

Article

Research on Discharge and Temperature Regime of a Karst River Substantially Altered by Hydropower Plant Operation

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Abstract

This article presents the results of hydrological research on the Ruda River, which is the largest tributary of the Cetina River, located in the Dinaric karst of Croatia. The hydrology of this river has been altered after the construction of the Orlovac Hydropower Plant (HP) and the Buško Blato reservoir in 1973. The main aim of this study was to generate new knowledge about the hydrological functioning of the river, with a focus on the discharge and water temperature regimes that experienced the most severe alterations. The methodology is based on classical hydrological, statistical, and time-series analysis methods, adapted to the particularities of the study area and available data. Daily and hourly time series of air temperature, precipitation, water temperature, and discharge are analyzed to find trends, change points, inter-annual, seasonal, and sub-daily variations, durations, time shifts, and linear dependencies. The results obtained provide information on the effects of climate change, the duration of diffuse, conduit, and mixed flow, the importance of groundwater exchange, retention times, heat transfer times, and reference water temperatures. It determined the role of the operational mode of the Orlovac HP in discharge from the spring, in inter-annual and sub-annual water redistribution, and in hydropeaking and thermopeaking. The obtained information defines the present state of the Ruda River hydrology and illustrates alterations.

Keywords: karst hydrology; Ruda River; time series analysis; river temperature; hydropeaking; karst spring discharge



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1. Introduction

The basic characteristic of karst is the presence of underground voids in limestone/dolomite rock mass. Karst underground voids are subsurface cavities formed primarily by the dissolution of soluble rocks (limestone, dolomite, gypsum, or salt). Following standard karst geomorphology and hydrogeology literature [1–5], the classification of karst underground voids can be approached by origin, geometry and morphology, hydrogeological function, and scale. From the standpoint of groundwater circulation, the most important thing is scale. The scale implies a size-based classification where four types of voids are distinguished: (1) microvoids (dissolved pores and microfractures, <1 mm), (2) mesovoids (enlarged fractures and small fissures, 1 mm–10 cm), (3) macrovoids (conduits, channels and small caves, 10 cm–10 m), and (4) megavoids (large, interconnected cave networks > 10 m). The size is controlled by lithology (rock-mass solubility and purity), structural geology (presence of faults, bedding, and joints), hydrology (recharge type, base level, and flow regime), chemical factors (CO₂ and acid concentrations in water), and

climate. The size, geometry, and connectivity of voids directly control how groundwater flows, stores, and responds within the karst aquifer [6,7], thereby defining the shape of karst spring hydrographs [8]. Diffuse, conduit, and mixed flow through the karst aquifer can be distinguished [9–12]. Diffuse flow occurs in small voids, such as microvoids, and dominates in poorly developed or low-karstification zones (e.g., dolomitic terrains). It is a slow, laminar flow following Darcy's law. Recharge is diffuse, spread over a wide area. In a karst spring hydrograph, diffuse flow has several characteristic manifestations related to timing, shape, and behavior of baseflow recession. Diffuse flow dominance is shown by smooth rising limbs, moderate and broad peaks, long and gentle recessions, stable baseflow, and low flashiness. During the recession period, the temperature and chemistry of the spring water are stable, implying a long residence time. The conduit flow is turbulent, dominated by gravity and pressure gradients within macrovoids. In addition to diffuse recharge through microvoids, conduit flow is also formed by concentrated recharge through vertical shafts. These voids drain the system quickly after recharge events, producing flashy hydrographs at karst springs. Hydraulic response to rainfall is fast, with a short residence time, so the temperature and chemistry of spring water are unstable. The mixed flow occurs in mesovoids with highly variable hydraulic conductivity, depending on fracture and fissure density, aperture, and connectivity, where water flows through a combination of laminar and transitional regimes. The distinction and characteristics of diffuse and conduit flow can also be understood through hydrogeochemistry, where the magnesium Mg^{2+} concentration is crucial [13–15].

Consequently, water temperature is a valuable natural tracer of groundwater circulation and residence time in karst systems [16–18]. A stable temperature of karst spring water indicates a long residence time for infiltrated rainwater in the underground karst system. Sudden temperature changes produced by the influx of surface rainwater or stream water indicate a short residence time. Karst spring water temperature helps infer recharge events, flow path lengths, velocity, and connectivity between groundwater and spring [19–23]. Namely, infiltrating water often has a different temperature than aquifer water, leading to drops or rises in spring temperature during and after rainfall events. Along the flow path within a karst conduit, the thermal signal is changed by mixing, heat exchange, and storage effects, so temperature patterns provide spatial information on flow-path length, conduit geometry, and exchange zones. Longer flow paths, contact with rock, and hyporheic zones reduce the amplitude of temperature changes and introduce lags [24–29]. If water moves rapidly in large conduits, channels, and caves, temperature fluctuations will be large and rapid because of little contact between rock and water. If water flows more slowly through fractures, small fissures, dissolved pores, and microfractures, there is more contact, so temperature variations will be dampened and delayed. The amplitude of temperature changes and the rate at which it responds to recharge and discharge events can give clues about storage, mixing, and residence time. For example, a narrow temperature range implies well-mixed flow or a long residence time. Even in karst springs with stable mean temperature, careful time-series analysis of temperature can yield insights into aquifer behavior, recharge dynamics, and mixing processes [30,31]. Downstream of the karst spring, the water-temperature regime of karst rivers is under the influence of a complex heat-exchange process with riverbeds and atmosphere [32]. However, this regime is usually mostly defined by the temperature of tributaries and, unfortunately, anthropogenic inflows such as wastewater, dam releases, and diversions [33,34].

The subject of this paper is the Ruda River located in Croatia, which is characterized by its unique ecological dynamics strongly influenced by anthropogenic factors and karst hydrology. Over the last few decades, investigations of this river have focused on biological and ecological problems. Biological monitoring and physical and chemical spot measure-

ments have been conducted as part of multi-river karst surveys and focused faunal studies. Major studies sampled macroinvertebrates, selected physical and chemical parameters, caddisflies, mayflies, and freshwater snails at multiple sites and seasons, producing community and water-quality snapshots rather than long continuous records [35–37]. Research on the Ruda River and its catchment highlighted the ecological sensitivity of karst tributaries and the biological responses to flow alteration and local habitat change. Studies revealed that regulation and direct hydrological alterations can reduce diversity at directly affected sites while lateral springs and karst connectivity can buffer impacts in other reaches [38]. The existing research provides a good biological baseline but lacks an integrated, systematic assessment of hydrology, including the present state, the extent of alterations, and the role of hydropower plant operation in discharge, spring, inter-annual, and sub-annual water redistribution, hydropeaking, and thermopeaking. This knowledge is critical for understanding the karst water system, ensuring a safe water supply, protecting the ecosystem, and managing sustainably. This paper presents the results of hydrological research on the Ruda River based on available data and information. The main aim was to generate new knowledge about the hydrological functioning of the Ruda River, focusing on discharge and water-temperature regimes that have undergone severe anthropogenic alterations. The methodology used includes classical hydrological and statistical methods, as well as time-series analysis methods that, to the best of our knowledge, have not yet been applied in a form similar to that presented here.

2. Materials and Methods

2.1. Study Area

The Ruda River is the largest tributary of the Cetina River, which lies in Middle Dalmatia, Croatia (Figure 1). The Ruda Spring is located at the bottom of Kamešnica Mountain at an approximate elevation of 298–302.5 m a. s. l. The catchment is set within the Dinaric karst, where conduit and fissure flow in carbonate aquifers produce springs that feed surface streams and create strong groundwater–surface water coupling. It is part of a complex karst hydrological system influenced by groundwater flows, ponors, and subsurface connections [39–43]. It is composed of thick Mesozoic carbonate rocks (limestones and dolomites) with high secondary porosity caused by fracturing and karstification. Dominant lithology is Cretaceous and Jurassic limestones, locally interbedded with dolomitic layers. These rocks are highly permeable due to intense tectonic faulting and dissolution. There are many faults and fractures, forming preferential groundwater flow paths toward the Ruda Spring. Impermeable flysch deposits occur locally, acting as hydrogeological barriers that guide groundwater toward spring zones. Consequently, the aquifer feeding the Ruda Spring is a karst aquifer with conduit and fissure flow. Due to the karstic nature of the terrain, the hydraulic connectivity between surface and subsurface waters is strong and rapid, leading to fast groundwater responses to rainfall events.

Human impacts and hydrological changes are strong, so the spring and river function under a substantially altered hydrological regime. The Ruda Spring is a vital source of freshwater. Allowed abstraction is 540 L/s or 8,000,000 m³ per year. Actual abstraction is approximately 4,500,000 m³ per year. Before the 1970s, the discharge from the spring was controlled by natural karst hydrology, fed by underground aquifers and precipitation cycles. The spring was fed by water from ponors in Livanjsko Polje (Bosnia and Herzegovina) and by the infiltrated water from higher karst plateaus of the Kamešnica Mountain. After the Buško Blato reservoir began operating in 1973, significant alterations in natural spring discharge and river flow were seen. The Buško Blato reservoir has an active storage of 786×10^6 m³, with an average level of 716.4 m a. s. l. Water from the Buško Blato reservoir is diverted through the Lipa reservoir and then used to generate hydropower at the Orlovac

Hydropower Plant (HP) in Croatia. The Lipa reservoir is situated at 700 m a. s. l., and its capacity is 1.6 million m³. It also serves as a compensation reservoir into which the canal system brings one-day inflows from the Livanjsko Polje. From there, through a 12,100 m long tunnel beneath the Kamešnica Mountain, the water is conveyed to the Orlovac HP. During the rainy period, when inflows exceed the Orlovac HP's consumption requirements, the Lipa reservoir fills, and the surplus water is pumped by a pumping station into the Buško Blato reservoir [44]. The installed capacity of this high-pressure underground hydropower plant is 237 MW, hydraulic head 380 m, and the average annual electricity production is approximately 800 GWh. Installed discharge through turbines is 70 m³/s [45]. After being used for power generation, this water is discharged via an open channel into the Ruda River, approximately 1.2 km downstream from the spring. Consequently, Ruda's flow regime is now mostly artificial, as it receives water primarily from hydropower operations rather than from its natural karst sources. In practice, the construction of the Buško Blato and Lipa reservoirs and the operation of the Orlovac HP have transformed the Ruda River into an engineered discharge outlet, disrupting its natural balance and the ecological health of the karst river. Artificial regulation decreased natural flow variability (less difference between wet and dry periods), altered temperature and sediment regimes, and reduced ecological connectivity along the river system.

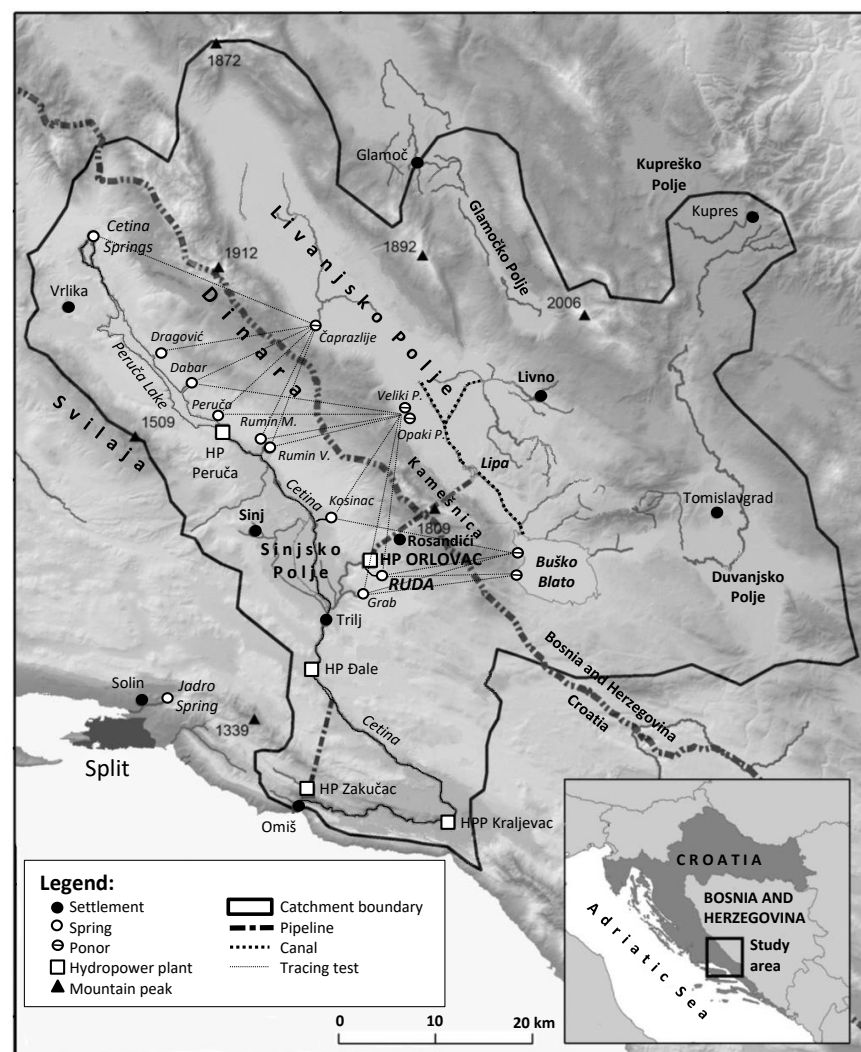


Figure 1. Location map of the Cetina River catchment with groundwater connections determined by tracing tests. Map orientation: North at the top.

2.2. Available Time Series

Information about precipitation and air temperatures in the catchment of Ruda Spring is obtained from the daily time series collected at the Livno Meteorological Station (MS) located in the Livanjsko Polje and the Rosandići Rain Gauge (RG) situated at the foothills of the Kamešnica Mountain (Figure 1). Information about daily and hourly discharges is obtained from three hydrological stations situated in the wider area of the Ruda Spring: Ruda 1, Ruda Kanal, and Ruda Orlovac (Figure 2). Discharges from the spring are calculated as the sum of discharges measured at the hydrological stations Ruda 1 and Ruda Kanal. Cumulative inflows and losses along the segment of the river from the Ruda Spring to the Ruda Orlovac Hydrological Station (HS) are represented by differences between measured discharges at the Ruda Orlovac HS and calculated discharges for the Ruda Spring. It should be noted that cumulative inflows and losses are dominantly generated by discharges from the Orlovac HP. However, there are intervals in time series when the discharge at Ruda Orlovac HE is lower than the discharge from Ruda Spring, which denotes the existence of losses at this segment of the river. They are registered during non-operational periods of Orlovac HP. Continuous monitoring of water temperatures is performed only at Ruda Orlovac HS. Basic statistical characteristics of observed air temperatures, precipitation, discharge, and water temperatures are presented in Table 1, including the monitoring periods, analyzed time steps, minimum and maximum recorded values, and means.

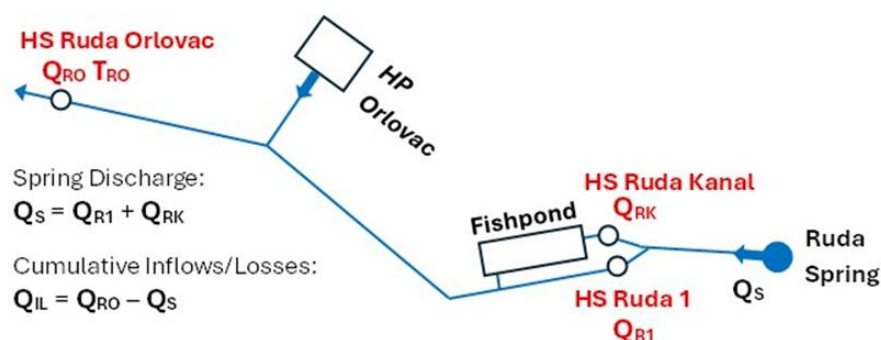


Figure 2. Schematic presentation of the locations of hydrological stations.

Table 1. Basic statistical characteristics of air temperatures, precipitations, discharges, and water temperatures, including periods of monitoring, analyzed time steps, minimal and maximal registered values, and means.

Hydrological Station					Meteorological Station					Rain Gauge		
Ruda Spring Q _S (m ³ /s) Daily 1968–1973					Ruda Orlovac Q _{RO} (m ³ /s) Daily 1973–1988					Livno P _L (mm) Annual 1969–2023		
1973–1988	1989–2022	Hourly 2005–2022	Hourly 2001–2021	Hourly 2008–2022	Hourly 2005–2022	Hourly 2001–2021	Hourly 2008–2022	Hourly 2001–2021	Hourly 2008–2022	Daily 1996–2022	Daily 1996–2022	Daily 1997–2022
Min.	0.62	2.09	1.54	2.92	3.01	1.92	2.92	1.4	773.2	−15.6	761.6	
Mean	13.3	14.2	12.1	12.6	25.9	24.3	24.7	11.9	1165.6	10.3	1115.8	3.07
Max.	43.3	42.3	49.8	48.0	125.0	108.0	122.0	24.6	1796.0	29.1	1777.8	120.0

2.3. Methods

Let $x = \{x_1, x_2, \dots, x_n\}$ and $y = \{y_1, y_2, \dots, y_n\}$ represent two analyzed time series or two sets of measured data that have means $\mu(x)$, $\mu(y)$, standard deviations $\sigma(x)$, $\sigma(y)$, and covariance $c(x, y)$ [46].

Values of the Duration Curve (DC) of the time series x are estimated by using an empirical cumulative distribution:

$$DC(x) = \left\{ p_i : p_i = \frac{\text{rank}(x_i)}{n+1}; i = 1, 2, \dots, n \right\} \quad (1)$$

Values of the Rescaled Adjusted Partial Sum (RAPS) of time series x are defined as [47,48]:

$$RAPS(x) = \left\{ s_i : s_i = \frac{1}{\sigma(x)} \sum_{k=1}^i (x_k - \mu(x)); i = 1, 2, \dots, n \right\} \quad (2)$$

Values of the Moving Average (MA) filter of time series x for a window size k are calculated by the following expression:

$$MA(x) = \left\{ m_i : m_i = \frac{1}{2k} \sum_{-k}^k x_{i+k}; i = k, k+1, \dots, n-k \right\} \quad (3)$$

The Pearson correlation coefficient between time series x and y is [43]:

$$r(x, y) = \frac{c(x, y)}{\sigma(x)\sigma(y)} \quad (4)$$

Linear Regression (LR) between x and y is defined by:

$$y_i = ax_i + b + \varepsilon_i, i = 1, 2, \dots, n, \quad (5)$$

where a is slope, b intercept, and ε_i residuals. Parameters of line, a and b , are determined by minimizing the sum of squared residuals. Goodness of fit of LR is estimated by a coefficient of determination R^2 , where $R = r(x, y)$. Statistical significance of R is evaluated for the level $\alpha = 0.05$ by using statistics [49]:

$$t = \frac{R\sqrt{n-2}}{\sqrt{1-R^2}}, \quad (6)$$

that follows a t-distribution with the degree of freedom $df = n - 2$.

Let $c_k(x, y)$ represent covariance between time series $x = \{x_1, x_2, \dots, x_{n-k}\}$, and $y = \{y_{1+k}, y_{2+k}, \dots, y_n\}$, and let $c_k(y, x)$ represent covariance between time series $y = \{y_1, y_2, \dots, y_{n-k}\}$ and $x = \{x_{1+k}, x_{2+k}, \dots, x_n\}$, where $k \geq 0$. Values of the Pearson Cross-Correlation Function (CCF) between time series x and y at lag k is defined as [46]:

$$CCF(x, y) = \{r_k : k = 0, \pm 1, \pm 2, \dots, \pm |n - k|\} \\ r_k = \begin{cases} \frac{c_k(x, y)}{\sigma(x)\sigma(y)} & : k \geq 0 \\ \frac{c_{|k|}(y, x)}{\sigma(x)\sigma(y)} & : k < 0 \end{cases} \quad (7)$$

3. Results

Analyzed time series are precipitations from the Livno MS (P_L), precipitations from the Rosandići RG (P_R), air temperatures from the Livno MS (T_L), water temperatures from the Ruda Orlovac HS (T_{RO}), discharges from the Ruda Spring (Q_S), discharges from the Ruda Orlovac HS (Q_{RO}), and inflows/losses (Q_{IL}) standing for discharges from the Orlovac HP. Mean, maximal, and minimal values for each year are presented in Figure 3. Homogeneity of time series was controlled by using the Levene test (Brown-Forsythe version) for variances, the independent t -test for means, and the Wilcoxon test for trends [49–51]. Results show that annual precipitations P_L and P_R are similar (Figure 3a), but they have a wide range from 761 to 1796 mm. Air temperatures from the Livno MS (Figure 3b) and discharges from the Ruda Spring (Figure 3c) are inhomogeneous. Annual air temperatures T_L have an upward trend, with an approximate increase of 1 °C over 20 years. Annual discharges Q_S have a mean shift in 1988. Namely, the mean annual discharge from Ruda Spring during the period 1973–1988 was 14.2 m³/s. During the period 1989–2022, it was

12.1 m³/s. The mean shift coincides with the beginning operation of Dale HP situated about 12 km downstream from the spring. Figure 3e also presents the results of the application of the MA filter to annual discharges Q_{IL} . Results describe inter-annual variations in intensity of operation of the Orlovac HP in the form of five-year means (size of window $k = 2$ in Equation (2)). The period of the most intensive operation of the Orlovac HP was 1977–1981, with a five-year mean of 19.2 m³/s. The period of the lowest intensity was 1984–1988 with five-years mean of only 7.9 m³/s.

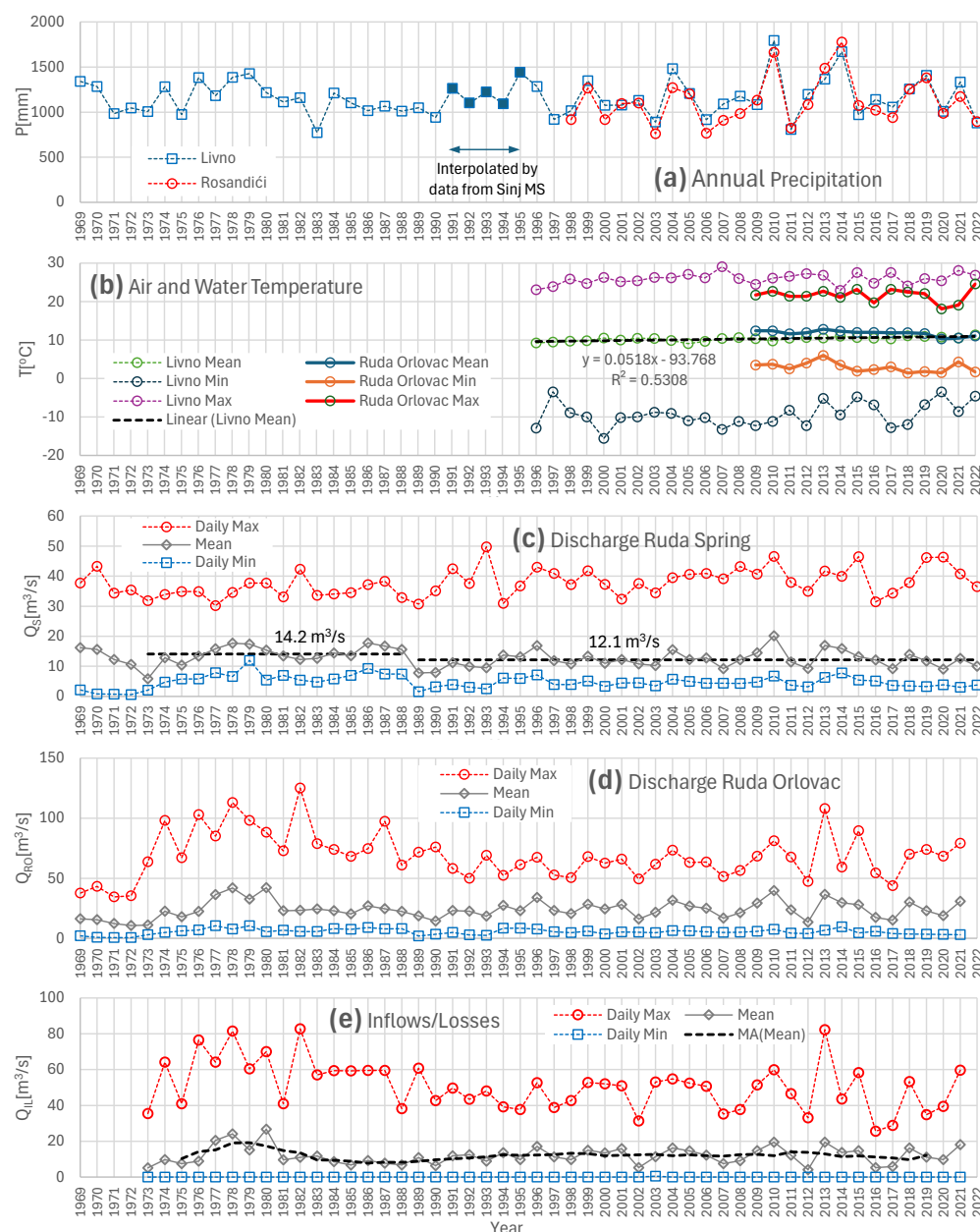


Figure 3. Mean, maximal, and minimal values for each year for (a) precipitations from Livno MS and Rosandići RG, (b) air temperatures from Livno MS and water temperatures from Ruda Orlovac HS, (c) discharges from Ruda Spring, (d) discharges from Ruda Orlovac HS, (e) inflows/losses standing for discharges from Orlovac HP.

The RAPS of annual precipitation P_L and annual discharges Q_{RO} , Q_S , and Q_{IL} are compared in Figure 4. Upward or positive trends in RAPS are periods with values mostly above average. Downward or negative trends are periods with values mostly below average. A sharp change in direction denotes a possible regime shift. The maximum or

minimum point is the potential change-point location. It can be noted that interannual variations in annual discharges Q_{RO} have generally followed those in annual precipitation P_L during the entire period. On the other hand, two components of Q_{RO} (Q_S and Q_{IL}) had different behaviors. They both deviated from the annual precipitation P_L , especially during the period before 1988. The change point in the year 1988 in $RAPS(Q_S)$ is clear, which confirms the inhomogeneity of annual discharges Q_S . Differences in variations between $RAPS(Q_S)$ and other functions are most obvious for the period 1983–1988, when only $RAPS(Q_S)$ shows positive trends. Concerning annual discharges Q_{IL} before 1988, $RAPS(Q_{IL})$ show positive trends for the period 1973–1981, and negative trends after that. Comparing $RAPS(Q_{IL})$ in Figure 4 with the results of the MA filter in Figure 3e, it can be noted that positive trends in $RAPS(Q_{IL})$ coincide with the period of the most intensive operation of the Orlovac HP, from 1977 to 1981. After this period, the lowest-intensity operation period is from 1984 to 1988, with negative trends in $RAPS(Q_{IL})$. It should be emphasized that negative trends in $RAPS(Q_{IL})$ coincide with positive trends in $RAPS(Q_S)$ during this period, which shows that the decrease in annual discharges from the Orlovac HP was offset by an increase in annual discharges from the Ruda Spring.

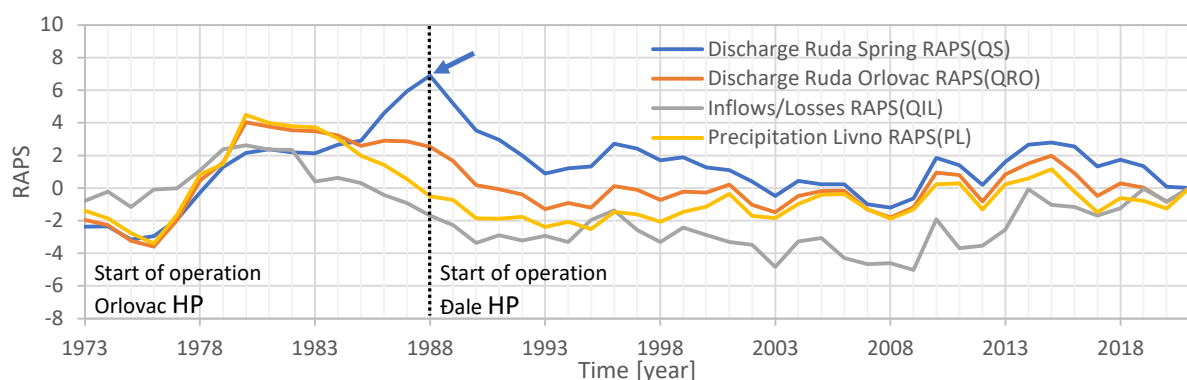


Figure 4. RAPS of annual precipitations from Livno MS and annual discharges from Ruda Spring, Ruda Orlovac HS, and Orlovac HP.

DC of daily discharges Q_S for periods 1973–1988 and 1989–2022 are compared in Figure 5a. High-flow segment describes rapid conduit flow, direct recharge response, and flood dynamics. A steeper slope denotes a more flashy system. In karst, it is usually very steep, which shows a strong hydraulic connection and low attenuation. The middle segment describes mixed flow (conduit + fracture) and transitional storage release. Shape shows the degree of internal regulation. The low-flow segment describes matrix drainage, long-term storage, and drought behavior. If flat, it shows strong baseflow regulation. If steep, it shows limited matrix storage. The simplest approach to comparing DC is to use pointwise comparisons at characteristic percentiles: P10 for high flows, P50 for mixed flows, and P90 for low flows. It can be noted that corresponding discharges for percentiles P10, P50, and P90 are higher for the first period. In Figure 5b, both DC are presented in a log-normal probability plot. Using a probability plot enhances the visualization of extreme values, makes regime changes more visible, helps identify the statistical distribution, and simplifies comparison between datasets. Breaks in slope may suggest multiple storage compartments. For example, karst systems often activate conduits above certain recharge thresholds. On the probability plot, this appears as a kink, an inflection point, or a sudden slope increase. This may show overflow conduits, epiphreatic activation, or temporary spring connections. However, the DC obtained for the period 1989–2022 is rather linear, so almost the entire range of discharges can be approximated by a log-normal distribution. Exceptions are only 1% highest values. The DC obtained for the period 1973–1988 has

a more complex structure that reveals differences in the functioning of the karst spring during the two periods. The shape of the DC for the period 1973–1988 at probabilities between 0.1 and 0.99 shows that the karst aquifer at Ruda Spring during this period had more inflows. During both periods, baseflow has been stable, which is a characteristic of a permanent spring.

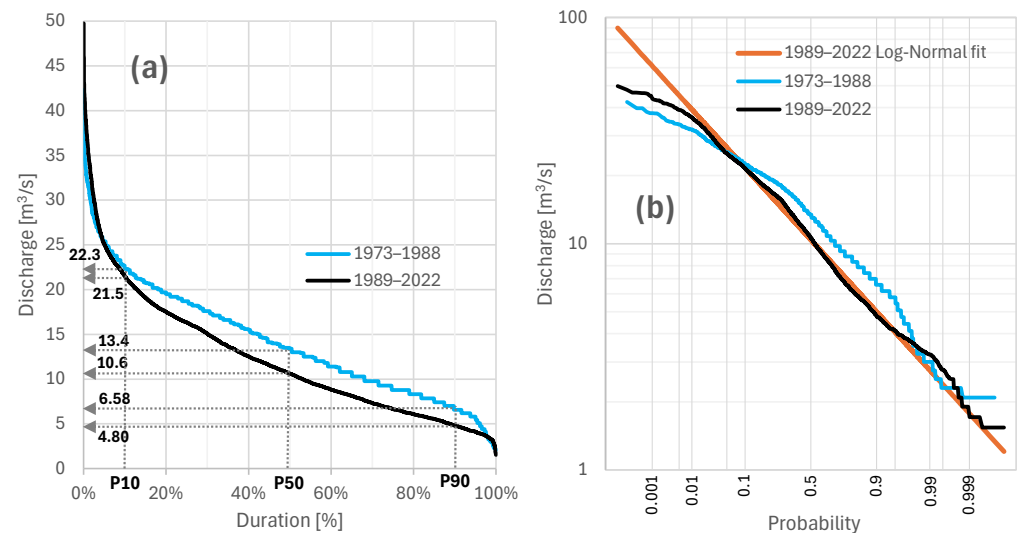


Figure 5. DC of daily discharges from Ruda Spring for periods 1973–1988 and 1989–2022 presented on (a) regular graph, and (b) probability graph.

RAPS of daily time series, including precipitation P_L , discharges Q_S , Q_{RO} , Q_{IL} , water temperatures T_{RO} , and air temperatures T_L are compared in Figure 6. They cover time periods 1996–2021 (P_L , Q_S , Q_{RO} , Q_{IL}) or 2009–2023 (T_{RO} , T_L), depending on comparison requirements and availability of daily data. Since daily time series are autocorrelated, seasonality, trends, and fluctuations are clear in all RAPS. Seasonality dominates in water temperatures and air temperatures, while in precipitation and discharge, it is only an additional fluctuation that distorts inter-annual trends. In daily precipitations T_L , three periods can be distinguished: 1996–2009, 2009–2015, and 2015–2021. The first period had below-average precipitation, so $RAPS(P_L)$ has generally negative trends. The second period had the most abundant precipitation, so trends are positive. These trends last until 2015 when they are changed again. The regime of daily discharges Q_S follows that of daily precipitation P_L , so interannual variations in $RAPS(Q_S)$ and $RAPS(P_L)$ are similar. However, due to retention of rainwater in the karst aquifer, sub-annual fluctuations are attenuated, and seasonal variations are amplified, so change points in 2009 and 2015 are evident in $RAPS(Q_S)$. The regime of daily discharges Q_{IL} is different in such a way that $RAPS(Q_{IL})$ is more uniform and without multi-year trends, so a change point does not exist. It is a consequence of the Buško Blato reservoir, which enables multi-year regulation of discharges, so daily discharges Q_{IL} have been generated over the years mostly by electric power demands.

In Figure 6, it can be seen that variations in $RAPS(Q_S)$, $RAPS(Q_{IL})$, and $RAPS(Q_{RO})$ exhibit time delays relative to variations in $RAPS(P_L)$. The values of these delays are estimated by CCF between two RAPS as the time lag at which CCF reaches its maximum. The four obtained CCFs are presented in Figure 7. The time delay between $RAPS(P_L)$ and $RAPS(Q_S)$ is the average retention time of rainwater in the karst aquifer of Ruda Spring, which is 68 days. The time delay between $RAPS(P_L)$ and $RAPS(Q_{IL})$ is the average retention time of rainwater that is used by the Orlovac HP. Because of the effects of the Buško Blato reservoir, this time is longer and amounts to 92 days. As expected, the time

delay between $RAPS(P_L)$ and $RAPS(Q_{RO})$ is between these two values and amounts to 82 days. Considering the effects of air temperatures on water temperatures, the obtained maximum in $CCF(RAPS(T_L), RAPS(T_{RO}))$ has the lowest value among all CCFs presented, but it is still statistically significant, confirming that air temperatures play a key role. The 16-day time delay is the average time needed for heat transfer from the air in Livanjsko Polje to the water in the Ruda River via the system of open canals, two reservoirs, and the Orlovac HP tunnel.

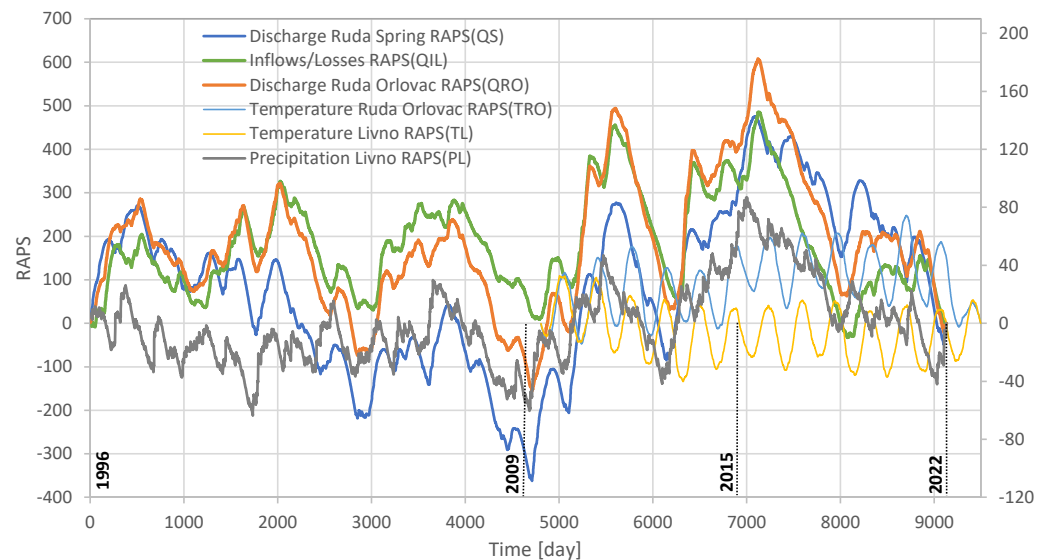


Figure 6. RAPS of daily precipitations from Livno MS, daily discharges from Ruda Spring, Ruda Orlovac HS, and Orlovac HP, daily air temperatures from Livno MS, and daily water temperatures from Ruda Orlovac HS.

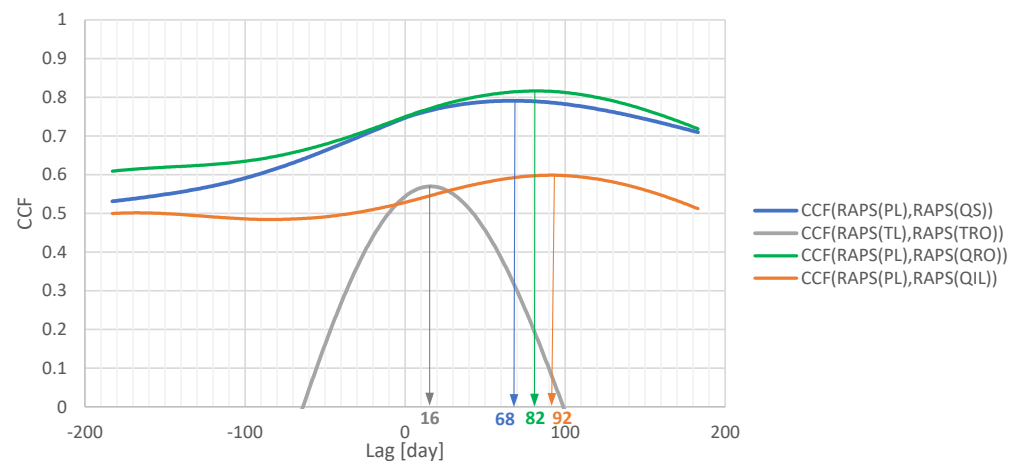


Figure 7. CCF between RAPS of daily data with estimated time delays.

Effects of the Orlovac HP on discharges at the Ruda Orlovac HS are presented in a seasonal daily graph (Figure 8). It shows the means, as well as the minimum and maximum registered discharges for each day of the year (1–365) at the Ruda Spring and the Ruda Orlovac HS during the period 1989–2021. These curves show differences in spring and river peaks, summer low flows, autumn response of the river and spring to rainfall, and winter baseflow conditions. The regime of the river has been primarily defined by the operation of the Orlovac HP. Maximal daily discharges at the Ruda Orlovac HS were seen during the spring months, April and May, up to $108 \text{ m}^3/\text{s}$. Maximal discharges from Ruda Spring, up to $49.8 \text{ m}^3/\text{s}$, were observed during the autumn months, from October to December, which are the most precipitation-rich. Mean daily discharges have a similar seasonal regime to the

maximum. The ratio between mean daily discharges $\text{MEAN}(Q_{RO})/\text{MEAN}(Q_S)$ calculated for each day of the year ranges from 1.34 in September to even 3.00 in Jun. Ratio between maximal discharges $\text{MAX}(Q_{RO})/\text{MAX}(Q_S)$ goes up to 4.88 in July. The regime of minimal discharges has changed the least, because these values are mostly registered during the nonoperation of the Orlovac HP.

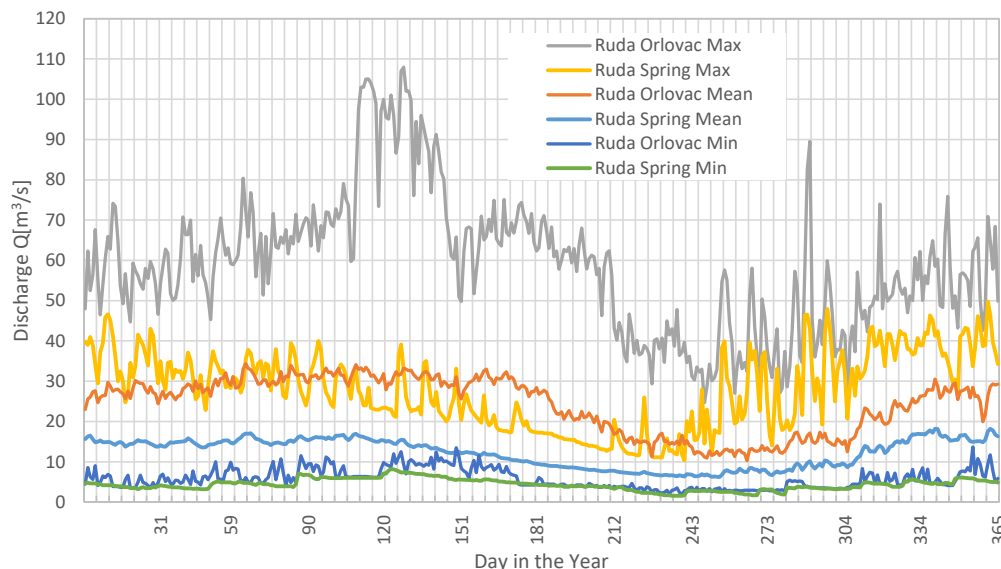


Figure 8. Mean discharges and minimal and maximal registered discharges for each day of the year at the Ruda Spring and the Ruda Orlovac HS.

The water temperature regime of the river is influenced by air temperature in Livanjsko Polje and by discharge from Orlovac HP. LR between monthly air temperatures T_L and monthly water temperatures T_{RO} is presented in Figure 9a. Linear dependence is clear, and the coefficient of determination R^2 is high. However, the greatest influence is observed during winter and summer. LR between monthly discharges Q_{IL} and monthly water temperatures T_{RO} for February and August are presented in Figure 9b. Values of two intercepts, 9.1 and 15.3 °C, represent average water temperatures for February and August at the Ruda Orlovac HS without discharges from the Orlovac HP.

Regarding seasonal variations in daily air and water temperatures, Figure 10 shows mean values, as well as the minimum and maximum recorded values, for each day of the year at the Livno MS and the Ruda Orlovac HS during 2009–2022. Daily air temperatures have clear seasonality. In the coldest month, January, they ranged from -13 to 9 °C with a mean of about 1 °C. In the warmest month, July, they were between 12 and 28 °C with a mean of about 22 °C. Irregular fluctuations are evident, especially at minimal values during the winter period, from December to February, when minimal air temperatures were between -13 and 1 °C. Two components, seasonal and fluctuations, are also observable in water temperatures, but both are attenuated because of the heat capacity of water. During winter months, daily water temperatures ranged from 2 to 10 °C, whereas during summer they were from 12 to 24 °C. Minimal daily water temperatures in the coldest month, January, were between 2 and 4 °C. Maximal daily values occurred in July and August, between 20 and 24 °C.

Figure 11a,b represent basic statistical characteristics of variations in hourly discharges Q_{RO} and hourly water temperatures T_{RO} , respectively. Mean values, median, minimal and maximal registered values, as well as percentiles P5 and P95 for each hour of the day (1–24) are presented. The maximum hourly discharge Q_{RO} during the analyzed period was $122 \text{ m}^3/\text{s}$. Two peaks in mean discharges, median values, and extreme high discharges

P5 are clear, the first at 12 h and the second at 20 h. Since Orlovac HP often works in low operational mode during night hours, discharges at peak hours are more than twice as large as discharges at night hours. For example, ratios between discharges at 20 h and discharges at 3 h are 2.17, 2.46, and 2.12 for mean, median, and P5, respectively. Similar two peaks are also observable in water temperatures at 13 and 21 h, most clearly in the percentiles P95 and P5 (denoted as T_{RO_95} and T_{RO_5}), indicating a strong interdependency between discharge and water temperature variations. Results also reveal that water temperature in some peak hours during winter can be as low as 0.4 °C, while during summer it can reach up to 25.9 °C.

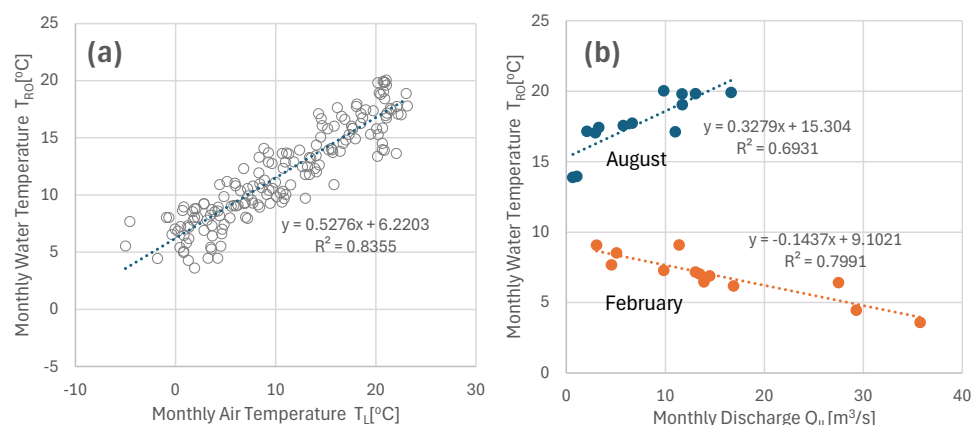


Figure 9. (a) LR between monthly air temperatures from Livno MS and monthly water temperatures from Ruda Orlovac HS. (b) LR between monthly discharges from Orlovac HP and monthly water temperatures from Ruda Orlovac HS for February and August.

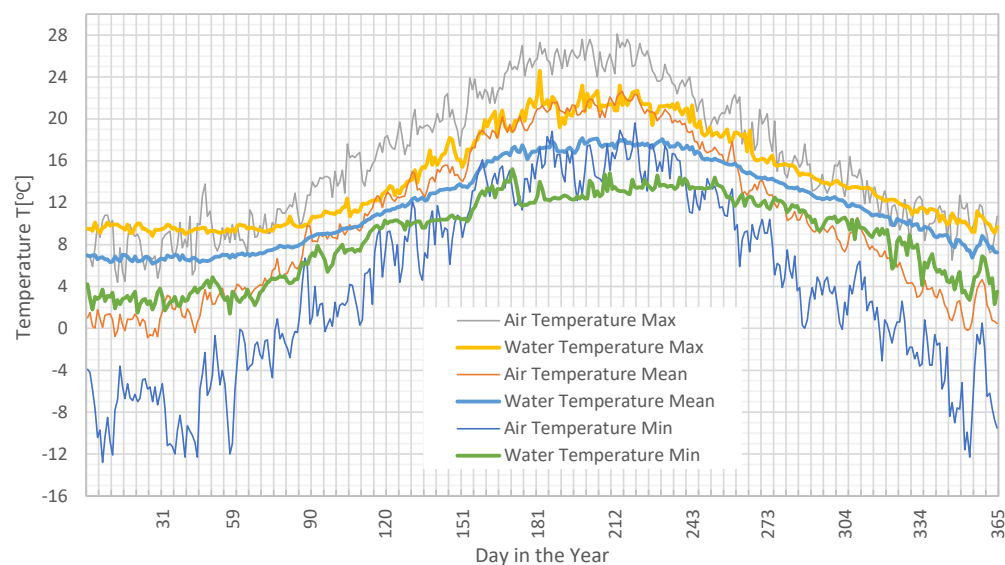


Figure 10. Mean temperatures, and minimal and maximal registered temperatures for each day of the year for air at the Livno MS and for water at the Ruda Orlovac HS.

Similarly, for Q_{RO} in Figure 11a, characteristic values P5 and means for each hour in the day have also been calculated for hourly discharges Q_{IL} . The obtained series are denoted as Q_{IL_5} and Q_{IL_MEAN} . LR between Q_{IL_MEAN} and T_{RO_95} , Q_{IL_MEAN} and T_{RO_5} , Q_{IL_5} and T_{RO_95} , Q_{IL_5} and T_{RO_5} , are presented in Figure 12. The coefficient of determination R^2 is remarkably high, between 0.90 and 0.96. It shows that strong interdependencies exist between hourly discharges from the Orlovac HP and hourly water temperatures at the Ruda Orlovac HS, ranging from average to extreme discharge values. Intercepts for

discharges Q_{IL_MEAN} (7.2 and 15.9 °C) and Q_{IL_5} (7.5 and 15.2 °C) represent referent values for minimal and maximal water temperatures at the Ruda Orlovac HS without discharges from the Orlovac HP.

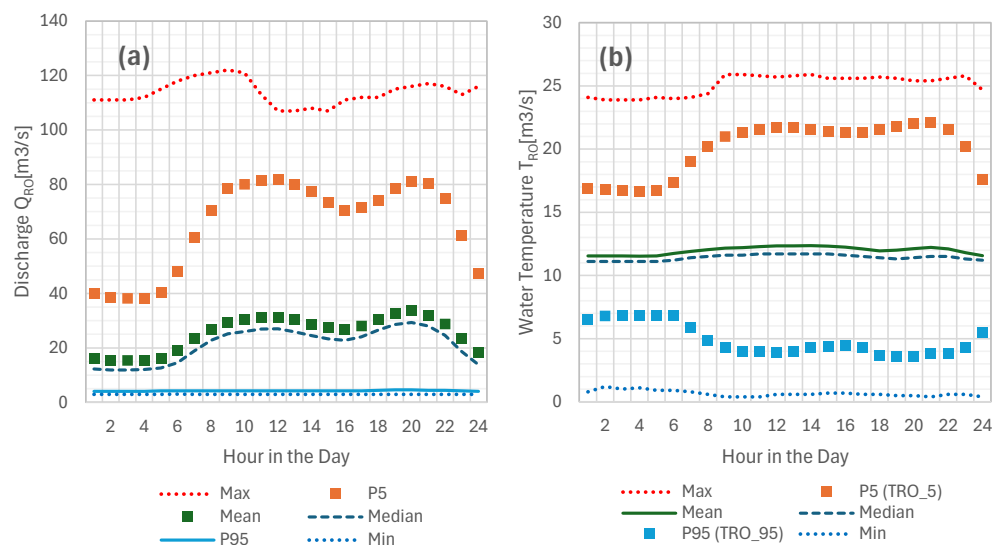


Figure 11. Mean values, median, minimal, and maximal registered values, percentiles P5, and percentiles P95 for each hour of the day for (a) discharges and (b) water temperatures at Ruda Orlovac HS.

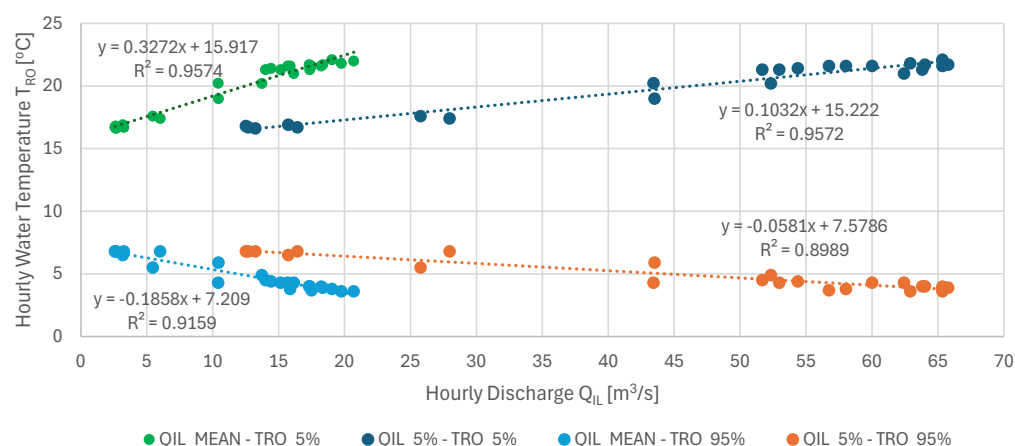


Figure 12. LR between extreme discharges from Orlovac HP and extreme water temperatures at Ruda Orlovac HS, as well as between mean discharges from Orlovac HP and extreme water temperatures at Ruda Orlovac HS.

4. Discussion

The first step in the analysis of time series was the identification and explanation of trends and change points. Multiple hydrological and meteorological investigations have demonstrated statistically significant upward trends in air temperatures from meteorological stations in Croatia and Bosnia and Herzegovina [52–55]. The Livno MS is not an exception, so an upward trend exists. However, there is no statistical evidence that this upward trend in air temperatures in Livanjsko Polje has been reflected in regimes of precipitation on the catchment, discharges from the Ruda Spring, or temperatures of the Ruda River.

The effects of hydropower plants on the River Cetina have been documented in several studies [40,42,43,45], including the effects of the Dale HP on groundwater levels [56]. The mean shift in discharge from Ruda Spring registered in 1988 coincides with the beginning

of operation of this hydropower plant. Results show that there was a difference between the operation of the Orlovac HP before the connection of the Dale HP to the hydroelectric power system of the Cetina River and after the connection, which most probably affected the functioning of Ruda Spring.

Differences in the functioning of Ruda Spring before and after 1988 were analyzed by using the DC of daily discharges. DC is one of the most useful tools in the analysis of karst springs because it condenses long discharge time series into a form that clearly shows variability, regulation capacity, and extremes. DC allows comparison of different karst springs, the same spring before and after engineering works, or natural vs. regulated regime [57–59]. Probability distributions are sometimes used to parameterize the relationship between discharges and exceeding probabilities, transforming the empirical DC into a continuous analytical function suitable for interpolation, extrapolation, and comparison. When presented in a probability plot, DC becomes even more informative for interpreting karst aquifer behavior, making the comparison clearer [60]. In this study, a log-normal distribution has been used. The results obtained revealed that DC from the period after 1988 can be approximated by this distribution in almost the entire range of probabilities, from 0.01 to 0.99, which indicates that the Ruda Spring had a relatively consistent functioning without multiple storage compartments (without activations some additional conduits above certain recharge thresholds, epiphreatic activations, temporary spring connections, activations of ponors, etc.). This is not the case for the period before 1988, when DC had an irregular form that cannot be approximated by any theoretical distribution. Comparison of DC from two periods revealed that DC from the period before 1988 had larger discharges at all segments, low flow, middle flow, and high flow, which implies the existence of continuous inflows during this period. Exceptions are only extreme values, high flows below a probability of 0.01, and low flows above 0.99.

Small yet systematic changes over time are often hidden by the variability of data itself, but sometimes they enclose particularly essential information [61,62]. RAPS is a statistical method used for detecting these changes in hydrological time series such as precipitation, river discharge, groundwater levels, and water temperature. RAPS visualizes cumulative deviations from the mean value, and thereby highlights change points, data clustering, long-term trends, irregular fluctuations, and periodicities in the time series. Most hydrological papers have applied RAPS to annual precipitation totals or annual mean discharges, because it provides the clearest signal of structural change [47,63–65]. Daily values are less appropriate for classical RAPS trend detection because of the strong autocorrelation that produces fluctuations and seasonality. So, RAPS of daily data has been used much less often, for regime change analysis or event-based hydrology [66–68]. In this study, RAPS of daily precipitations and discharges were used for comparison of regimes and for estimation of retention times. Results show that interannual variations in discharges from Ruda Spring have followed variations in precipitation, while variations in discharges from the Orlovac HP have been more uniform, reflecting effects of water retention in Buško Blato Reservoir. It was noted that time delays between RAPS of precipitations and RAPS of discharges exist, which represent retention times. Average retention times for the entire period were estimated as the lags with the maximal correlation in the CCF between RAPS of precipitation and RAPS of discharge. Because of rainwater retention in the Buško Blato Reservoir, the retention time of rainwater used by the Orlovac HP was 24 days longer than the retention time of rainwater in the karst aquifer of Ruda Spring. The average time needed for heat transfer from the air in Livanjsko Polje to the water in the Ruda River was obtained in an analogous way by using CCF between RAPS of air temperature and RAPS of water temperature. It shows that changes in air temperature at the Livno MS have been recorded in the water temperature at the Ruda Orlovac HS after 16 days.

Seasonal effects of the Orlovac HP on the discharge regime of the Ruda River were quantified by comparing seasonal daily graphs of the Ruda Spring and the Ruda Orlovac HS. Seasonal daily graphs presented mean values for each day of the year computed over the entire observed period, as well as minimal and maximal values registered for each day. They removed inter-annual variability and highlighted the typical seasonal regimes comparing natural vs. regulated discharges. Results show that minimal discharges have increased, total volume of discharges has doubled, but maximal discharges have changed most significantly. They have increased by almost five times in the summer months, and they have larger fluctuations due to the irregular operation of the Orlovac HP.

The regime of river water temperature is under the strong influence of the air temperature in Livanjsko Polje and by the discharge from Orlovac HP. LR was used to confirm interdependence, establish linear relationships between variables, control the level of statistical significance of relationships, and estimate referent water temperatures (water temperatures without discharges from the Orlovac HP). The established LR between monthly air temperatures at the Livno MS and monthly water temperatures at the Ruda Orlovac HS had a coefficient of determination R^2 of about 0.84. LR between monthly discharges from the Orlovac HP and monthly water temperatures at the Ruda Orlovac HS for February and August had values of 0.80 and 0.69, respectively. As a result of this influence, the water temperature regime of the Ruda River was changed. Depending on discharges, monthly water temperatures may increase during summer to above 20 °C and decrease during winter to below 4 °C. On the other hand, two intercepts show that referent water temperatures for February and August were about 9.1 and 15.3 °C, respectively.

In addition to discharges, seasonal variations in daily water temperatures at the Ruda Orlovac HS were analyzed using seasonal daily graphs presenting mean daily temperatures for each day of the year, computed over the entire observed period, and the minimum and maximum temperatures recorded for each day. Results show that the minimum and maximum daily water temperatures range from less than 2 °C in January to above 24 °C in July. Mean values are 6–8 °C for winter days and 16–18 °C for summer days.

In addition to significant seasonal variations, large sub-daily variations in discharges at the Ruda Orlovac HS were also registered. Namely, discharges from the Orlovac HP have two peaks within the day, at 12 and 20 h, where the largest peak discharges are multiple times greater than minimum discharges in night hours. Ratios between discharges in peak hours and night hours go up to almost 30 for median values. Hourly variations in discharges at the Ruda Orlovac HS are typical for a river influenced by a peaking hydropower plant. This plant works in a way that rapidly increases or decreases release to meet fluctuations in electricity demand (hydropeaking operational mode). Because of rapid start/stop cycles needed to match energy peak demand, it has highly variable water release with sub-daily changes and large amplitudes. This type of water release alters river systems, potentially stressing downstream ecological and physical processes by altering discharge and water-temperature regimes [69,70]. Hydropeaking usually produces thermopeaking—rapid, short-term fluctuations in river water temperature caused by hydropower plant operations [71–74]. Consequently, strong interdependences between extreme discharges P5 from the Orlovac HP and extreme water temperatures P5 and P95 at the Ruda Orlovac HS were detected, and two peaks within the day in hourly water temperatures at the Ruda Orlovac HS were registered. These two peaks have a time delay of one hour from peaks in discharges. The time delay is the travel time of water from the Buško Blato reservoir to the Orlovac HP. Estimated referent hourly water temperatures were about 7 °C for the winter period and 16 °C for summer, which is in accordance with field measurements. Namely, water temperatures measured during 2004 and 2005 about 100 m downstream from the Ruda Spring ranged from 6.8 °C in February to 16.9 °C in

August, with an average of 11.8 °C [38]. Hourly water temperatures measured at the Ruda Orlovac HS had a much wider range, from 0.4 to 25.9 °C, which proves large alterations of the temperature regime.

5. Conclusions

Discharge and water temperature regimes of the Ruda River were investigated using a methodology based on classical hydrological, statistical, and time-series analysis methods adapted to the particularities of the study area and available data. RAPS of annual data are used to compare interannual variations in precipitation and discharges, and to find change points. Differences in two operational periods of the Orlovac HP, before and after 1988, are clarified by the MA filter. Empirical and analytical forms of DC of discharges are used to (1) compare the regime of Ruda Spring before and after 1988, (2) detect the existence of groundwater interchange, and (3) obtain basic information about the duration of diffuse, conduit, and mixed flow at the spring. RAPS of daily data are used to compare precipitation, discharge, water temperature, and air temperature regimes, and retention and heat transfer times have been estimated using CCF between two RAPS. LR between extreme discharges P5 from the Orlovac HP and extreme water temperatures P5 and P95 at the Ruda Orlovac HS have been used to (1) confirm the direct interdependence between the discharge from the hydropower plant and the river temperature, (2) establish relationships, and (3) estimate referent water temperatures for the Ruda Orlovac HS without discharges from the Orlovac HP. The results obtained advance existing knowledge about the hydrology of the Ruda River.

Air temperatures in the catchment have a statistically significant trend, which is a result of global climate change registered at meteorological stations in wider regions. Discharges from Ruda Spring exhibit a mean shift in 1988, which coincides with the beginning of the operation of Dale HP. This mean shift is a consequence of differences in the operation of Orlovac HP before and after 1988, and it confirms that annual discharges from the spring depend on the operating mode of Orlovac HP.

After 1988, the karst aquifer of Ruda Spring has had persistent storage without significant gains or losses through interchange with neighboring catchments, depending on groundwater levels, or gains through allogenic recharge. The Ruda Spring is a permanent karst spring with a stable baseflow and significant seasonal variations depending on recharge conditions. The average retention time of the rainwater is about 68 days.

The discharge regime of the Ruda River has been under the strong influence of the discharge from Orlovac HP. Discharges from Orlovac HP have been generated over the years, mostly by electric power demands. Installed discharge is larger than the maximal discharge seen at the spring. The maximum hourly discharge at the Ruda Orlovac HS was 122 m³/s, while the maximum discharge from the Ruda Spring during the same period was only 48 m³/s. Sub-annual redistribution of water occurs from autumn to spring months. Sub-daily variations with two pronounced peaks at 12 and 20 h are typical for a river influenced by a peaking hydropower plant. The average retention time of the rainwater used by the Orlovac HP is about 92 days.

The water temperature regime of the Ruda River has been substantially altered. Depending on discharge, the monthly water temperature ranges from below 4 °C during winter to above 20 °C during summer. In addition to seasonal variations, hydropeaking led to thermopeaking, resulting in two peaks in sub-daily variations in water temperature. Since the water from the Buško Blato reservoir takes time to reach the Orlovac HP, these two peaks have a time lag of about one hour from peaks in discharge. Hourly temperatures seen at the Ruda Orlovac HS ranged from 0.4 to 25.9 °C. Without discharges from the Orlovac HP, water temperatures would range from about 7 °C to about 16 °C. Changes in

the air temperature in Livanjsko Polje are observable in the river water temperature after 16 days.

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Abbreviations

The following abbreviations are used in this manuscript:

HP	Hydropower plant
DC	Duration curve
RAPS	Rescaled adjusted partial sums
MA	Moving average
LR	Linear regression
CCF	Cross-correlation function
HS	Hydrological station
MS	Meteorological station
RG	Rain gauge

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