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Analysis of Climatic and Hydrological Characteristics of the Južna Morava River Basin up to the Korvingrad Hydrological Station

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Abstract

This study examines the climatic and hydrological processes within the Južna Morava River Basin, with particular focus on changes in precipitation, temperature, and river discharge. Data from the Korvingrad hydrological station (for discharge) and the Leskovac meteorological station (for climatic parameters) covering the period 1961–2023 were used. The analysis shows that mean annual precipitation is 637.06 mm, with a slight increasing trend of 2.25 mm per year, while mean annual air temperature has risen significantly by approximately 1.7°C over the observed period. The discharge of the Južna Morava River depends primarily on annual precipitation totals, while temperature has a secondary, indirect influence through evapotranspiration processes, especially during dry periods. Seasonal maximum discharge occurs in spring, with minimum values recorded during the summer months. The results indicate that changes in the hydrological regime of the Južna Morava Basin result from the combined effects of precipitation and temperature, with precipitation as the dominant factor in annual variability and temperature as a key driver of long-term discharge decline trends. Trend significance was assessed using the Mann–Kendall test and Sen's slope estimator, confirming a weak and statistically insignificant long-term tendency in discharge.

1. Introduction

The climatic characteristics of river basins, particularly precipitation and temperature, are key factors in shaping the hydrological regime, as they influence evapotranspiration, runoff, and infiltration processes, and thus overall water availability within a basin (Chattopadhyay & Edwards, 2016; Nijssen et al., 2001; IPCC, 2014). The hydrological characteristics of river systems primarily depend on the discharge regime, which is determined by the amount and spatial distribution of precipitation. Increased precipitation and snowmelt directly enhance river flows, whereas rising temperatures intensify evapotranspiration, reducing available water resources and potentially leading to lower discharges, especially during dry periods (Batalla & Vericat, 2010).

The rise in greenhouse gas concentrations in the atmosphere has caused global climate change, which has a significant impact on water resources at all spatial scales, from local to global (IPCC, 2013). Climate change influences the water cycle by altering precipitation, temperature, atmospheric humidity, and evapotranspiration, leading to the spatiotemporal redistribution of water resources and changes in their availability, as well as extremes such as floods and droughts (IPCC, 2021; Yang et al., 2020; Zhao et al., 2021). Variations in the distribution of river flows and groundwater are

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mainly determined by changes in temperature, evapotranspiration, and, most importantly, precipitation (Chiew, 2006).

Analyses of long-term time series indicate that the increase in global temperature is unevenly distributed and varies across regions, as demonstrated by Twardosz et al. (2021). Their study, covering 1951 to 2020 and including 210 meteorological stations across Europe, identified two distinct intervals: until 1985, temperatures remained relatively stable, whereas from 1985 to 2020 there was a significant linear increase in mean annual temperature of 0.051°C per year, indicating an accelerated warming trend and suggesting potential implications for hydrological processes.

Rising temperatures cause winter precipitation to occur increasingly as rain rather than snow, altering the seasonal distribution of river discharge in many continental and mountainous regions. The discharge maximum, previously linked to spring snowmelt, now occurs earlier in the year or is entirely absent, while winter discharge values have increased (Kundzewicz et al., 2008).

Dibike et al. (2018) emphasise that climate change will increase both precipitation and temperature, resulting in modifications to the hydrological regime. For example, in the Athabasca River, spring discharges are expected to rise by 11–71%, while summer discharges are projected to decline. Under warmer climatic conditions, total precipitation is expected to increase, as higher temperatures enhance atmospheric moisture content and thus the potential for precipitation formation (Konstali & Sorteberg, 2022).

Numerous researchers (Do et al., 2017; Asadieh & Krakauer, 2017; Aich et al., 2014; Juckem et al., 2008) have examined changes in river flow regimes, revealing notable oscillations in certain regions, ranging from increased flood frequency to reduced discharge. Changes in flow regimes are often the result of human activities, as demonstrated by numerous studies (Poff et al., 1997; Panda et al., 2011; Wang et al., 2017; Gardner et al., 2023). The construction of large hydraulic structures, particularly dams, provides significant benefits but also poses potential ecological risks. While dams contribute to improved water resource management, water supply security, and flood control, their construction alters river regimes, affects sediment transport, and reduces biodiversity (Biemans et al., 2011; Rosenberg et al., 2000; Graf, 2006; Poff et al., 2007).

Analysing long-term trends in precipitation, temperature, and discharge enables the assessment of climate change impacts on water availability and supports sustainable water resource management planning (Okafor et al., 2017).

In Serbia, several studies have focused specifically on the Južna Morava River Basin, including analyses of discharge variability (Langović, 2019) and assessments of hydrological and climatic drought intensity (Miletić et al., 2023). It has been established that most rivers within the Južna Morava basin show decreasing trends in mean and seasonal discharge (Langović, 2019), with approximately 85% of the analysed watercourses exhibiting negative tendencies. Miletić et al. (2023) identified a clear dependence of river discharge on precipitation amounts, confirming that precipitation is the primary factor shaping the runoff regime in the Južna Morava basin. Similar patterns have been documented in other river basins. In the Rasina River basin, reduced discharge has been linked to climate variability and increased water use (Stričević et al., 2024). In the Sava River basin, seasonal trends indicate a slight decrease in discharge during spring, summer, and autumn, and a slight increase in winter. Precipitation generally shows minor negative trends, except in autumn, when a statistically significant increase is observed. Air temperature has risen in all seasons, with statistically significant warming during the warm period (Leščešen et al., 2022). A significant decrease in discharge has also been recorded for the Jablanica River (Gocić et al., 2016). In the Toplica River basin, discharge continues to decline, with more frequent spring floods and reduced summer water levels. Rising temperatures strongly affect summer discharge by increasing evaporation and raising water demand for agriculture and irrigation (Martić Bursać et al., 2022).

In this study, climatic and hydrological processes in the Južna Morava River Basin were analysed using data from the Korvingrad hydrological station and the Leskovac meteorological station. The analysis used multiannual data on precipitation, air temperature, and discharge. The aim of this research is to examine the long-term climatic and hydrological characteristics of the Južna Morava Basin up to the Korvingrad hydrological station for the period 1961–2023, with particular focus on the interrelationship between precipitation, temperature, and river discharge.

2. Study area

The Južna Morava River originates at the confluence of the Binačka Morava and the Preševska Moravica near Bujanovac, at an elevation of 392 m above sea level. Its total length is 246 km, and the drainage basin covers an area of 15,469 km². The river receives 157 tributaries—75 on the left and 82 on the right. The most significant left tributaries are the Veternica, Jablanica, Pusta Reka, and Toplica, while the largest right tributaries are the Vrla, Vlasina, Nišava, Toponička Reka, and Sokobanjska Moravica (Gavrilović & Dukić, 2014). The course of the Južna Morava ends near Stalać, where it joins the Zapadna Morava to form the Velika Morava (Figure 1).

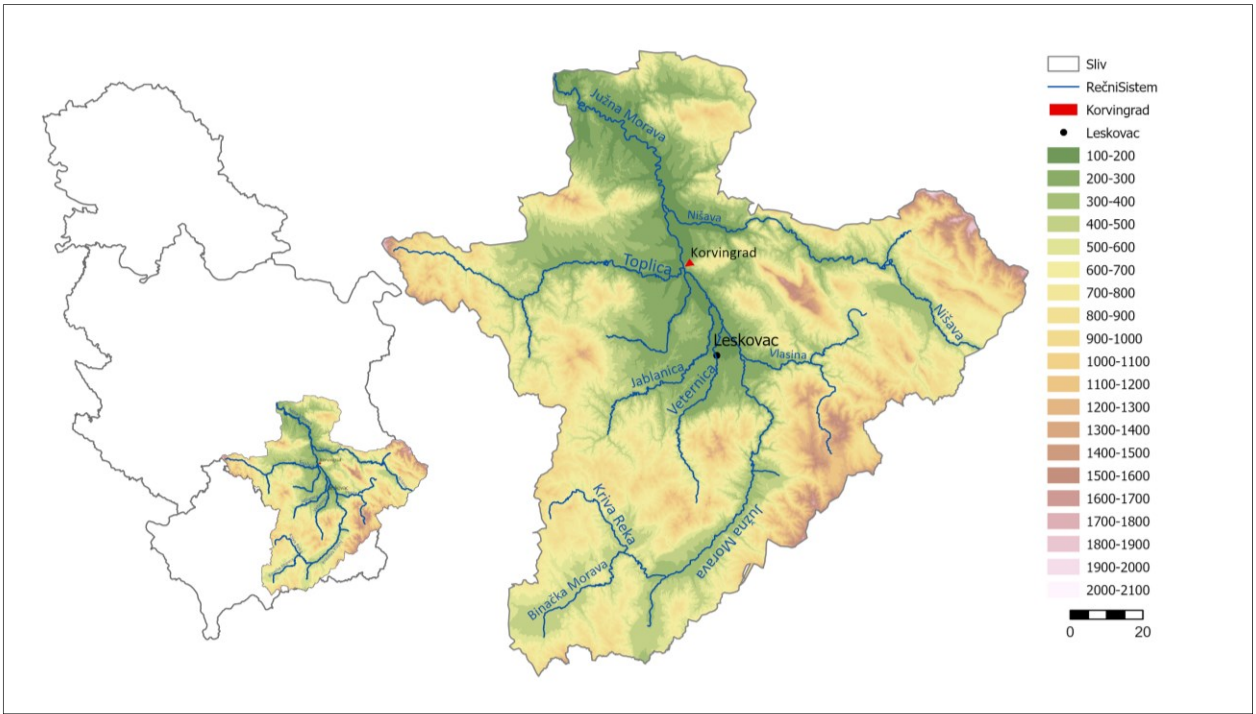

Figure 1. Location of the Južna Morava River Basin in Serbia and the position of the Korvingrad hydrological station

The Južna Morava Basin has a temperate continental climate, with Pannonian influence noticeable in the north and Aegean influence in the south (Pavlović, 2019). Within the basin, the areas most vulnerable to drought include the Niš, Leskovac, and Vranje basins, the latter being the location of the longest recorded drought in Serbia, which lasted for 61 consecutive days (Dragićević et al., 2011). The valley of the Južna Morava is surrounded by numerous mountains, including Kukavica, Vardenik, Čemernik, Babička Gora, Seličevica, Mali Jastrebac, Suva Planina, and Stara Planina (Pavlović, 2019). These mountain massifs alter the movement of air masses; after crossing them, the air descends, warms, and dries, leading to a marked reduction in precipitation within the valley. As a result, narrow transverse valleys, such as the Grdelica Gorge, may receive more precipitation than the broader Leskovac and Vranje basins, which are protected by high mountain barriers (Ducić & Radovanović, 2005).

In Serbia, the highest number of torrential floods occurs in the Južna Morava River basin, where erosion processes are strongly developed; for example, 93.6% of the Grdelica Gorge area is affected by erosion of varying intensity, while riverbank erosion in the lower course of the Južna Morava caused the loss of more than 200 ha of arable land between 1924 and 2020 (Kostadinov & Marković, 1996; Kostadinov et al., 2018; Langović et al., 2024). A gradual decline in erosion intensity has also been observed across the wider basin, reflected in lower erosion coefficients in the Jablanica River Basin and reduced sediment yield in the Toplica River following anti-erosion measures (Gocić et al., 2020; Kostadinov, 2008).

The Korvingrad hydrological station is located 105.7 km upstream from the confluence of the Južna Morava River, and the catchment area at this profile covers 9,396 km² (Martić Bursać, 2015). Within this area are the Leskovac Basin, the Pečenjevce constriction, the Brestovac Basin, and the Korvingrad constriction, which together form the middle course of the Južna Morava (Pavlović, 2019).

3. Materials and methods

Sampling The research analyses multi-decadal data for the Južna Morava River basin, using records from the Leskovac meteorological station and the Korvingrad hydrological station. The analysis covers the period 1961–2023 and includes climatic parameters (precipitation and air temperature) and river discharge. Annual and seasonal variations were analysed in order to identify the dominant climatic drivers of discharge variability.

To determine long-term changes, the linear trend method (linear regression, least squares method) was applied. This method is among the most commonly used in the analysis of hydrometeorological and climatic data (Ghebrezgabher et al., 2016), as well as in studies examining discharge trends and their relationship with climate change (Hatcher et al., 2013; Yeste et al., 2020; Didovets et al., 2024).

The analyzed parameter is a time series represented as a set of ordered pairs (x_i, y_i), where x_i denotes time (year, month, etc.), and y_i denotes the measured value (temperature, discharge, etc.) (1). It is assumed that this time series can be modeled using a linear function:

$$\hat{y} = ax + b \tag{1}$$

which approximates the change of the observed parameter over time. In this case, the criterion for the best approximation is defined as the minimum sum of squared deviations between the measured values y_i and the approximated values $\hat{y}_i$.

$$S(a,b) = \sum_{i=1}^{n}[y_i - (ax_i + b)]^2 \tag{2}$$

By minimizing the function $S(a,b)$ with respect to the parameters a and b, the standard least squares solutions are obtained:

$$a = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sum_{i=1}^{n}(x_i-\bar{x})^2} \tag{3}$$

$$b = \bar{y} - a\bar{x} \tag{4}$$

where $\bar{x}$ and $\bar{y}$ represent the arithmetic means of the observed values.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{5}$$

The parameter a represents the slope of the trend line and the rate of change per unit of time, while the parameter b represents the estimated initial level of the series.

The linear trend was calculated in Excel using the Trendline option, with the corresponding regression equation and the coefficient of determination R^2 displayed. The coefficient of determination represents a measure of the goodness of fit of the linear regression model and is defined as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{\sum_{i=1}^{n}(y_i-\bar{y})^2} \tag{6}$$

The closer the value of R^2 is to one, the more effectively the linear model explains the variability of the data, whereas low R^2 values indicate that the change in the observed parameter cannot be adequately described by a linear function.

To analyze trends in time series, the non-parametric Mann–Kendall test (Mann, 1945; Kendall, 1975) was applied. This test is used when it is assumed that the variable x_t follows the model:

$$x_t = f(t_i) + \varepsilon_i \tag{7}$$

where $f(t_i)$ denotes a continuous monotonic function (representing either an increase or decrease over time), while residuals ε_i are assumed to be independent, normally distributed with zero mean, and with a constant variance throughout the study period (Salmi et al., 2002). The MK test assesses the null hypothesis (H_0) of no monotonic trend in the dataset against the alternative hypothesis (H_1), which assumes the presence of either an upward or downward trend.

The MK test statistic S is computed as follows:

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{8}$$

where x_j and x_k represent the annual observations for years j and k, respectively, with $j > k$. The sign of the difference between the compared values is defined as:

$$sgn(x_j - x_k) = \begin{cases} 1 & if\, x_j - x_k > 0 \\ 0 & if\, x_j - x_k = 0 \\ -1 & if\, x_j - x_k < 0 \end{cases} \tag{9}$$

For series containing fewer than 10 data points, the statistic S is evaluated using exact tables. If the number of observations is 10 or greater, a normal approximation is applied, and the variance of S is estimated using:

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \tag{10}$$

where g represents the number of tied groups and t_p is the number of tied observations in the pth. The standardized test statistic Z is then derived as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & if\ S < 0 \end{cases} \tag{11}$$

A trend is considered statistically significant when the absolute value of the Z statistic exceeds the critical value of the standard normal distribution corresponding to the selected significance level (typically α = 0.05, 0.01 or 0.001). A positive Z value indicates an increasing trend, whereas a negative Z value suggests a decreasing trend.

Sen's slope estimator, introduced by Sen (1968), is a non-parametric method used to estimate the slope of a monotonic trend over time. The procedure assumes a linear relationship in the form:

$$f(t) = Qt + \beta \tag{12}$$

where Q represents the slope, β is a constant, and t denotes time. To calculate the estimate of Q, the slopes of all possible data point pairs are determined using:

$$Q_i = \frac{(x_j - x_k)}{j-k}, \quad i = 1, 2, \ldots, n \tag{13}$$

where x_j and x_k are the observed values at times j and k (with j > k), respectively. If there are n observations in the time series, the total number of pairwise slopes is n(n - 1)/2

(Yusoff et al., 2021). The Sen's slope estimate is defined as the median of these values and is calculated as:

$$Q_{med} = \begin{cases} Q_{\frac{n+1}{2}}, & if\ n\ is\ odd \\ \frac{Q_{\frac{n}{2}} + Q_{\frac{n+2}{2}}}{2}, & if\ n\ is\ even \end{cases} \quad (14)$$

4. Results and discussion

The average annual precipitation during the period 1961–2023 at the Leskovac meteorological station was 637.06 mm. The highest annual total was recorded in 2014 (899.20 mm), while the lowest was observed in 2011 (405.10 mm) (Figure 2).

The highest monthly precipitation in the observed period amounted to 229.3 mm, recorded in January 2021, whereas August 1988 was the driest month, with no precipitation (0.0 mm). Based on monthly precipitation values, it can be concluded that precipitation is most pronounced during the spring months, while winter and summer months show relatively lower values. The highest averages were recorded in May (63.50 mm) and June (67.98 mm), while the lowest were in February (43.10 mm) and August (44.61 mm). Throughout the year, a gradual increase in precipitation can be observed from March to June, followed by a decline during the summer months. In the autumn period (September–November),

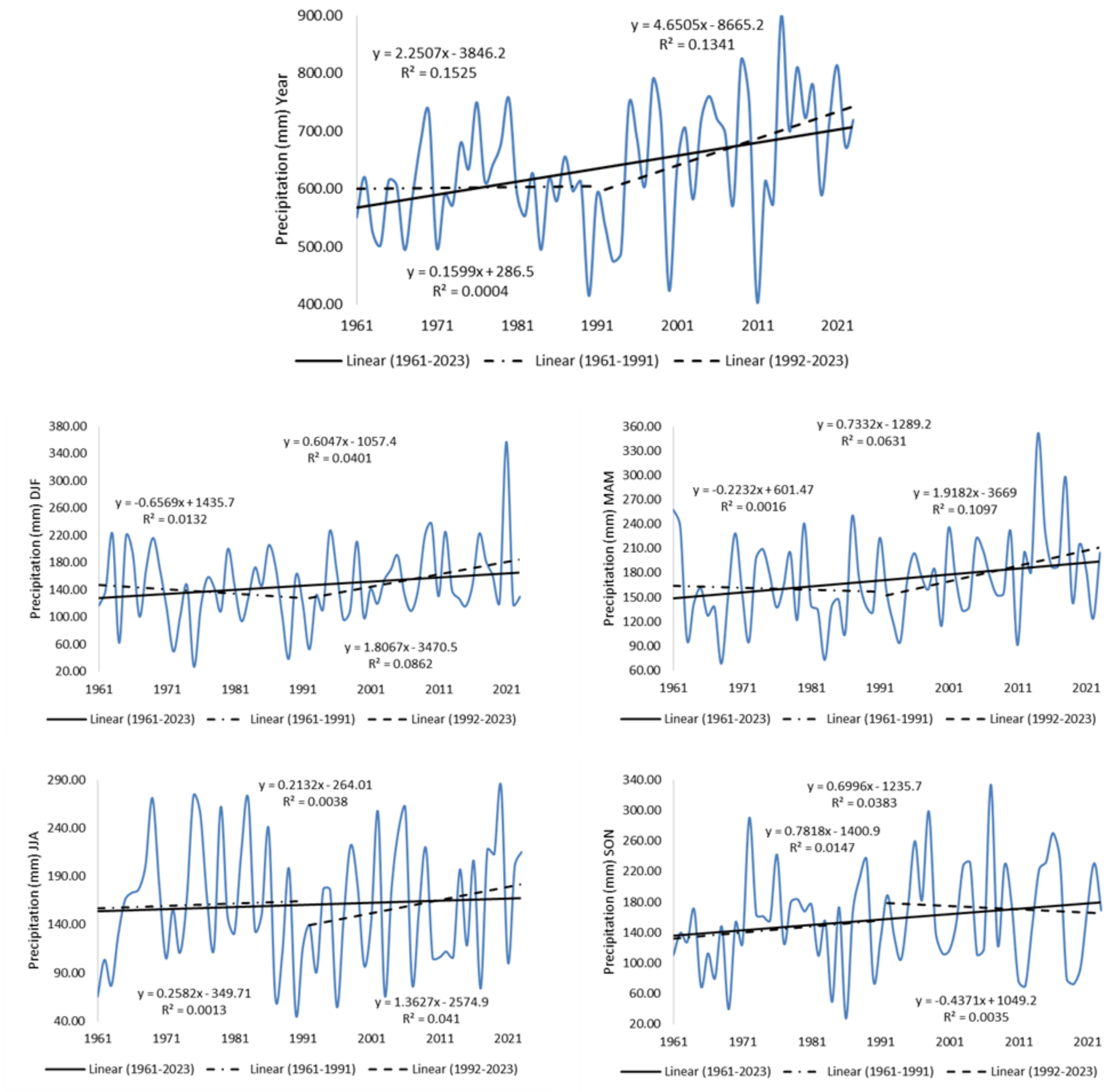

Figure 2. Average annual and seasonal precipitations, trend equations, and trend lines for the Leskovac meteorological station (1961–2023)

precipitation increases again, with a particularly pronounced maximum in November (60.92 mm). The winter months (December– January–February) are characterized by lower precipitation compared to spring and early summer.

The linear trend analysis of annual precipitation for the period 1961–2023 indicates a slight increase, with the average annual precipitation rising at a rate of approximately 2.25 mm per year. Over a timescale of more than six decades, this corresponds to a total increase of about +142 mm (Figure 2). When the observation period is divided into shorter segments, a change in trend intensity is evident – during the earlier period (1961–1991), the increase is almost negligible, at around +0.16 mm per year, whereas in the later period (1992–2023), a more pronounced rise of approximately +4.65 mm per year is observed. Although the linear trend indicates a long-term tendency toward increased precipitation, interannual variability remains considerably pronounced.

The analysis of the winter season (December–January–February) for the period 1961–2023 indicates a slight increasing tendency in precipitation, with an average rise of approximately 0.60 mm per year (a total of around +37 mm). However, this change is considered weak, as the trend is modest compared to the interannual variability, which in extreme cases exceeds 200 mm. When the period is divided into two segments, a shift in trend is observed – the earlier period shows a slight decrease in precipitation (–0.66 mm/year), whereas the later period exhibits a mild increasing tendency (+1.81 mm/year (Figure 2).

The analysis of spring precipitation (March–April–May) also reveals a slight upward tendency, with a linear trend of +0.73 mm per year, corresponding to an increase of approximately +46 mm over six decades. When the period is divided into two time segments, the earlier period shows a slight decreasing trend (–0.22 mm/year), while the later period displays an increase (+1.92 mm/year (Figure 2).

During the summer period (June–July–August), the linear trend suggests a weak increase in precipitation of +0.21 mm per year. In the earlier period, precipitation shows a minor increase (+0.26 mm/year), while in the later period the trend is more pronounced (+1.36 mm/year (Figure 2).

Although precipitation trends during autumn (September–October–November) indicate an increase of approximately +0.70 mm per year (equivalent to around +44 mm over six decades), this tendency is weak in comparison with interannual variability. The linear trend indicates a modest long-term increase in precipitation, while interannual variability remains markedly pronounced (Figure 2).

Based on the precipitation time series, pronounced interannual variability is evident, with annual values ranging from approximately 400 mm to nearly 900 mm. The spatial distribution of precipitation depends on geographic location, topography, and local factors (Bajat et al., 2013), while large-scale atmospheric oscillations, such as the NAO, EA, and EAWR, also significantly influence interannual precipitation variability in Serbia (Pavlović, 2012; Tošić & Putniković, 2021). Although dry and wet years alternate, the linear trend indicates a slight increase in precipitation throughout the entire period. Similar results were obtained by Gocić and Trajković (2014) in their analysis of precipitation across Serbia, who noted decreasing trends at certain stations (Zaječar, Vranje, Negotin, and Kraljevo), while other stations, including Leskovac, recorded an increase.

During the period 1961–2023, a total of 28 years had precipitation above the multiannual average (637.10 mm), while in 35 years, total precipitation fell below the average. The largest positive deviations were recorded in 2014, with 899.20 mm, 41% above the mean, and in 2009, with 822.90 mm, 29% above average. Elevated values were also observed in 2016 and 2021, confirming the tendency for more frequent wetter years in recent decades. In recent decades, years with higher precipitation totals have occurred more frequently, consistent with global climate trends showing increasing precipitation in both dry and wet regions worldwide (Donat et al., 2016).

Conversely, the driest year was 2011, with only 405.10 mm, 36% below the mean, while 1990 recorded 415.70 mm, 35% below average.

The Mann–Kendall test results for annual precipitation indicate a statistically significant increasing trend over the period 1961–2023, with a test statistic value of $Z = 3.00$, corresponding to a significance level of $p < 0.01$. Based on the Sen's slope method, the estimated rate of increase is +2.33 mm/year. The average annual precipitation during this period is 637.06 mm, with a standard deviation of 105.65 mm, suggesting that the trend is present but moderate in comparison to interannual variability. At the seasonal level, only the spring period (March–April–May) in the later segment of the observation interval (1992–2023) exhibits an upward trend reaching the threshold of statistical significance at $p < 0.10$, with an estimated increase of approximately +1.69 mm/year, while trends in the remaining seasons are not statistically significant (Table 1).

Table 1. Mann–Kendall test statistics for precipitation trends at the Leskovac meteorological station.

Period		*Min.*	*Max.*	*Mean*	*St.dev.*	*Z*	*S*	*α*
1961-2023	T_{av}	405.10	899.20	637.06	105.65	3.00	2.33	**
	DJF	27.40	357.10	147.11	55.35	1.10	0.37	-
	MAM	68.40	351.60	171.33	53.50	1.87	0.71	+
	JJA	46.40	283.40	160.65	63.50	0.63	0.30	-
	SON	27.60	333.50	157.97	65.51	1.53	0.78	-
1961-1991	T_{av}	415.70	757.20	602.44	77.25	0.20	0.27	-
	DJF	27.40	222.30	137.59	51.99	-0.51	-0.62	-
	MAM	68.40	257.70	160.48	51.25	-0.20	-0.27	-
	JJA	46.40	273.00	160.56	64.93	0.31	0.31	-
	SON	27.60	290.20	143.81	58.68	1.22	1.46	-
1992-2023	T_{av}	405.10	899.20	670.59	119.12	1.93	4.35	+
	DJF	9.47	77.70	25.79	16.58	1.28	1.11	-
	MAM	91.30	351.60	181.84	54.32	1.80	1.69	+
	JJA	54.60	283.40	160.73	63.13	1.25	1.42	-
	SON	70.30	333.50	171.69	69.69	-0.21	-0.42	-

Z–value of trend; S–Sen's slope; α – level of significance *** - α=0.001 ; ** - α=0.01; * - α=0.05; + - α=0.1

The mean annual air temperature for the period 1961–2023 at Leskovac was 11.2°C. The warmest year within this period was 2023, with an average temperature of 12.9°C, while the coldest year was 1983, with a mean temperature of 9.3°C. The lowest monthly mean temperature was recorded in January 2017, when the average temperature reached -6.2°C. The absolute maximum temperature was measured on 24 July 2007 at 43.7°C, while the absolute minimum occurred on 13 January 1985, with -30.3°C.

Analysis of the average monthly temperatures for the period 1961–2023 indicates a typical seasonal pattern characteristic of the temperate-continental climate of the Balkan Peninsula. The lowest mean monthly temperature was recorded in January (−0.2°C), while the maximum was reached in July (21.6°C), resulting in an annual amplitude of 21.8°C. During the winter period (December–January–February), values range from −0.2 to 2.2°C, indicating frequent frost occurrences, particularly in January. Previous analyses of mean monthly temperatures in Serbia (Milovanović et al., 2018) confirm that the lowest values are recorded in January. The spring period exhibits accelerated warming: March registers 6.5°C, April 11.5°C, and May 16.3°C. The increase of nearly 10°C between March and May highlights the rapid transition from winter to summer conditions, which is a distinctive feature of the continental climate. A similar trend of rising spring temperatures has been observed in Europe for the 1951–2020 period, with regression analyses confirming the most pronounced increase during spring (Twardosz et al., 2021). The summer maximum occurs in July (21.6°C), while August shows a slight decrease (21.2°C) but still maintains high values. The extended period of elevated summer temperatures has also been confirmed in studies for the Eastern Mediterranean (Lelieveld et al., 2012), attributed to the enhanced influence of the subtropical anticyclone during summer, which stabilizes the atmosphere and reduces cloud cover. Autumn brings gradual cooling, with September averaging 16.6°C, October 11.1°C, and November decreasing to 6.3°C.

Trend analysis of mean annual air temperatures for 1961–2023 shows a clear increase (Figure 3). The linear regression equation indicates that the average temperature rises at a rate of 0.028°C per year, which over six decades corresponds to an increase of approximately +1.7°C. A similar trend was observed at the Kruševac meteorological station, where the mean annual temperature increased by 1.2°C during 1961–2018 (Stričević et al., 2022). Compared to the Southeastern European region, the meteorological station in Lugoj (Romania) also recorded an increase in the long-term average temperature of approximately 1.7°C over the last 60 years (Dunca & Bădăluță-Minda, 2023).

Division of the analysed period into two time intervals reveals a clear shift in trend direction. In the earlier period (1961–1991), a slight decreasing tendency is observed, with a rate of approximately −0.032°C per year, corresponding to a total decline of about −1.0°C over that interval. In contrast, the later period (1992–2023) is characterised by a distinct increase of around 0.049°C per year, resulting in an approxi-

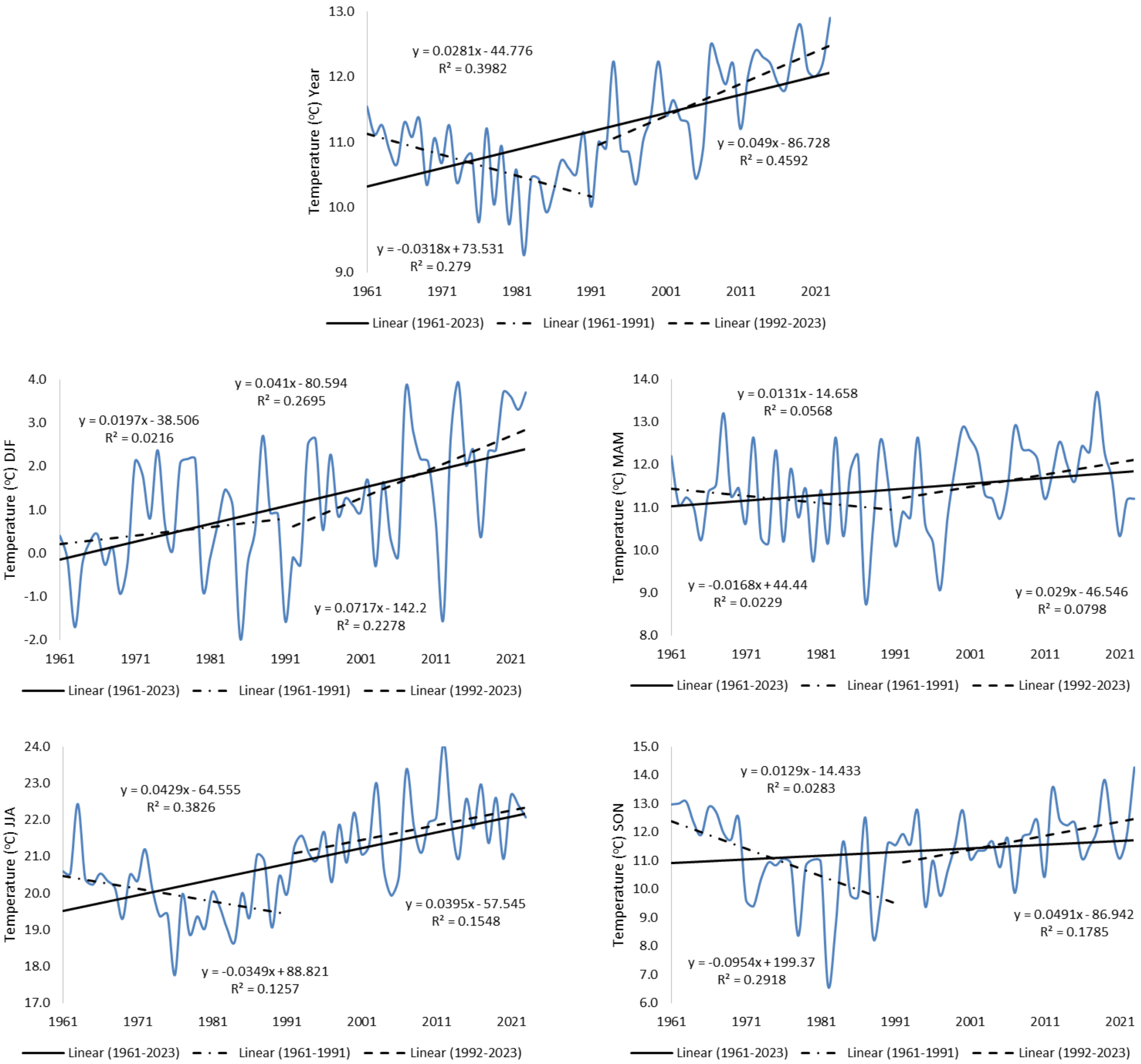

Figure 3. Average annual and seasonal temperatures, trend equations, and trend lines for the Leskovac meteorological station (1961–2023)

mate rise of +1.5°C. These results indicate that the increase in annual temperature is of a long-term nature, with a considerably more pronounced warming rate in recent decades compared to the earlier interval, during which a minor cooling tendency was recorded.

At the beginning of the analyzed period (1960s and 1970s), annual temperatures generally ranged between 10.0°C and 11.0°C, while in the last two decades values above 12.0°C have become more frequent. The difference between the minimum and maximum values over the observed period is approximately 3.5°C, indicating relatively pronounced interannual fluctuations.

Observations over multi-decadal periods reveal certain specificities in temperature trends. Between 1961 and 1980, relative stability prevailed with a slight decrease in temperature, accompanied by several colder years. During the period 1981–2000, pronounced oscillations between colder and warmer years were observed, but without a clear upward trend, while the late 1990s marked the beginning of a period with more frequent warm years. The period 2001–2023 is characterized by a strong increase in temperature, with almost all years exceeding the long-term average of 11.2°C, and the highest values within the entire interval were also recorded during this period. The period from 2011 to 2023 is particularly notable, as values consistently exceeded the long-term mean, and extremely warm years have become

Table 2. Mann–Kendall test statistics for temperature trends at the Leskovac meteorological station

Period		*Min.*	*Max.*	*Mean*	*St.dev.*	*Z*	*S*	*α*
1961-2023	T_{av}	9.3	12.9	11.2	0.8	4.66	0.03	***
	DJF	-2.0	3.9	1.1	1.4	4.24	0.04	***
	MAM	8.8	13.7	11.4	1.0	1.73	0.01	+
	JJA	17.8	24.1	20.8	1.3	4.96	0.04	***
	SON	6.6	14.3	11.3	1.4	1.10	0.01	-
1961-1991	T_{av}	9.3	11.5	10.6	0.5	-2.99	-0.03	**
	DJF	-2.0	2.7	0.5	1.2	1.16	0.03	-
	MAM	8.8	13.2	11.2	1.0	-0.63	-0.01	-
	JJA	17.8	22.4	20.0	0.9	-2.41	-0.04	*
	SON	6.6	13.1	10.9	1.6	-3.33	-0.10	***
1992-2023	T_{av}	10.4	12.9	11.7	0.7	3.49	0.05	***
	DJF	-1.5	3.9	1.7	1.4	2.68	0.08	**
	MAM	9.1	13.7	11.7	1.0	0.94	0.02	-
	JJA	19.9	24.1	21.7	0.9	2.27	0.04	*
	SON	9.4	14.3	11.7	1.1	2.29	0.05	*

Z–value of trend; S–Sen's slope; α – level of significance *** - α=0.001 ; ** - α=0.01; * - α=0.05; + - α=0.1

more frequent. Such a rise in temperatures has multiple implications, ranging from changes in precipitation and hydrological regimes to increased drought risk and impacts on agriculture and ecosystems.

Seasonal temperature analysis at the Leskovac meteorological station for the period 1961–2023 indicates distinct differences in trend intensity across the year. During the winter season (December–January–February), a clear increase in air temperature is observed, with an average rise of approximately 0.041°C per year, corresponding to about +2.5°C over six decades. In the first part of the analysed period (1961–1991), the warming rate was considerably lower, around 0.020°C per year (approximately +0.6°C in total), whereas in the later years (from 1992 onward), the trend intensified to about 0.072°C annually, resulting in an increase of roughly +2.2°C (Figure 3). In spring (March–April–May), a slight warming tendency is present, with a linear trend of around 0.013°C per year or approximately +0.8°C across the full time span. The earlier part of the series (1961–1991) reveals a very weak cooling tendency (−0.017°C per year, around −0.5°C), while in more recent decades a shift towards warming is evident, with an average increase of about 0.029°C per year, amounting to approximately +0.9°C (Figure 3). The most pronounced warming is recorded during the summer months (June–July–August), where the trend reaches approximately 0.043°C per year, translating into an increase of nearly +2.6°C over the observed period. In the first half of the series (1961–1991), a slight downward tendency was observed (−0.035°C per year; around −1.0°C total), whereas in the later years the trend shifted to a positive direction with an increase of approximately 0.040°C per year, equivalent to roughly +1.2°C (Figure 3). Autumn (September–October–November) shows a mild upward trend, with an increase of approximately 0.013°C per year, resulting in about +0.8°C over the six-decade interval. The first part of the analysed period (1961–1991) is characterised by a slight decrease in temperature (−0.095°C per year; around −2.9°C), while the second part (from 1992 onward) indicates renewed warming, with an average rise of around 0.049°C per year, amounting to approximately +1.5°C (Figure 3).

The Mann–Kendall test results for mean annual air temperature at the Leskovac meteorological station reveal a statistically significant warming trend over the period 1961–2023, with Z = 4.66 ($p < 0.001$). Sen's slope indicates an increase of approximately +0.03°C per year, while the long-term average temperature is 11.2°C. This confirms a consistent upward trend in annual temperature, despite moderate year-to-year variability.Seasonal analysis shows that the most pronounced warming occurs during winter (December–January–February) and summer (June–July–August), with Z-values of 4.24 and 4.96 and estimated temperature increases of about +0.04°C per year. A weaker but still positive trend is observed in spring, while autumn exhibits no statistically relevant trend, despite a slight upward tendency (Table 2). A comparison between the two subperiods indicates that temperature rise became noticeably more pronounced after 1992, particularly during winter (Z = 2.68; $p < 0.01$) and summer (Z = 2.27; $p < 0.05$), whereas the earlier interval

(1961–1991) is marked by either negligible changes or slight cooling.

The average discharge of the Južna Morava River at the Korvingrad hydrological station during the period 1961–2023 was 54.89 m^3/s (Figure 4). Similar average values for the same station during 1960–2014, amounting to 53.70 m^3/s, were reported by Urošev et al. (2016), indicating that mean discharges at this location have not shown significant changes over the decades. Data from the Mojsinje hydrological station, located closer to the river mouth, show a higher mean annual discharge of 89.60 m^3/s for the period 1961–2020, as reported by Dobric et al. (2023).

Analysis of mean annual discharges for the period 1961–2023 shows a slight downward trend. Linear regression results indicate a decrease of approximately 0.132 m^3/s per year, amounting to about 8.2 m^3/s over the six-decade period. However, the coefficient of determination is low (R^2 = 0.0184), indicating that the linear trend accounts for only a small fraction of the overall discharge variability (Figure 4). In the first half of the analysed period (1961–1991), a more pronounced decreasing trend is observed (–0.408 m^3/s per year), whereas the interval from 1992 to 2023 is characterised by a mild increasing tendency (+0.571 m^3/s per year). Although the more recent period indicates an opposite trend direction compared to the earlier one, the low coefficients of determination (R^2 = 0.0579 and 0.0753) suggest that the linear model is not a reliable indicator of long-term discharge change, as interannual variability remains the dominant factor.

The year 2015 stands out for the highest mean annual discharge of 96.95 m^3/s. This high discharge resulted from

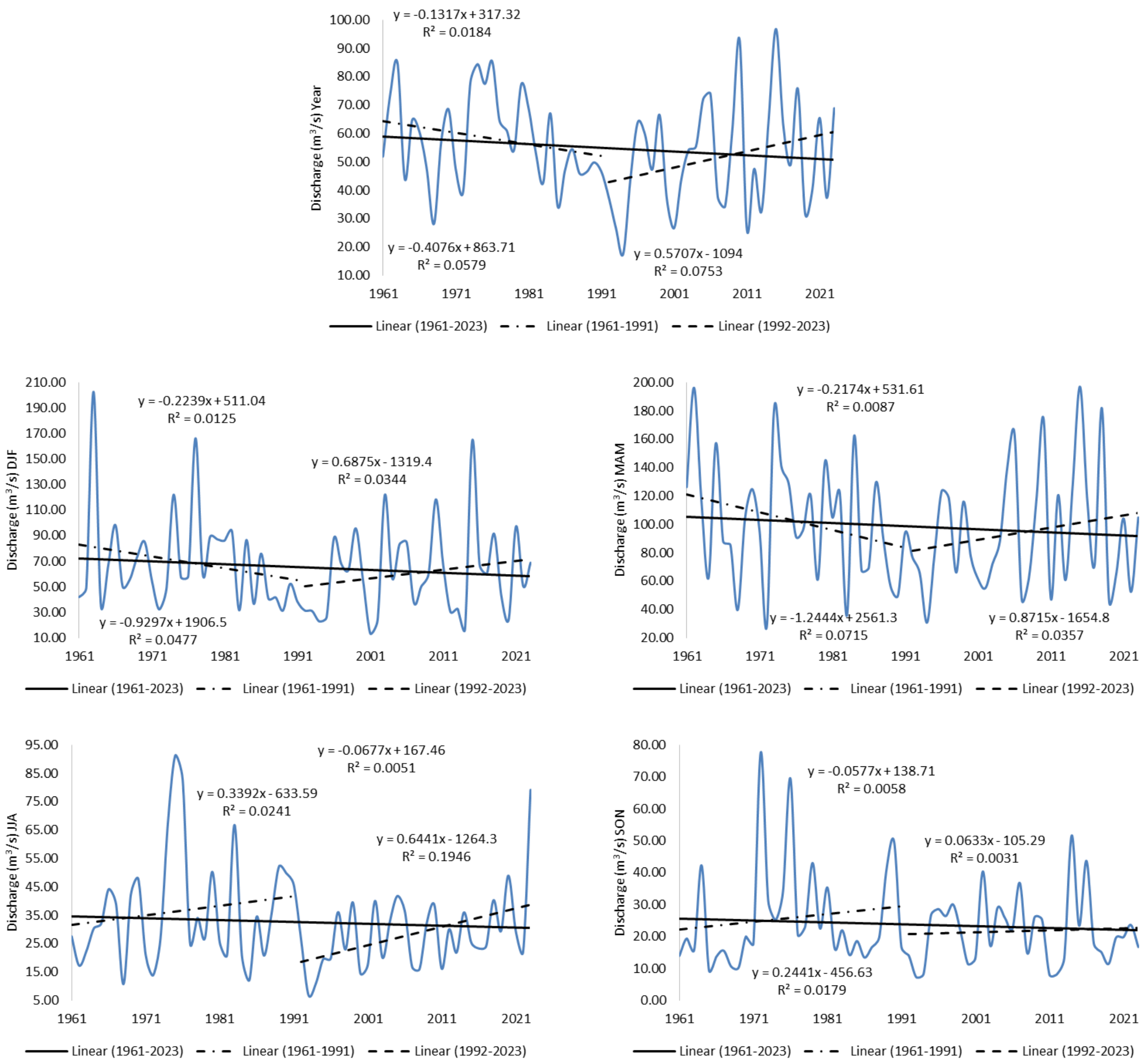

Figure 4. Average annual and seasonal discharge, trend equations, and trend lines for the Korvingrad hydrological station (1961–2023)

abundant precipitation, as 2015, with 700.50 mm, was one of the wettest years in the observed period, exceeding the long-term average (1961–2023). In contrast, the lowest mean annual discharge was recorded in 1994, amounting to only 17.54 m^3/s. This year was the third driest in the analysis period and also one of the warmest, with an average temperature of 12.2°C, approximately 1°C above the long-term mean. The combination of low precipitation and elevated temperatures contributed to reduced water availability and minimal annual discharges.

The observed series can be divided into several characteristic periods. From 1961 to the late 1970s, discharge values were generally stable and above average, with particularly high values in 1964, 1970, and 1974 (>70 m^3/s). The late 1980s and the first half of the 1990s were marked by lower discharge values, mostly below the long-term average. The second half of the 1990s saw occasional years with higher flows, but oscillations persisted. During 2000–2009, discharges were somewhat more stable, with several years above the mean (2005, 2006), but also episodes with lower values (2007, 2008). After 2010, pronounced fluctuations are observed, with the most extreme values occurring in the series. The years 2010, 2014, and 2015 are characterised by record-high discharges (>90 m^3/s), while 2011 and 2012 were among the driest, with values of only 25 to 30 m^3/s. This pattern indicates increased discharge variability over the last decade, which can be associated with climate change and the more frequent occurrence of intense precipitation events as well as pronounced droughts.

During the winter season (December–January–February), the mean discharge of the South Morava River at the Korvingrad station exhibits a slight decreasing trend over the 1961–2023 period. Linear regression analysis indicates a decline of –0.224 m^3/s per year, which corresponds to an overall reduction of approximately 14 m^3/s over 63 years. However, the very low coefficient of determination (R^2 = 0.0125) confirms that the linear trend explains only a limited share of total discharge variability. A segmentation of the time series into two sub-periods highlights notable differences in hydrological behavior (Figure 4). In the interval 1961–1991, a more pronounced decreasing tendency is recorded (–0.093 m^3/s per year; R^2 = 0.0477), whereas during 1992–2023 a slight increasing trend is observed (+0.069 m^3/s per year; R^2 = 0.0344). Such contrasting behavior suggests a potential shift in the hydrological regime after the early 1990s, most likely related to enhanced climatic variability, more frequent winter precipitation extremes, and increased discharge fluctuations.

The analysis of mean spring discharge (March–April–May) at the Korvingrad station for the period 1961–2023 reveals a slight decreasing trend of –0.217 m^3/s per year. The extremely low coefficient of determination (R^2 = 0.0087) indicates that the linear trend accounts for only a negligible portion of the overall variability. Assessment of shorter temporal segments shows a more pronounced decline between 1961 and 1991 (–1.244 m^3/s per year), followed by a weak increasing tendency in the 1992–2023 interval (+0.872 m^3/s per year). Nevertheless, due to the low R^2 values (0.0715 and 0.0357), these results cannot be considered statistically reliable.

During the summer period (June–July–August), discharge analysis for 1961–2023 indicates a very weak decreasing trend of –0.068 m^3/s per year. The extremely low coefficient of determination (R^2 = 0.0051) suggests that the trend explains only a minimal portion of discharge variability (Figure 4). Analysis of the two temporal segments reveals opposite developments: a slight increase in discharge is detected in the 1961–1991 period (+0.339 m^3/s per year), followed by a more pronounced rise after 1992 (+0.644 m^3/s per year). However, due to the low explanatory power of the regression models (R^2 = 0.0241 and 0.1946), particularly in the earlier interval, these trends cannot be considered statistically reliable.

Analysis of the average seasonal discharge during the autumn period (September–October–November) shows a very slight decreasing trend in the full time series (1961–2023), with a reduction of approximately 0.058 m^3/s per year, which corresponds to a total decline of around –3.4 m^3/s over six decades. However, the coefficient of determination (R^2 = 0.0058) indicates that the trend explains only a negligible portion of the overall variability. In the first subperiod (1961–1991), the trend is mildly negative (–0.244 m^3/s per year), whereas in the later subperiod (1992–2023) it shifts towards a slight positive trend (+0.063 m^3/s per year). In both subperiods, the R^2 values are very low (0.0179 and 0.0031), suggesting that the observed change in trend is weak.

The highest mean monthly discharges, approximately twice the long-term average, occur in March (115 m^3/s) and April (104.47 m^3/s). High discharge values at the end of winter and the beginning of spring are caused by snowmelt and precipitation. During the summer months, reduced rainfall and higher air temperatures lead to lower discharges. In autumn, discharge increases again, associated with intensified precipitation during this period. The lowest mean monthly discharge was recorded in September, at 16.51 m^3/s. In con-

Table 3. Mann–Kendall test statistics for discharge trends at the Korvingrad hydrological station

Period		*Min.*	*Max.*	*Mean*	*St.dev.*	*Z*	*S*	*α*
1961-2023	T_{av}	17.54	96.79	54.89	17.79	-1.36	-0.18	-
	DJF	13.35	202.65	65.04	36.71	-0.68	-0.14	-
	MAM	28.35	196.97	98.47	42.63	-1.07	-0.31	-
	JJA	6.92	91.31	32.60	17.35	-0.30	-0.04	-
	SON	7.28	77.70	23.76	13.94	0.01	0.00	-
1961-1991	T_{av}	28.11	85.42	58.26	15.40	-1.53	-0.49	-
	DJF	31.40	202.65	69.37	38.71	-0.78	-0.44	-
	MAM	28.35	196.27	102.39	42.31	-1.26	-1.39	-
	JJA	10.73	91.31	36.70	19.86	0.92	0.34	-
	SON	9.47	77.70	25.79	16.58	1.26	0.21	-
1992-2023	T_{av}	17.54	96.79	51.63	19.51	1.48	0.58	-
	DJF	13.35	164.67	60.84	34.75	0.96	0.56	-
	MAM	30.80	196.97	94.68	43.27	0.37	-1.32	-
	JJA	10.73	91.31	36.70	19.86	2.16	0.53	*
	SON	9.47	77.70	25.79	16.58	-0.02	-0.01	-

Z–value of trend; S–Sen's slope; α – level of significance *** - α=0.001 ; ** - α=0.01; * - α=0.05; + - α=0.1

trast, the highest recorded discharge was 367.29 m³/s in February 1963, linked to abundant precipitation in January of the same year, the third wettest month in the observed period. The lowest discharge occurred in August 1993, measuring only 4.32 m³/s. Although August of that year was not the month with the lowest precipitation, it was marked by extremely high temperatures, with a monthly mean of 22.8°C, nearly twice the long-term average. Elevated temperatures caused intense evapotranspiration and reduced runoff, resulting in minimal discharge. Similar findings were reported by Martić Bursać et al. (2022) for the Toplica River, a left tributary of the Južna Morava, where reductions in summer discharges were influenced not only by high temperatures and intensive evapotranspiration but also by anthropogenic activities, such as increased water use in agriculture.

The Mann–Kendall test results indicate that no statistically significant long-term trend in discharge was detected at the Korvingrad hydrological station over the 1961–2023 period (Z ranging from −1.36 to +0.01; α > 0.1). However, Sen's slope reveals a slight decrease in the mean annual discharge (−0.18 m³/s per year), with a more pronounced decline observed during winter (−0.136 m³/s/year) and spring (−1.07 m³/s/year). During the earlier assessment period (1961–1991), negative trends were dominant across all seasons, particularly in spring (−0.49 m³/s/year) and winter (−0.44 m³/s/year), suggesting a relatively drier discharge regime, although without statistical significance. Following 1992, a noticeable shift in the discharge regime is evident, with most seasons exhibiting positive tendencies. The only statistically significant trend was identified for summer (1992–2023), where the discharge increased at a rate of +0.53 m³/s/year (α < 0.05). This upward tendency in summer flow over recent decades is likely associated with a higher frequency of intense precipitation events during the warmer part of the year. Nevertheless, strong interannual variability dominates over the linear trends, suggesting that changes in discharge within the Južna Morava basin are not the result of a gradual long-term process but rather a consequence of hydrological extremes and unstable climatic conditions (Table 3).

Analysis of annual precipitation, air temperature, and mean annual discharges of the Južna Morava (1961–2023) demonstrates a clear link between hydrological and climatic regimes. Discharge largely follows changes in annual precipitation, while air temperature also affects it through evapotranspiration and the retention and distribution of water within the basin.

During the first decades of the analysed period (1961–1980), discharges were generally above the long-term mean, coinciding with years of higher precipitation. In the 1980s and 1990s, precipitation declined, accompanied by lower annual discharges, confirming their mutual dependence. The lowest mean annual discharge was recorded in 1994 (17.54 m³/s), during a period of reduced precipitation and elevated temperatures, indicating the combined effect of drought and increased evapotranspiration on river discharge.

Conversely, the highest discharges occurred in 2010, 2014, and 2015, when precipitation was above average (e.g., 2014 with 899.2 mm), confirming that increased precipitation directly contributes to higher river flows. These years were also characterised by higher temperatures, indicating that the effect of elevated temperatures was insufficient to offset the impact of intense precipitation.

Long-term trends show a marked increase in mean annual temperature (+1.7°C over 63 years), a slight rise in precipitation (+2.25 mm per year), and a mild declining trend in discharges. This suggests that, despite slightly higher precipitation, increased temperatures can lead to reduced discharges through enhanced evapotranspiration. In other words, rising temperatures have an indirect negative effect on river discharges, especially in dry years when precipitation is below average. These findings are consistent with research in Serbia, which shows that rising temperatures lead to a reduction in mean annual streamflow. An increase of about 1°C is associated with approximately 20% lower annual discharge, confirming the high sensitivity of streamflow to the combined influence of key climatic parameters (Dimkić, 2017).

Seasonally, maximum discharges occur in spring (March–April), coinciding with the period of highest precipitation and snowmelt, while minimum values are observed in August and September, when high temperatures and reduced rainfall result in minimal discharges.

The analysis indicates that changes in the discharge regime of the Južna Morava Basin result from the combined effects of precipitation and temperature, with precipitation being the decisive factor for annual fluctuations and temperature a key driver of long-term declining trends in discharge. In the past decade, increased hydrological variability has been observed, consistent with global climate change, which causes more frequent alternations between extremely wet and dry years.

5. Conclusion

The combined effect of rising temperatures and slightly increased precipitation influences the discharge regime of the Južna Morava. Maximum discharges occur during periods of higher precipitation and snowmelt, primarily in March and April, while minimum discharges are recorded during the summer months with high temperatures and low rainfall (e.g., August 1993). This pattern shows that river discharge does not increase linearly with temperature but is strongly controlled by the distribution of precipitation. Years with high temperatures but low rainfall are marked by reduced discharges due to intensified evapotranspiration (e.g., 1994 and 2011), whereas years with higher precipitation and moderate temperatures show significant increases in discharge, confirming the dominant role of precipitation in shaping river discharge.

In conclusion, there is a clear positive relationship between precipitation and discharge in the Južna Morava basin, while temperature has a more complex, indirect influence. Rising temperatures increase evapotranspiration, which can reduce discharge during dry periods. Discharge therefore depends on the combined effects of temperature and precipitation – decreasing in hot, dry periods and reaching higher values during wet, cooler periods.

Although long-term fluctuations in discharge are primarily governed by precipitation and temperature variability, the results of the Mann–Kendall test suggest that these changes are not statistically significant for most of the analysed periods. However, the Sen's slope estimator reveals a slight decrease in annual discharge, indicating a weak but consistent tendency towards reduced streamflow, particularly during winter and spring.

These findings highlight that accurate prediction of hydrological regimes and effective water resources management in the Južna Morava basin require an integrated assessment of temperature, precipitation, and their interactive effects on river discharge.

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