, underwater archeological remains highlight the importance of protecting cultural heritage while sustainably utilizing karst water resources (Bulut and Yuceer, 2023). The analyzed springs rank among the most water-abundant sources in the Dinaric Karst and are the most prolific in Croatia, underscoring their continuing ecological, historical, and societal significance (Fig. 1).



Fig. 1 - Map showing the locations of the Jadro and Ombla springs and meteorological stations Sinj, Imotski, Ričice, and Trebinje (top). Photos of Jadro and Ombla springs (bottom). Photos reproduced with permission from Branimir Jukić.

Fig. 1 - Ubicazione delle sorgenti Jadro e Ombla e delle stazioni meteorologiche di Sinj, Imotski, Ričice e Trebinje (in alto). Foto delle sorgenti Jadro e Ombla (in basso). Foto gentilmente concessa da Branimir Jukić.

Karst springs and their associated aquifers provide immense benefits to people and ecosystems worldwide. Recent analyses reveal that karstified carbonate rocks cover 15.2% of the global ice-free continental surface (Goldscheider et al., 2020), with the highest proportion in Europe (21.8%) and the largest absolute area in Asia (8.35 million km<sup>2</sup>). Globally, 31.1% of exposed carbonate rocks are found in plains, 28.1% in hilly terrains, and 40.8% in high mountains. Approximately 151,400 km, or 15.7% of marine coastlines, are underlain by carbonate rocks. These rocks are distributed across various climates: 34.2% in arid, 28.2% in cold, 15.9% in temperate, 13.1% in tropical, and 8.6% in polar regions. Additionally, 1.18 billion people, accounting for 16.5% of the global population, reside on karst terrains, with Asia hosting the largest number (661.7 million) and Europe (25.3%) and North America (23.5%) having the highest regional percentages (Goldscheider et al., 2020).

According to the Karst Index of Shah et al. (2022) both analyzed springs fall into the category of highly karstified systems. This classification is consistent by several observed characteristics: (i) very high discharge variability, ranging from a few to more than 100 m<sup>3</sup>/s at Ombla and from 3.6 to 70 m<sup>3</sup>/s at Jadro; (ii) rapid and pronounced springflow responses to rainfall events, typical of conduit-dominated aquifers; and (iii) steep recession limbs of hydrographs, reflecting fast drainage through well-developed karst conduits. These features confirm that the groundwater circulation system feeding both springs are highly karstified and extremely sensitive to external inputs. This classification is particularly significant as it highlights the sensitivity of the associated karst aquifers, which is essential for implementing effective protection measures for these vulnerable groundwater resources. The key challenge in fulfilling this task lies in the fact that karst aquifers represent a highly heterogeneous and extremely complex groundwater circulation system.

Using water temperature data from karst springs as a parameter for groundwater studies is straightforward compared to chemical parameters and yields reliable conclusions. Modern measuring devices enable high-precision, continuous temperature monitoring (with errors as low as  $\pm 0.03^{\circ}\text{C}$ ).

Continuous measurements and analyses of water temperature in karst systems allow us to address numerous questions related to the complex processes of water circulation and storage, both within the karst aquifer and in the surface portion of the catchment area. The temperature of water discharged from karst springs integrates influences from both surface and subsurface environments through which it moves and resides. Therefore, by analyzing its spatial and temporal variations, it is possible to estimate its origin and subsurface residence time. Groundwater temperature serves as an interactive tracer, with its value responding rapidly to differences between the water and surrounding aquifer temperatures. Measurements of water temperature in karst systems can be taken in piezometers and/or wells, or directly at spring discharge points of karst aquifers. The physical

and geochemical parameters of groundwater discharged at karst springs act as natural tracers, offering reliable insights into surface and subsurface processes within each individual catchment. Numerous processes influence spring water temperature, from surface infiltration into the subsurface to water transport through the aquifer (Martin and Dean, 1999; Anderson, 2005; Covington et al., 2011; Lehman, 2011; Fidelibus and Pulido-Bosch, 2019; Tamburini and Menichetti, 2019; Chi et al., 2020).

Groundwater temperature is influenced by recharge temperature, the mixing of different waters resulting from surface and subsurface inputs, and the influence of the Earth's geothermal gradient (Long and Gilcrease, 2009). As surface water enters the aquifer system and flows downward through the matrix and karst conduits of varying dimensions, the initial temperature difference diminishes due to heat exchange at the water-rock interface. The degree of heat exchange is controlled by the thermal properties of the rocks and conduit characteristics, such as their length, cross-sectional area, and flow velocity (Renner and Sauter, 1997; Kaufmann et al., 2014). Through conductive and advective processes, water tends to reach thermal equilibrium with the surrounding rocks and sediments (Dogwiler and Wicks, 2005). Furthermore, in complex karst aquifers, inflows of water with distinct characteristics from various recharge areas under different hydrological conditions can cause significant temperature variations.

Numerous studies have utilized flow and temperature measurements in karst springs to characterize the physical characteristics of large conduits within karst aquifers (Renner and Sauter, 1997; Genthon et al., 2005; Long and Gilcrease, 2009; Kogovšek and Petrič, 2010; Gabrovšek and Turk, 2011; Stroj et al., 2020). Bundschuh (1997) provided an in-depth examination of heat transfer mechanisms in karst aquifers. Additionally, O'Driscoll and DeWalle (2006) explored the relationships between air and water temperatures to investigate interactions within groundwater flow systems in Pennsylvania (USA). Their study focused on comparing water-air temperature correlations and energy exchanges across various karst catchment structures.

Kogovšek and Petrič (2010) analyzed the propagation of temperature signals within the subsurface system of the Malenščica karst spring catchment (Slovenia) under various hydrological conditions. Their findings demonstrated that temperature serves as an effective natural tracer for water circulation in the studied area. This is a highly complex karst system with well-developed karst conduits active during both winter and summer when the Cerkniško polje is flooded. Minimum and maximum spring temperatures were recorded during high-water periods when spring recharge from the Cerknica area and extremely low or high air temperatures dominated. During low-water periods, recharge from the Javornik karst aquifer prevails.

A significant karst spring serves as the discharge point for groundwater from a complex, integrated karst water system (Kresic, 2023), encompassing both surface and

subsurface karst features that significantly influence its hydrological behavior. While surface features are typically visible, subsurface characteristics often remain unknown. For most karst springs where significant quantities of water are discharged, the exit opening is clearly defined and visible. This is true for the Jadro and Ombla springs, two major karst springs in the Dinaric Karst of Croatia, which will be analyzed in this study.

## Materials and Methods

### Jadro Spring

The Jadro River originates from its spring (Fig. 1) on the western slopes of Mosor, near the village of Majdan, at an elevation of 35 meters above sea level (m asl). The geographic coordinates of the hydrological gauge are: 43° 32' 34" N; 16° 31' 19" E. From its source, the Jadro River flows for 4,318 meters until it reaches the Adriatic Sea. The entire catchment area of the Jadro Spring displays exceptional morphological, landscape, and physiognomic diversity, complemented by a rich cultural, historical, and archaeological heritage (Kapelj et al., 2012). For more than two millennia, the spring's high-quality waters have sustained the development of civilizations in the region, supplying numerous historically significant settlements (Marasović and Margeta, 2017; Bonacci and Roje-Bonacci, 2023).

Due to the extremely complex karst geological-hydrogeological structure of the analyzed area and insufficient research, the boundaries and, consequently, the catchment area of the Jadro Spring remain poorly defined. Various values for the catchment area have been reported in the literature, determined using different methods, including: (1) 450 km<sup>2</sup> (Denić-Jukić and Jukić, 2003); (2) 396 km<sup>2</sup> (Jukić and Denić-Jukić, 2009); and (3) 502.5 km<sup>2</sup> (Krešić and Bonacci, 2010).

Although the catchment boundaries are uncertain, the maximum elevation of the Jadro catchment can be estimated at approximately 1,300 m a.s.l. in the upper parts of the Mosor and Kozjak mountains. This large elevation difference (over 1,250 m) between recharge and discharge zones contributes to the stable water temperature conditions and relatively narrow temperature range observed at the spring.

The average discharge of the Jadro Spring from 1995 to 2021 was 9.80 m<sup>3</sup>/s, with values ranging from a minimum of 6.8 m<sup>3</sup>/s (in 2017) to a maximum of 13.7 m<sup>3</sup>/s (in 2010). The lowest observed mean daily discharge was 3.65 m<sup>3</sup>/s (in 2018), while the highest reached 70.1 m<sup>3</sup>/s (in 2004). None of the three characteristic annual discharge series (minimum, mean, and maximum) showed any trend of increase or decrease during the 1995–2021 period (Bonacci and Roje-Bonacci, 2023).

Bonacci and Roje-Bonacci (2023) analyzed the relationship between water temperature, electrical conductivity, and spring discharge for the Jadro Spring from January 1, 2010, to December 31, 2021, across three temporal scales (daily, monthly, and annual). Their findings indicated a direct proportionality between water temperature and electrical conductivity, while water temperature and spring discharge were inversely proportional. As spring discharge increases,

both water temperature and electrical conductivity decrease. The narrow range of water temperature and electrical conductivity suggests that the karst aquifer feeding the spring is not directly influenced by air temperatures and that flow does not occur through large karst conduits with a free water surface. The groundwater level is situated deep below the surface, exceeding 200 meters.

Bonacci et al. (2023a) analyzed groundwater levels, groundwater temperatures, and electrical conductivity in three deep boreholes within the Jadro Spring catchment, observed from October 2010 to December 2021. The maximum rates of groundwater level rise and fall indicated that the boreholes are located in distinctly different karst environments. The annual mean discharges of the Jadro Spring were found to be directly dependent on the annual mean groundwater levels. For approximately 99% of the time, groundwater levels in all three boreholes were deeper than 210 m below the surface. Water temperatures varied among the three boreholes. In two boreholes closer to the spring, temperatures ranged narrowly between 12.4 °C and 12.5 °C, while in the more distant borehole, located at the center of the catchment, they varied between 13.2 °C and 13.4 °C. The annual mean water temperature of the spring ranged from 12.65 °C (in 2015) to 12.99 °C (in 2013), with an average value of 12.895 °C during the 2013–2021 period. The spring's water temperature variation exhibited a distinct seasonal pattern over the course of the year.

### Ombla Spring

The karstic source of Ombla is located 5 km northwest of the city center of Dubrovnik, in the settlement of Komolac at an elevation of approximately 2.4 m a.s.l. (the zero point of the hydrological gauge is 2.377 m a.s.l.). The hydrological station began operating on November 11, 1952. The geographic coordinates of the hydrological gauge are: 42° 40' 31" N; 18° 08' 14" E. Ombla supplies the city of Dubrovnik with high-quality drinking water.

The source zone consists of three deep siphon channels with three concentrated discharge points: (1) Main Source, (2) Babe, and (3) Crkvice. It is estimated that around 80% of the total yield comes from the Main Source (Milanović, 2021).

The spring itself is located in Croatia, while the largest part of the watershed is in Bosnia and Herzegovina. Geological and hydrogeological analyses by Milanović (1996) estimated the Ombla watershed area to be around 600 km<sup>2</sup>. However, using the hydrological water balance method, Roje-Bonacci and Bonacci (2013) determined that the watershed area is considerably larger, ranging between 900 km<sup>2</sup> and 1000 km<sup>2</sup>. Approximately 90% of the watershed is composed of highly permeable limestone. The presence of numerous karst surface features and predominantly bare terrain facilitates the rapid infiltration of water from the surface to the underground (Buljan et al., 2000). The highest recharge zones of the Ombla system are located in the mountainous hinterland between Trebinje and the Bileća region, reaching elevations of around 1,200–1,300 m a.s.l. This creates a relief contrast

of over 1,250 m between the highest recharge areas and the spring outlet, providing significant hydraulic potential and influencing the observed range of temperature variability at the spring.

Ombla is a highly productive upward karst spring with an average flow rate of 26.2 m<sup>3</sup>/s. Observed discharges have ranged from a minimum of 3.9 m<sup>3</sup>/s to a maximum of 117 m<sup>3</sup>/s. Three significant karst springs are located nearby: Zaton and Zavelje, which are permanent, and the Slavljani Spring, which is intermittent. Analyses have shown that all three springs are hydraulically connected to the Ombla Spring. During periods of high groundwater levels, when the flow of Ombla exceeds 70 m<sup>3</sup>/s, water from the Ombla watershed overflows into the watersheds of the above-mentioned springs. The Ombla Spring represents a typical example of a karst spring with a limited capacity for maximum discharge (Bonacci, 1995).

Bonacci et al. (2023b) analyzed hourly water temperature measurement data from the Ombla Spring, recorded between January 1, 2007 (00:00) and December 31, 2021 (23:00). Their analysis revealed two distinct subperiods with different characteristic water temperatures (minimum, average, and maximum). In the first subperiod, from January 1, 2007 (00:00) to January 24, 2012 (08:00), the minimum, average, and maximum temperatures were 12.5 °C, 13.83 °C, and 15.0 °C, respectively. In the second subperiod, from January 24, 2012 (09:00) to December 31, 2021 (23:00), a sharp decrease in characteristic temperatures occurred, with values of 10.9 °C, 12.91 °C, and 14.0 °C. The cause of this sharp temperature drop has not yet been determined.

### Data used

This study analyzed time series of hourly, daily mean, monthly, and yearly water temperatures from the Jadro and Ombla Springs for the period from January 1, 2013, at 00:00 to December 31, 2021, at 24:00. The measurements were conducted using the THALIMEDES instrument by OTT, a digital water temperature sensor, and the ADOS telemetry system.

Additionally, monthly precipitation data for the period from January 2013 to December 2021 were used, measured at three stations in Croatia (Sinj, Imotski, and Ričice) (Figure 1) within the Jadro spring region, as well as at the Trebinje station, located in the Ombla spring watershed. The monthly precipitation data from the three Croatian stations (Sinj, Imotski, and Ričice) were averaged for each month during the period from January 2013 to December 2021. These data represent the precipitation regime of the broader Jadro watershed and are referred to as *TA1* in this study while the data from Trebinje pertain to the Ombla watershed and are labeled as *TA2*.

### Methods of analysis

In this study, classical statistical methods were used to analyze time series of monthly and daily mean water temperatures from both the Jadro and Ombla springs.

The linear regression method was applied to quantitatively

express the relationship between the dependent and independent variables or to determine the trend of the analyzed time series of water temperatures. The regression line equation (linear trend) is as follows:

$$Y = (A \times t) + B$$

where *Y* represents the value of the analyzed parameter in year *t*, while *A* and *B* are the linear regression coefficients calculated using the least squares method. The coefficient *A* represents the slope of the regression line. In the case of the water temperature time series, its dimension is expressed in °C over the analyzed period. It provides an indicator of the average intensity of the trend whether an increase or decrease in values of the analyzed time series.

Linear regression was used to calculate the relationships between the average monthly and hourly water temperatures from the Jadro and Ombla Springs over the available period. The coefficient of determination (*R*<sup>2</sup>) was also computed and reported for all analyzed relationships. The coefficient of determination represents the square of the correlation coefficient (*R*). In statistical analysis, correlation coefficients (*R*) provide a quantitative measure of both the direction and strength of the relationship between variables. The coefficient of determination is a summary measure that indicates how well one variable explains the variation in another variable in regression analysis, or how well the regression line fits the data. The coefficient of determination represents the percentage of measured data points closest to the fitted line. For example, a coefficient of determination of 0.60 indicates that 60% of the data fit the regression model. Generally, a higher coefficient indicates a better fit of the model. The Chaddock's scale for interpreting correlation analysis results is as follows: (1) 0.00–0.30 Negligible correlation; (2) 0.30–0.50 Weak correlation; (3) 0.50–0.70 Moderate correlation; (4) 0.70–0.90 Strong correlation; (5) 0.90–1.00 Very strong correlation (Hinkle et al., 2003; Nikitina and Chemukha, 2023). However, it is important to note that neither the coefficient of determination nor the correlation coefficient, on their own, provide any information about causality between the analyzed parameters.

Unlike correlation, which is a mathematical procedure used to explain the relationship between two random variables, autocorrelation examines the relationship of a variable with its own lagged values. Autocorrelation analyzes the dependency of the current value of a quantity on its own previous values. It is a mathematical function that enables determining how data from a specific period depend on the same data from previous periods  $\Delta T$ . In this study, autocorrelation series were calculated for the monthly water temperatures of both analyzed springs and for the monthly air temperatures from three stations in the broader Jadro watershed in Croatia (*TA1*) and from Trebinje (*TA2*).

Duration curves of hourly water temperatures measured at the Jadro and Ombla Springs from January 1, 2013, at 00:00 to December 31, 2021, at 24:00 were calculated. A duration curve is a graphical representation that organizes data to estimate the portion of time during which the

analysed parameter is equal to or exceeds a specified value. This cumulative curve shows the percentage of time within the analyzed period when the parameter of interest was equal to or greater than a given value, irrespective of chronological order (Vogel and Fennessey, 1995). The duration curve is constructed based on the cumulative frequency of specific values. Cumulative frequency represents the duration and is graphically displayed by the duration curve. The duration curve illustrates the relationship between the frequency and the magnitude of the analyzed parameter, in this case, the water temperature of the spring.

**Results and Discussion**

This section analyzes the relationships between the characteristic (minimum, mean, and maximum) water temperatures of the Jadro and Ombla karst springs across time scales of year, month, day, and hour, covering the period from January 1, 2013, at 00:00 to December 31, 2021, at 24:00. Additionally, the relationships between the water temperatures of both springs and the air temperatures on a monthly scale will also be examined.

**Year as a unit of analysis**

Figure 2 illustrates the time series of the characteristic (minimum, mean, and maximum) annual water temperatures for the Jadro (red) and the Ombla (blue) karst springs over the nine-year period from 2013 to 2021.

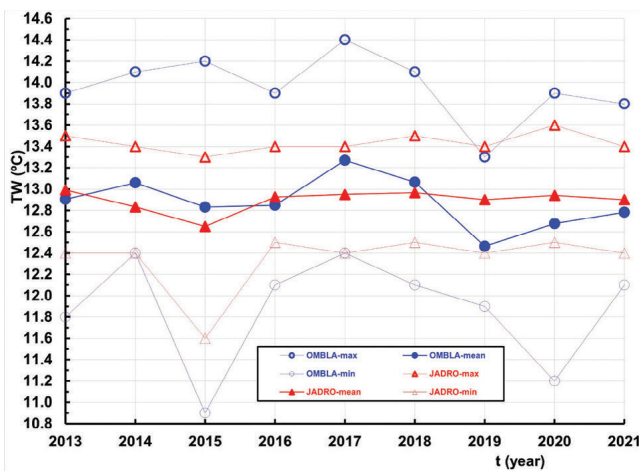


Fig. 2 - Series of characteristic (minimum, mean, and maximum) annual water temperatures of the Jadro Spring (red) and the Ombla Spring (blue) from 2013 to 2021 (9 years).

Fig. 2 - Statistiche descrittive (minimo, medio e massimo) delle temperature annuali delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu) dal 2013 al 2021 (9 anni).

Table 1 presents the characteristic (minimum, average, and maximum) water temperature values for both springs, measured from January 1, 2013, at 00:00 to December 31, 2021, at 24:00. It is evident that the average water temperatures throughout the analyzed period were nearly identical for both springs.

Tab. 1 - Characteristic (minimum, average, and maximum) water temperature (TW) values of the Jadro and Ombla springs measured from 0:00 on January 1, 2013, to 24:00 on December 31, 2021.

Tab. 1 - Statistiche descrittive (minimo, medio e massimo) dei valori di temperatura dell'acqua misurata alle sorgenti Jadro e Ombla dalle ore 00:00 del 1 gennaio 2013 alle 24:00 del 31 dicembre 2021.

TW (°C)	Jadro	Ombla
Minimum	11.6	10.9
Average	12.894	12.878
Maximum	13.6	14.4
Standard deviation	0.3062	0.5648

The temperature range for the Jadro spring was 2.0 °C, which is notably smaller than the 3.4 °C range observed at the Ombla spring.

**Month as a unit of analysis**

Figure 3 presents the time series of mean monthly water temperatures for the Jadro Spring and the Ombla Spring over 108 months of joint operation from January 2013 to December 2021.

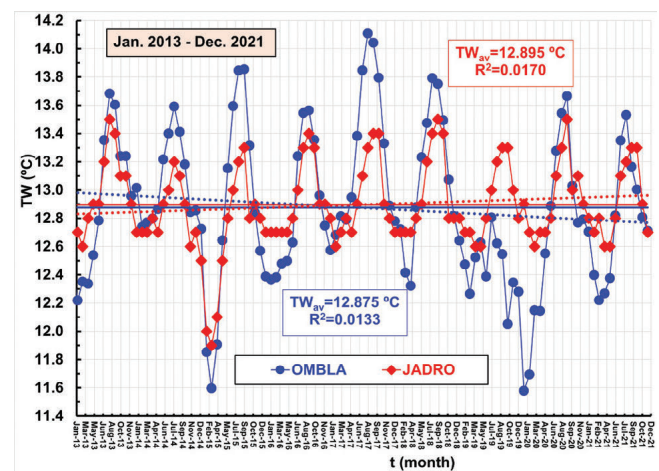


Fig. 3 - Series of mean monthly water temperatures of the Jadro spring (red) and the Ombla spring (blue) from January 2013 to December 2021 (108 months).

Fig. 3 - Serie temporale delle temperature medie mensili delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu) dal 2013 al 2021 (108 mesi).

The trend of increasing mean monthly water temperatures at the Jadro is statistically insignificant. At the Ombla, a statistically insignificant trend of decreasing temperatures is observed. Notably, between June 2019 and May 2020, significantly lower-than-usual water temperatures were recorded at the Ombla compared to the Jadro. This discrepancy was particularly pronounced during the summer months, from June to September 2020, when the water temperatures at Ombla were generally lower than those measured at Jadro.

Table 2 presents the matrix of the coefficient of determination ( $R^2$ ) values between the time series of monthly water temperatures from the Jadro spring ( $TW_J$ ), the water temperatures from the Ombla spring ( $TW_O$ ), air temperatures at three stations ( $TA_I$ ), air temperature at Trebinje station

(TA2), and flow at the Jadro spring (QJ) for the period from January 2013 to December 2021.

Tab. 2 - Matrix of determination coefficients (R<sup>2</sup>) between the series of monthly water temperatures of the Jadro spring (TWJ), Ombla spring (TWO), air temperatures at three stations (TA1), air temperature at Trebinje (TA2), and Jadro spring discharge (QJ) for the period January 2013 – December 2021. Cases where the parameters are inversely proportional are highlighted in red.

Tab. 2 - Matrice del coefficiente di determinazione (R<sup>2</sup>) tra le serie temporali mensili di temperatura dell'acqua delle sorgenti Jadro (TWJ) e Ombla (TWO), le temperature dell'aria a tre stazioni meteorologiche (TA1) e a Trebinje (TA2), e la portata della sorgente di Jadro (QJ) per il periodo gennaio 2013 – dicembre 2021. I casi in cui i parametri sono inversamente proporzionali sono evidenziati in rosso.

R <sup>2</sup>	TWJ	TWO	TA1	TA2	QJ
TWJ	1	0.562	0.382	0.325	0.224
TWO		1	0.428	0.371	0.161
TA1			1	0.985	0.387
TA2				1	0.370
QJ					1

The flow at the Ombla Spring was not analyzed, as measurements at this spring were no longer conducted by the Croatian Meteorological and Hydrological Service since 2015.

Figure 4 displays the time series of the average monthly water temperatures at the Jadro and Ombla springs from January 2013 to December 2021 (108 months).

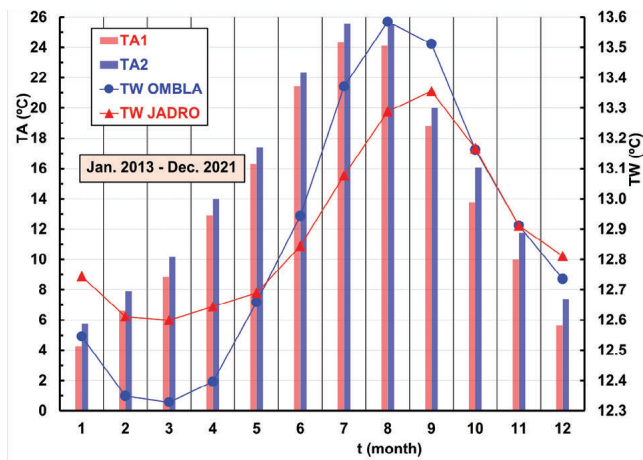


Fig. 4 - Time series of average monthly water temperatures of the Jadro Spring (red) and the Ombla Spring (blue) from January 2013 to December 2021 (108 months). The histogram represents average monthly air temperatures in the region over the same period, measured at three TA1 stations (red: Sinj, Imotski, Ričice) and one Trebinje TA2 station (blue).

Fig. 4 - Serie temporale delle temperature medie mensili delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu) dal 2013 al 2021 (108 mesi). L'istogramma rappresenta la media mensile della temperatura dell'aria nella regione nel medesimo periodo, misurata a tre stazioni (TA1, in rosso: di Sinj, Imotski, Ričice) e alla stazione di Trebinje (TA2, in blu).

The average monthly air temperatures in the region over the same period (January 2013 to December 2021, 108 months) are shown as histograms for the three stations (TA1) and the Trebinje station (TA2). The minimum values are observed in March for both springs, while the maximum values at the Ombla spring occur one month earlier, in August, compared

to the Jadro spring, where the maximum values are observed in September.

Histograms of the mean differences between the mean monthly water temperatures of the two springs ( $\Delta TW$ ) and the mean monthly air temperatures ( $\Delta TA = TA2 - TA1$ ) are presented in Figure 5. It is important to note that the average monthly air temperatures in Trebinje are consistently higher than those at the three northern stations in the Jadro spring region.

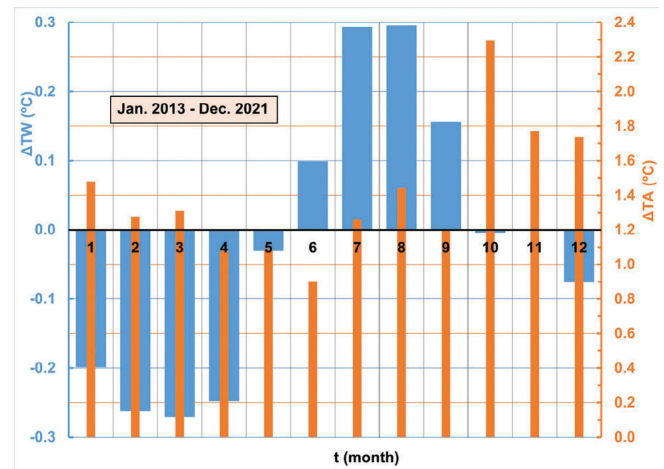


Fig. 5 - Histograms of the average differences between the mean monthly water temperatures of the two analyzed springs ( $\Delta TW$ ) and the differences in mean monthly air temperatures ( $\Delta TA = TA2 - TA1$ ).

Fig. 5 - Istantogrammi delle differenze medie tra le temperature medie mensili delle acque delle due sorgenti analizzate ( $\Delta TW$ ) e delle differenze nelle temperature medie mensili dell'aria ( $\Delta TA = TA2 - TA1$ ).

The largest difference is observed in October, while the smallest occurs in June. The average monthly water temperatures at the Jadro were higher than those at the Ombla from December to April. In contrast, from June to September, the water temperatures at Jadro were lower than those at Ombla. During May, October, and November, the temperatures were nearly identical. The data in Figures 4 and 5 suggest that the water temperatures at both springs are influenced by air temperatures, with a more direct correlation at the Ombla Spring than at the Jadro Spring.

The behavior of the relationship between average water temperatures and air temperatures over the 12 months of the year during the analyzed period (January 2013 – December 2021) can be studied in detail in the graphical relationship shown in Figure 6. The red curve represents the relationship between the average monthly water temperatures at the Jadro Spring and the average monthly air temperature in the TA1 region from January 2013 to December 2021. The blue curve illustrates the relationship between the average monthly water temperatures at the Ombla spring and the average monthly air temperature at the Trebinje station (TA2) for the same period.

Autocorrelation plots for the time series of mean monthly water temperatures for the Jadro Spring (red) and Ombla Spring (blue), as well as air temperatures at the three TA1

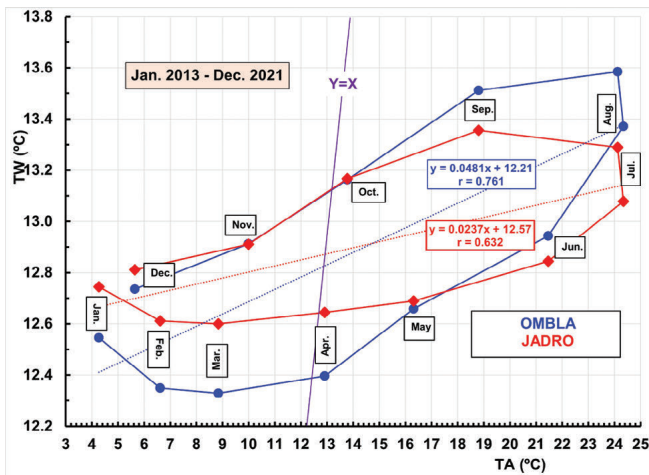


Fig. 6 - Relationship between the average monthly water temperatures of the Jadro spring (red) and the Ombla spring (blue) and the average monthly air temperatures in the region from January 2013 to December 2021 (108 months).

Fig. 6 - Relazione tra le temperature medie mensili delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu) e delle temperature medie mensili dell'aria nella regione da gennaio 2013 a dicembre 2021 (108 mesi).

stations and the Trebinje TA2 station, are presented in Figure 7. The autocorrelation coefficient is denoted as  $r$  to avoid confusion with the correlation coefficient  $R$  used earlier. The x-axis represents the Time Lag (in months), while the y-axis shows the corresponding  $r$  values.

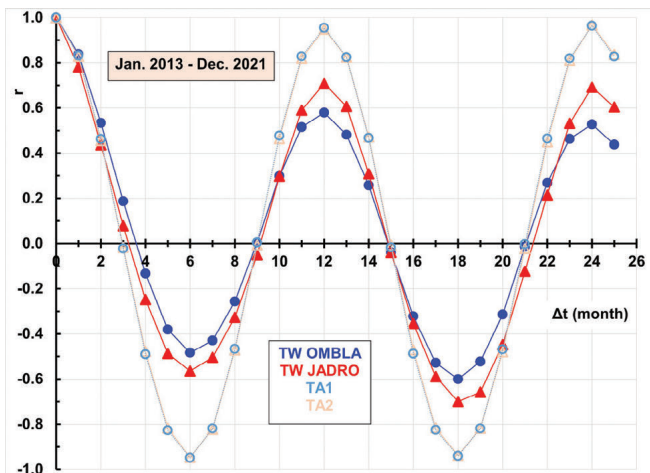


Fig. 7 - Autocorrelograms of the mean monthly water temperatures of the Jadro (red) and Ombla (blue) springs, and of air temperatures at the TA1 and TA2 stations. The y-axis denotes the autocorrelation coefficient ( $r$ ), and the x-axis represents Time Lag (months).

Fig. 7 - Autocorrelogrammi delle temperature medie mensili delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu), e della temperatura dell'aria alle stazioni TA1 e TA2. L'asse delle ordinate indica il coefficiente di autocorrelazione ( $r$ ) e l'asse delle ascisse rappresenta lo scarto temporale (mesi).

A clear seasonal influence is evident across all four parameters, with peaks at 12-month intervals, reflecting the annual cycle. The  $r$  values are consistently higher for air temperatures than for the water temperature, but both springs exhibit strong periodicity. Importantly, when both Time Lag and  $r$  values are considered together, the mean monthly water temperatures of the Ombla and Jadro springs demonstrate

a very similar internal connection. The Jadro series exhibit slightly stronger persistence of successive lags compared to Ombla, suggesting somewhat more stable temperature dynamics over time. Notably, the autocorrelation plots for the air temperature series are nearly identical, reflecting the strong similarity in the air temperature regimes of the broader regions encompassing the two springs.

**Day as a unit of analysis**

Figure 8 presents the time series of the mean daily water temperatures for the Jadro Spring ( $TW_J$ , solid red line) and the Ombla Spring ( $TW_O$ , solid blue line), alongside the flow values for the Jadro Spring ( $Q_J$ , dashed red line) and the Ombla Spring ( $Q_O$ , dashed blue line) from January 1 to December 31, 2013.

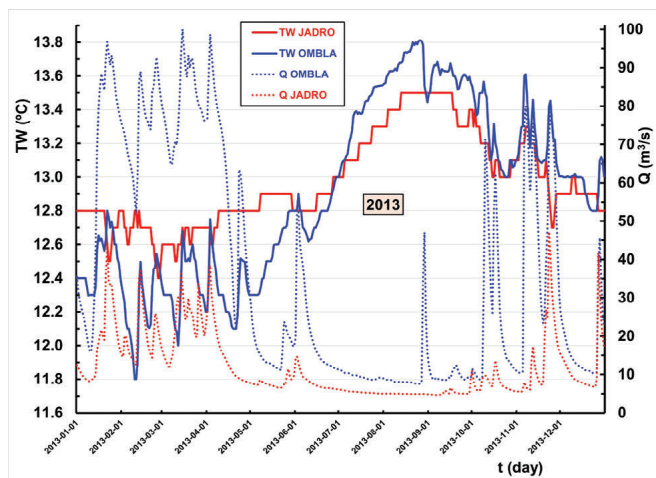


Fig. 8 - Series of mean daily water temperatures of the Jadro spring (solid red line) and the Ombla spring (solid blue line), along with discharge rates of the Jadro spring (dotted red line) and the Ombla spring (dotted blue line) from January 1 to December 31, 2013.

Fig. 8 - Serie temporali delle temperature medie giornaliere delle acque delle sorgenti Jadro (linea continua rossa) e Ombla (linea continua blu), e delle portate delle sorgenti Jadro (linea puntinata rossa) e Ombla (linea puntinata blu) da 1 gennaio 2013 a 31 dicembre 2013.

The temperature series for both springs exhibit noticeable similarities in behavior. An inverse relationship between mean daily flow and water temperature is evident: during periods of lower flow, typically in the summer months, water temperatures tend to be higher. For the Jadro, the correlation coefficient ( $R$ ) between daily flow and temperature series over the nine available years was consistently negative, ranging from -0.172 in 2013 to -0.640 in 2020, with an average of -0.481. A detailed analysis of the Ombla spring could not be conducted due to the absence of flow measurements after 2015. However, in 2013, the correlation coefficient ( $R$ ) for the Ombla Spring was -0.552, decreasing to -0.121 in 2014. The correlation coefficients ( $R$ ) between daily flows of the Jadro and Ombla Springs were notably high in 2013 and 2014, at 0.818 and 0.664, respectively.

Table 3 provides the matrix of determination coefficients ( $R^2$ ) for the time series of daily water temperatures at the Jadro

Tab. 3 - Matrix of determination coefficients ( $R^2$ ) between the series of daily water temperatures of the Jadro spring ( $TWJ$ ) and Ombla spring ( $TWO$ ) throughout the entire year (I–XII) and during the following four subperiods: (1) January–April (I–IV); (2) May–September (V–IX); (3) October–December (X–XII); and (4) May–December (V–XII). Cases where the parameters are inversely proportional are highlighted in red.

Tab. 3 - Matrice del coefficiente di determinazione ( $R^2$ ) tra le serie temporali giornaliere di temperatura dell'acqua delle sorgenti Jadro ( $TWJ$ ) e Ombla ( $TWO$ ) per l'intero anno (I–XII) e per i sottoperiodi seguenti: (1) gennaio-aprile (I–IV); (2) maggio-settembre (V–IX); (3) ottobre-dicembre (X–XII); e (4) maggio-dicembre (V–XII). I casi in cui i parametri sono inversamente proporzionali sono evidenziati in rosso.

$R^2$	I. – XII.	I. - IV.	V. – IX.	X. - XII.	V. - XII.
2013.	0.7944	0.0192	0.8893	0.458	0.7822
2014.	0.7723	0.0077	0.8293	0.944	0.8927
2015.	0.8606	0.9857	0.9477	0.0077	0.5676
2016.	0.8379	0.0003	0.9076	0.5663	0.8126
2017.	0.7413	0.0192	0.8968	0.6865	0.7530
2018.	0.8046	0.0968	0.8826	0.7102	0.8041
2019.	0.049	0.0451	0.0392	0.561	0.0598
2020.	0.5822	0.5420	0.9285	0.053	0.7043
2021.	0.6115	0.0302	0.7603	0.5163	0.5878

Spring ( $TWJ$ ) and the Ombla Spring ( $TWO$ ) throughout the year and during the specific four sub-periods: (1) January–April, (2) May–September, (3) October–December, and (4) May–December.

It is evident that the values vary depending on the time period considered. For the entire year, the coefficients of determination are generally high, except for 2019. The strongest similarity in water temperature behavior between the two springs occurs during the May–September sub-period, corresponding to the warmer and drier part of the year. Conversely, the coefficients of determination are notably lower during the January–April sub-period. A more comprehensive study and elucidation of these phenomena would require extended time series and additional datasets and information, which are either unavailable or have not been recorded.

Figures 9 (minimum), 10 (average daily mean), and 11 (maximum) display the time series of minimum, average, and maximum daily water temperatures for the Jadro (red) and the Ombla (blue) measured between January 1, 2013, and December 31, 2021. The minimum daily water temperatures at Jadro were almost always higher than those at Ombla, with only seven instances where Ombla recorded higher minimum temperatures. The average daily water temperatures at Ombla exceeded those at Jadro on 181 days and were lower on 185 days. The maximum daily water temperatures at Ombla were higher or equal to those at Jadro on 324 days, and lower on only 42 days.

**Hour as a unit of analysis**

The time series of hourly water temperature values for the Jadro (red) and the Ombla (blue) measured from 00:00 on January 1, 2013, to 24:00 on December 31, 2021 (78,888 data points) are presented in Figure 12.

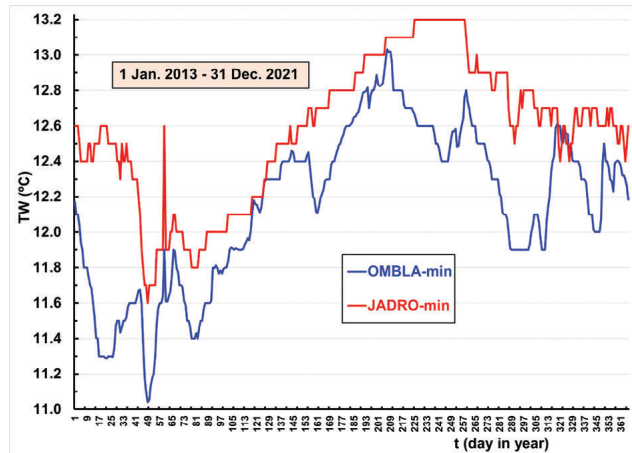


Fig. 9 - Series of minimum daily water temperatures of the Jadro spring (red) and the Ombla spring (blue) measured from January 1, 2013, to December 31, 2021.

Fig. 9 - Serie temporali dei valori minimi delle temperature giornaliere delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu) misurate dal 1 gennaio 2013 al 31 dicembre 2021.

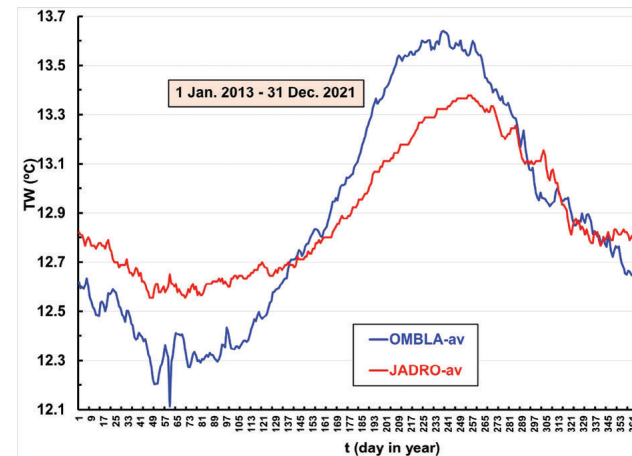


Fig. 10 - Series of average daily water temperatures of the Jadro spring (red) and the Ombla spring (blue) measured from January 1, 2013, to December 31, 2021.

Fig. 10 - Serie temporali dei valori medi delle temperature giornaliere delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu) misurate dal 1 gennaio 2013 al 31 dicembre 2021.

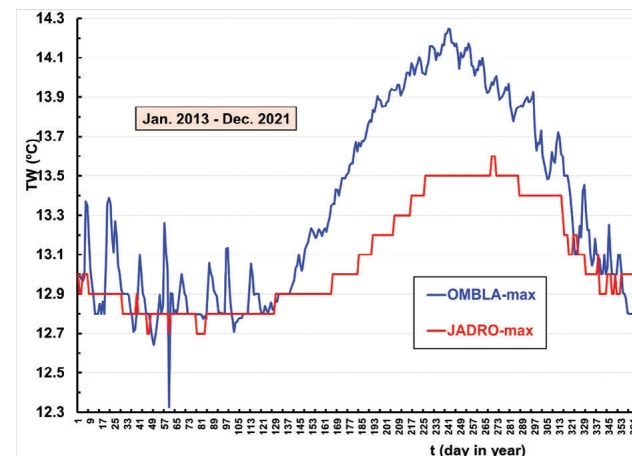


Fig. 11 - Series of maximum daily water temperatures of the Jadro spring (red) and the Ombla spring (blue) measured from January 1, 2013, to December 31, 2021.

Fig. 11 - Serie temporali dei valori massimi delle temperature giornaliere delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu) misurate dal 1 gennaio 2013 al 31 dicembre 2021.

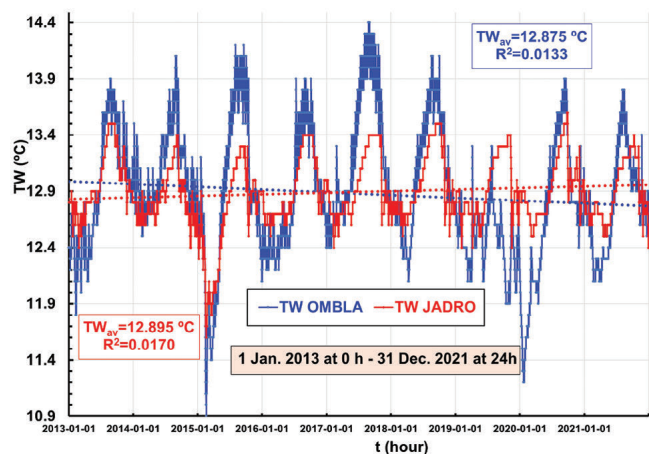


Fig. 12 - Series of hourly water temperature values of the Jadro spring (red) and the Ombla spring (blue) measured from 0:00 on January 1, 2013, to 24:00 on December 31, 2021 (78,888 data points).

Fig. 12 - Serie temporali dei valori orari di temperatura delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu) misurate dalle ore 00:00 del 1 gennaio 2013 alle ore 24:00 del 31 dicembre 2021 (78,888 dati).

At this temporal resolution, the temperature differences between the two springs become more pronounced. Notably, between June 2019 and May 2020, the Ombla Spring exhibited significantly lower water temperatures compared to the Jadro Spring.

Figure 13 displays the duration curves of hourly water temperatures for the Jadro (red) and the Ombla (blue) over the same period, illustrating the cumulative frequency distribution of water temperatures based on 78,888 hourly measurements.

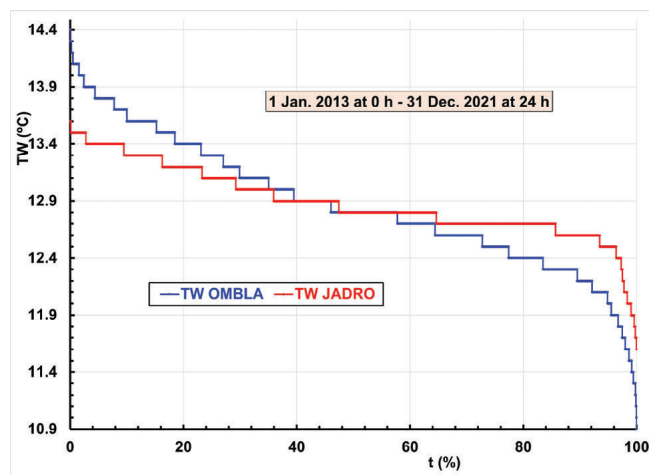


Fig. 13 - Duration curves of hourly water temperature values for the Jadro spring (red) and the Ombla spring (blue) measured from 0:00 on January 1, 2013, to 24:00 on December 31, 2021 (78,888 data points).

Fig. 13 - Curve di durata dei valori orari di temperatura delle acque delle sorgenti Jadro (in rosso) e Ombla (in blu) misurate dalle ore 00:00 del 1 gennaio 2013 alle ore 24:00 del 31 dicembre 2021 (78,888 dati).

## Discussion and guidelines for further analyses

The analyses presented above reveal both similarities and differences in the water temperature behavior of the two largest coastal karst springs in the Dinaric karst region of Croatia. By examining temperature variations across multiple temporal scales (hourly to annual), we were able to identify distinct hydrogeological behaviors that reflect the structure and functioning of their respective aquifer systems. Both springs respond clearly to atmospheric forcing, but in hydrogeologically distinct ways. Ombla exhibits a stronger and faster coupling between air and water temperature, indicating shallower and more direct flow paths with rapid recharge. In contrast, Jadro displays a more buffered thermal response, consistent with deeper, less ventilated aquifer circulation.

It can be conclusively stated that air temperature significantly influences the variations in water temperatures at both springs, which are located 167.2 km apart in a straight line. We hypothesize that the differences in water temperature ranges between the Jadro and Ombla springs arise from variations in the location, size, and natural characteristics of their catchments. These include differences in surface terrain, geological structure, and hydrogeological properties, as well as the relative depth of the groundwater table below the surface. In particular, the larger catchment size and shallower water table at Ombla may allow a stronger influence of air temperature and surface infiltration, resulting in a wider temperature range compared to Jadro.

The correlations, autocorrelation functions, and duration curves provide quantitative evidence supporting earlier qualitative assumptions about the contrasting thermal inertia and conduit dimensions in the two systems. These results extend prior conceptual models by confirming that Ombla's larger, more permeable catchment and higher discharge variability correspond to wider water temperature ranges and weaker temporal persistence, whereas Jadro's narrower ranges reflect deeper circulation and longer residence times.

Although the exact boundaries of the catchment areas remain undefined, the Ombla Spring catchment is likely about twice the size of that of Jadro, which may partly explain its slightly greater water temperature variations. In larger catchments, recharge occurs over a wider range of altitudes, terrains, and exposure conditions, which increases the diversity of infiltration temperatures and flow paths before reaching the spring. This heterogeneity reduces the averaging effect typically observed in smaller catchments and can enhance both seasonal and short-term variability in spring water temperatures. Limited available measurements also suggest that the groundwater table in the Jadro catchment lies somewhat deeper below the surface than in the Ombla catchment, which likely dampens the influence of surface air temperature and contributes to Jadro's narrower temperature range.

The observed trends and relationships (weak interannual trends, inverse relation between discharge and temperature) are consistent with findings from Bonacci & Roje-Bonacci (2023) and Bonacci et al. (2023a,b), thereby reinforcing the view that both systems are highly karstified but hydrogeologically

distinct in their internal thermal regulation mechanisms.

The deviation from the typical relationship between the water temperatures of the two springs observed in 2019 has yet to be reliably explained. Potential causes range from natural factors to human-induced activities. Local variations in air temperature and precipitation, particularly within the larger Ombla spring catchment, could have played a role. The impact of earthquakes, which are relatively more frequent and stronger in the Ombla region compared to the Jadro area (Cvijanović, 1971; Herak et al., 1988; Sović, 1999; Herak et al., 2001), should not be overlooked. Earthquakes can induce both short-term and long-term changes in the water flow paths and the characteristics of karst groundwater circulation (Carro et al., 2005; Adinolfi et al., 2012; Gosar and Brenčič 2013; Bonacci, 2020; Di Matteo et al., 2020). Furthermore, extensive surface and underground construction activities, including large-scale blasting and tunnel excavations in the upper horizons of the Ombla catchment during this period, cannot be ignored. These activities may have triggered the abrupt and relatively short-lived changes in the water temperature at the Ombla Spring.

The anomaly observed in 2019 is now interpreted not as a focal point but as a further indicator of Ombla's sensitivity to external disturbances, highlighting its complex and dynamic flow regime. This complements the broader conclusion that both springs exemplify two characteristic end-members of Dinaric karst hydrodynamics – Ombla as an open, quick responding system and Jadro as a deep, thermally buffered system.

Given the significant ecological, economic, and social importance of these abundant karst springs, intensifying comprehensive research efforts is essential. Current knowledge remains limited, largely due to the relatively short period of available discharge data and the lack of comprehensive monitoring of other relevant parameters. Drawing more reliable conclusions requires well-organized, continuous, and interdisciplinary monitoring and analysis of climatological, hydrological, hydrogeological, hydrochemical, ecological, and other parameters. The goal of such enhanced monitoring is to fill existing data gaps, improve understanding of spring dynamics, and support more robust assessments of temporal variability and long-term trends. Modern technology offers effective tools to achieve these objectives.

To ensure more reliable management of the valuable water resources provided by these two springs, establishing a permanent monitoring network for various parameters is critical.

### Competing interest

The authors declare no competing interest.

### Author contributions

Conceptualization, O.B.; methodology, O.B. and T.R.B.; software, O.B. and A.Z.C.; validation, A.Z.C. and T.R.B.; formal analysis, O.B. and T.R.B.; investigation, O.B. and A.Z.C.; data curation, O.B. and A.Z.C.; writing—original draft preparation, O.B.; writing—review and editing, A.Z.C.; visualization, O.B. and A.Z.C.; supervision, T.R.B.; project administration, T.R.B.

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

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## REFERENCES

- Adinolfi, F. R.; Carucci, V.; Falgiani, A.; Manetta, M.; Parisse, B.; Petitta, M.; Rusi, S.; Spizzico, M.; Tallini, M. (2012). Changes on groundwater flow and hydrochemistry of the Gran Sasso carbonate aquifer due to the 2009 L'Aquila earthquake. *Italian Journal of Geosciences*, 131(3), 459-474. <https://doi.org/10.3301/IJG.2012.05>.
- Anderson, M. P. (2005). Heat as a ground water tracer. *Ground Water*, 43(6), 951-968. <https://doi.org/10.1111/j.1745-6584.2005.00052.x>.
- Bakalowicz, M. (2015). Karst and karst groundwater resources in the Mediterranean. *Environmental Earth Sciences*, 74(1), 5-14. <https://doi.org/10.1007/s12665-015-4239-4>.
- Bergheim, L. (2020). Exploring the intersection of climate change and cultural heritage: the case of Croatia's Eastern Adriatic Coast. Ph.D. Thesis, University of Maine, Orono, ME, USA.
- Bonacci, O. (1987). Karst hydrology with special references to Dinaric karst. Springer Verlag, Berlin.
- 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. (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. (2020). Potresi u kršu i njihov utjecaj na izvore i otvorene vodotoke "Earthquakes in karst and their impact on springs and open watercourses". *Hrvatska Vodoprivreda*, XXVIII(231), 17-21.
- Bonacci, O.; Roje-Bonacci, T. (2023). Water temperature and electrical conductivity as an indicator of karst aquifer: the case of Jadro Spring (Croatia). *Carbonates and Evaporites*, 38, 55. <https://doi.org/10.1007/s13146-023-00881-x>.
- Bonacci, O.; Roje-Bonacci, T.; Vrsalović, A. (2023a). Different groundwater behaviour in deep karst boreholes: the case of Jadro spring basin (Dinaric karst, Croatia). *Acque Sotterranee*, 12(4), 59-69. <https://doi.org/10.7343/as-2023-682>.
- Bonacci, O.; Roje-Bonacci, T.; Vrsalović, A.; Kuk, K. (2023b). What happened to the karst spring Ombla water temperature? Carbonates and Evaporites, 38, 68. <https://doi.org/10.1007/s13146-023-00881-x>.
- Buljan, R.; Prelogović, E.; Paviša, T. (2000). Izvorište Ombla. Zbornik radova 2. hrvatskog geološkog kongresa (ur. Vlahović, I.; Biondić, R.). "The Ombla spring. In: Vlahović, I.; Biondić, R. (eds). *Proceedings of the 2<sup>nd</sup> Croatian Geological Congress*". Institut za Geološka Istraživanja, Zagreb, 555-560.
- Bulut, N., Yuceer, H. (2023) A literature review on the management of underwater cultural heritage. *Ocean Coast Manag* 245:106837
- Bundschuh, J. (1997). Temporal variations of spring water temperatures in relation to the extents of the heat transport modes occurring in the karstified lower Gypsum-Keuper aquifer (Karnian, southern Germany U: Proceedings of the 6th Conference on Limestone Hydrology and Fissured Media (ur. Jeannin, P. Y.) La Chaux-de-Fonds, Switzerland, 129-132.
- Carro, M.; De Amicis, M.; Luzi, L. (2005). Hydrogeological changes related to the Umbria-Marche Earthquake of 26 September 1997 (Central Italy). *Natural Hazards*, 34(3), 315-339. <https://doi.org/10.1007/s11069-004-2074-0>.
- Chi, G.; Xing, L.; Xing, X.; Li, C.; Dong, F. (2020). Seepage characteristics of karst water system using temperature tracer technique. *Earth and Space Science*, 7(8), e2019EA000712. <https://doi.org/10.1029/2019EA000712>.
- Covington, M. D.; Luhmann, A. J.; Gabrovšek, F.; Saar, M. O.; Wicks, C. M. (2011). Mechanisms of heat exchange between water and rock in karst conduits. *Water Resources Research*, 47(10), W10514. <https://doi.org/10.1029/2011WR010683>.
- Cvijanović, D. (1971). Seizmičnost dubrovačkog područja "Dubrovnik region seismicity". *Acta Seismologica Iugoslavica*, 31-56.
- Cvijić, J. (1893). Das Karstphänomen. *Pencks Geogr Abh* 5(3), 217-330.
- 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).
- Di Matteo, L.; Dragoni, W.; Azzaro, S.; Pauselli, C.; Porreca, M.; Bellina, G.; Cardaci, W. (2020). Effects of earthquakes on the discharge of groundwater systems: The case of the 2016 seismic sequence in the Central Apennines, Italy. *Journal of Hydrology*, 583, 124509. <https://doi.org/10.1016/j.jhydrol.2019.124509>.
- Dogwiler, T.; Wicks, M. C. (2005). Thermal variations in the hyporheic zone of karst stream. *Speleogenesis and Evolution of Karst Aquifers*, 3(1), 1-11. <https://doi.org/10.5038/1827-806X.35.2.1>.
- Fidelibus, M. C.; Pulido-Bosch, A. (2019). Groundwater temperature as an indicator of the vulnerability of karst coastal aquifers. *Geosciences*, 9(1), 23. <https://doi.org/10.3390/geosciences9010023>.
- Ford, D.; Williams, P. (2007). Karst hydrogeology and geomorphology. Wiley, Chichester, UK. <https://doi.org/10.1002/97811186684986>.
- Gabrovšek, F.; Turk, J. (2011). Water temperature as a natural tracer of groundwater in karst: the case of the Pivka and Unica Rivers. U: *Karstology and development challenges on karst I. Carsologica* 12 (ur. Knez, M.; Petrič, M.; Slabe, T.) ZRC Publishing, Ljubljana, 38-46.
- Genthon, P.; Bataille, A.; Fromant, A.; D'Hulst, D.; Bourges, F. (2005). Temperature as a marker for karstic waters hydrodynamics. Inferences from 1 year recording at La Peyrère cave (Ariège, France). *Journal of Hydrology*, 311(1-4), 157-171. <https://doi.org/10.1016/j.jhydrol.2005.01.015>.
- Goldscheider, N.; Chen, Z.; Auler, A. S.; Bakalowicz, M.; Broda, S.; Drew, D.; Hartmann, J.; Jiang, G.; Moosdorf, N.; Stevanovic, Z.; Veni, G. (2020). Global distribution of carbonate rocks and karst water resources. *Hydrogeology Journal*, 28(5), 1661-1677. <https://doi.org/10.1007/s10040-020-02139-5>.
- Gosar, A.; Brenčić, M. (2013). Possible relation between the sudden sinking of river Iška and the sequence of weak earthquakes in September-October 2010 near Iška Vas (Central Slovenia). *Acta Carsologica*, <https://doi.org/10.3986/ac.v41i2-3.563>.
- Herak, D.; Herak, M.; Prelogović, E.; Cabor, S. (1988). Some characteristics of the Adriatic Sea earthquake sequence (January-February 1986). *Bolletino di Geofisica Teorica ed Applicata*, XXX(119-120), 385-394.
- Herak, M.; Orlić, M.; Kunovec-Varga, M. (2001). Did the Makarska earthquake of 1962 generate a tsunami in the central Adriatic archipelago?, *Journal of Geodynamics*, 31(1), 71-86. [https://doi.org/10.1016/S0264-3707\(00\)00018-1](https://doi.org/10.1016/S0264-3707(00)00018-1).
- Hinkle, D. E.; Wiermsa, W.; Jurs, S. G. (2003). Applied statistics for the behavioural sciences. Houghton Mifflin, Boston.
- Ilakovac, B. (1982). Rimski akvedukt! Na području sjeverne Dalmacije. "Roman aqueduct in the area of northern Dalmatia". Arheološki muzej Zadar i Sveučilišna naklada Liber, Zagreb, p. 279.
- 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.; Švonja, M. (2012). Hidrogeološka obilježja sliva Jadra i Žrnovnice "Hydrogeological characteristics of the Jadro and Žrnovnica catchments". *Tusculum*, 5(1), 205-216.
- Kaufmann, G.; Gabrovšek, F.; Romanov, D. (2014). Deep conduit flow in karst aquifers revisited. *Water Resources Research*, 50(6), 4821-4836. <https://doi.org/10.1002/2014WR015314>.
- Kogovšek, J.; Petrič, M. (2010). Water temperature as a natural tracer - a case study of the Malenščica karst spring (SW Slovenia). *Geologia Croatica*, 63(2), 171-177. <https://doi.org/10.4154/gc.2010.14>.
- Kranjc, A. (2004). Dinaric karst. U: *Encyclopedia of caves and karst science* (ur. Gunn, J.) Fitzroy Dearborn, New York, 591-594.
- Kresic, N. (2023). *Hydrogeology 101*. Blue Ridge Press LLC, Warrenton, VA, USA.
- Kresic, N.; Bonacci, O. (2010). Spring discharge hydrograph. U: *Groundwater hydrology of springs, engineering, theory, management, and sustainability* (ur. Kresic, N.; Stevanovic, Z.) Butterworth-Heinemann/Elsevier, New York, 129-164.
- Lehmann, A. J. (2011). Water temperature as a tracer in karst aquifers. PhD Thesis, University of Minnesota, US.

- Long, A. J.; Gilcrease, P. C. (2009). A one-dimensional heat-transport model for conduit flow in karst aquifers. *Journal of Hydrology*, 378(3-4), 230-239. <https://doi.org/10.1016/j.jhydrol.2009.09.024>.
- Marasović, K.; Margeta, J. (2017). A study of Roman water intake structures at the Jadro River's spring. *Vjesnik za Arheologiju i Historiju Dalmatinsku*, 110(2), 509-532
- Margeta J (2023) Lead was an acceptable material for Roman water supply. *Water History*. <https://doi.org/10.1007/s12685-023-00335-0>
- Margeta, J. (2025). Climate hazards management of historic urban centers: the case of Kaštela Bay in Croatia. *Climate* 13:153. <https://doi.org/10.3390/cli13070153>
- Martin, J. B.; Dean, R. W. (1999). Temperature as a natural tracer of short residence times for groundwater in karst aquifers. U: *Karst Modelling*. (ur. Palmer, A.; Palmer, M.; Sasowsky, I.) Karst Waters Institute Special Publication, 5, 236-242.
- McCormick, M.; Büntgen, M. U.; Cane, M. A.; Cook, E. R.; Harper, K.; Huybers, P. J.; Litt, T. (2012). Climate change during and after the Roman Empire: reconstructing the past from scientific and historical evidence. *Journal of Interdisciplinary History*, 43(2), 169-220.
- Milanović, P. (1996). Ombla Spring, Croatia. *Environmental Geology*, 27(2), 105-107. <https://doi.org/10.1007/BF01061679>.
- Milanović, P. T. (2021). Karst Istočne Hercegovine i dubrovačkog priobalja. Bina, Banja Luka, Bosna i Hercegovina.
- Nikitina, M. A.; Chernukha, I. M. (2023). Nonparametric statistics. Part 3. Correlation coefficients. Theory and practice of meat processing, 8(3):237-251. <https://doi.org/10.21323/2414-438X-2023-8-3-237-251>
- O'Driscoll, M. A.; DeWalle, D. R. (2006). Stream-air temperature relations to classify stream-ground water interactions in a karst setting, central Pennsylvania, USA. *Journal of Hydrology*, 329(1-2), 140-153. <https://doi.org/10.1016/j.jhydrol.2006.02.010>.
- Parise, M. (2018). Recent advances in karst research: from theory to fieldwork. In: Stevanović, Z.; Kresic, N.; Culver, D. C. (Eds.), *Advances in Karst Science: From Theory to Fieldwork* (Geological Society, London, Special Publications, 466), pp. 309-327. <https://doi.org/10.1144/SP466.26>
- Renner, S.; Sauter, M. (1997). Heat as a natural tracer: Characterisation of a conduit network in a karst aquifer using temperature measurements of the spring water. U: *Karst Waters & Environmental Impacts* (ur. Günay, G.; Johnson, I). Balkema, Rotterdam, 423-431.
- Roglić, V. (1976). Socio-geografski aspekt dinarskog krša, dinarskog kulturnog areala i dinarskog brdsko-planinskog prostora. *Hrvatski Geografski Glasnik*, 38(1), 253-268.
- Roje-Bonacci, T.; Bonacci, O. (2013). The possible negative consequences of underground dam and reservoir construction and operation in coastal karst areas: an example of the hydro-electric power plant (HEPP) Ombla near Dubrovnik (Croatia). *Natural Hazards and Earth System Sciences*, 13(8), 2041-2052. <https://doi.org/10.5194/nhess-13-2041-2013>.
- Shah, R. A.; Jeelani, G.; Yadav, J. S.; Rai, S. K. (2022). Hydrogeochemical and stable isotopic evidence to different water origins of karst springs in the western Himalayas, India. *Environmental Earth Sciences*, 81, 297. <https://doi.org/10.1007/s12665-022-10397-7>.
- Sović, I. (1999). Croatian macroseismic database. *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy*, 24(6), 501-503. [https://doi.org/10.1016/S1464-1895\(99\)00061-7](https://doi.org/10.1016/S1464-1895(99)00061-7).
- Stroj, A.; Briški, M.; Oštrić, M. (2020). Study of groundwater flow properties in a karst system by coupled analysis of diverse environmental tracers and discharge dynamics. *Water*, 12, 2442. <https://doi.org/10.3390/w12092442>.
- Tamburini, A.; Menichetti, M. (2019). Groundwater temperature as a natural tracer to characterize hydraulic behaviour and geometry of carbonate aquifers: Mt. Nerone karst system, central Italy. *Rendiconti Online Società Geologica Italiana*, 47, 121-125. <https://doi.org/10.3301/ROL.2019.22>.
- Vogel, R. N.; Fennessey, N. M. (1995). Flow duration curves ii: a review of applications in water resources planning. *Journal of American Water Association*, 31(6), 1029-1039. <https://doi.org/10.1111/j.1752-1688.1995.tb03419.x>.
- Xanke, J.; Goldscheider, N.; Bakalowicz, M.; Barberá, J. A.; Broda, S.; Chen, Z.; Ghanmi, M.; Günther, A.; Hartmann, A.; Jourde, H.; Liesch, T.; Mudarra, M.; Petitta, M.; Ravbar, N.; Stevanović, Z. (2024). Carbonate rocks and karst water resources in the Mediterranean region. *Hydrogeology Journal*, 32(5), 1397-1418. <https://doi.org/10.1007/s10040-024-02810-1>.
- Zwitter, Ž. (2024). The Dinaric Karst in environmental history perspective. In: Kranjc, G. (Ed.), *Environmental Histories of the Dinaric Karst*, pp. 319-334. Springer, Cham. [https://doi.org/10.1007/978-3-031-56089-7\\_16](https://doi.org/10.1007/978-3-031-56089-7_16)