The West Morava Flow Dynamics and Teleconnection Impact: A Case Study of Jasika Hydrological Profile (Central Srbija)

Dragan Burić[1] and Ivana Penjišević[2]

[1]Univerzitet Crne Gore Filozofski fakultet
[2]Michigan State University Department of Geography Environment and Spatial Sciences

June 08, 2024

Abstract

The West Morava (WM) River, situated in Serbia's Central region, boasts the largest reservoir of freshwater resources within the country. The primary objective of this study was to investigate alterations in the flow (Q) of the WM River (length of 308 km) at the Jasika hydrological station (near the confluence) spanning from 1948 to 2023. Trend analyses and standardized deviation method across monthly, seasonal, and annual timeframes indicates an overall shift towards "drier" conditions along the river's trajectory. When examining the analysis at a daily level, utilizing the percentile method revealed a diminishing trend in the annual count of days small waters (Qd<9th), very small waters (Qd<25th), large waters (Qd>75th), and very large waters (Qd>91st). However, in the current segment of the 21st century (2001–2023), there has been a notable rise in the risk of floods, evidenced by a significant increase in the annual count of days with Qd>91st. It's worth noting that river flow is chiefly influenced by precipitation (P) and air temperature (T), which in turn impacts evaporation rates. The findings from the Pearson correlation coefficient analysis indicate that several atmospheric oscillations, including NAO, NAO-500, NCP, AO, MO1, MO2, WeMO, and EAWR, exert a significant influence on the local hydroclimate conditions, particularly during colder months. Additionally, SNAO and AMO exhibit substantial impact during the summer period. Notably, the influence of EA is pronounced on T during February, April, and August, with correlation coefficients ranging between 0.61–0.71. Conversely, the connections with ENSO, SOI, SCAND, and POLEUR appear to be comparatively weaker overall. Given the crucial importance of the WM River for Serbia, it is necessary to define as soon as possible certain plans related to flow equalization and sustainable management of water resources, but also mitigation and adaptation to current and specially projected future climate changes.

The West Morava Flow Dynamics and Teleconnection Impact: A Case Study of Jasika Hydrological Profile (Central Srbija)

Ivana Penjišević[1], Dragan Burić[2]*

[1] Department of Geography, Faculty of Sciences and Mathematics, University of Pristina, Kosovska Mitrovica, Serbia.

[2] Department of Geography, Faculty of Philosophy, University of Montenegro, Nikšic, Montenegro.

***Corresponding Author** : Dragan Burić. Department of Geography, Faculty of Philosophy, University of Montenegro, Nikšic, Montenegro. Email: draganburic33@gmail.com

ORCID

Ivana Penjiševićhttps://orcid.org/0000-0002-9605-0488

Dragan Burić

httpsHYPERLINK ”https://orcid.org/0000-0003-0905-1915”://HYPERLINK ”https://orcid.org/0000-0003-0905-1915”orcidHYPERLINK ”https://orcid.org/0000-0003-0905-1915”.HYPERLINK *"https://orcid.org/0000-0003-0905-1915"orgHYPERLINK "https://orcid.org/0000-0003-0905-1915"/0000-0003-0905-1915*

AbstractThe West Morava (WM) River, situated in Serbia's Central region, boasts the largest reservoir of freshwater resources within the country. The primary objective of this study was to investigate alterations in the flow (Q) of the WM River (length of 308 km) at the Jasika hydrological station (near the confluence) spanning from 1948 to 2023. Trend analyses and standardized deviation method across monthly, seasonal, and annual timeframes indicates an overall shift towards "drier" conditions along the river's trajectory. When examining the analysis at a daily level, utilizing the percentile method revealed a diminishing trend in the annual count of days small waters (Qd<9th), very small waters (Qd<25th), large waters (Qd>75th), and very large waters (Qd>91st). However, in the current segment of the 21st century (2001–2023), there has been a notable rise in the risk of floods, evidenced by a significant increase in the annual count of days with Qd>91st. It's worth noting that river flow is chiefly influenced by precipitation (P) and air temperature (T), which in turn impacts evaporation rates. The findings from the Pearson correlation coefficient analysis indicate that several atmospheric oscillations, including NAO, NAO-500, NCP, AO, MO1, MO2, WeMO, and EAWR, exert a significant influence on the local hydroclimate conditions, particularly during colder months. Additionally, SNAO and AMO exhibit substantial impact during the summer period. Notably, the influence of EA is pronounced on T during February, April, and August, with correlation coefficients ranging between 0.61–0.71. Conversely, the connections with ENSO, SOI, SCAND, and POLEUR appear to be comparatively weaker overall. Given the crucial importance of the WM River for Serbia, it is necessary to define as soon as possible certain plans related to flow equalization and sustainable management of water resources, but also mitigation and adaptation to current and specially projected future climate changes.

Keywords: flow, trend, standardized deviations, percentiles, teleconnections, The West Morava, Serbia

1. INTRODUCTION

Rivers stand as pivotal surface water bodies, historically drawing human interest and engagement. Presently, they serve as vital conduits for a multitude of economic endeavors such as agriculture, tourism, hydropower generation, navigation, fish farming, and various other essential activities. Consequently, rivers are regarded as a shared resource, collectively benefiting society. Thus, it becomes imperative to monitor alterations in water quantity (flow) and quality, along with other pertinent characteristics linked to both the water itself and its encompassing catchment area (such as sediment levels, erosive processes, and catchment degradation). Rivers essentially epitomize a "product" of the climate, rendering them exceptionally susceptible to contemporary climatic shifts. The flow dynamics of rivers are subject to temporal and spatial fluctuations, influenced by factors including precipitation patterns and temperature variations. However, it's crucial to acknowledge that human activities within the basin, both direct and indirect, increasingly exert influence on river flow, further complicating the dynamics of these essential watercourses.

The relationship between climate change and the hydrological cycle is indeed intricate, with a prevailing theory suggesting that rising temperatures amplify the hydrological cycle's intensity. This translates to heightened evaporation rates and an increase in both the frequency and volume of precipitation (Pratap & Markonis, 2022). Over the past few decades, the combination of a warming climate and human activities has brought about significant alterations to the hydrology of river basins in the Arctic Ocean region (Rawlins et al., (2021). For instance, research indicates a notable increase in the flow of rivers within Siberia, including the Ob, Jenisej, and Lena rivers, spanning the period from 1979 to 2019 (Hu et al., 2023). Studies conducted from the early 1960s to the early 2000s have revealed distinct hydrological trends across European rivers. Specifically, during winter months, there was a discernible rise in flow observed in numerous European rivers, particularly prevalent in Western and Northern Europe. Conversely, contrasting trends emerged for rivers in Southern and parts of Eastern Europe, where negative flow trends were predominant, particularly evident during summer months (Stahl et al., 2010; Stahl et al., 2012). Kwadijk et al. (2016) conducted research to assess the influence of climate change on rivers that drain into the North Sea. Their findings revealed that the majority of these rivers did not exhibit significant trends over the studied period. However, the authors observed a slight increase in flow during winter months, which they attributed to rising temperatures.

Specifically, the increase in temperature led to more frequent precipitation in the form of rain rather than snow. The authors highlight significant interannual and decadal variability in the annual flow of rivers that flow into the North Sea. They attribute this variability to fluctuations in the North Atlantic Oscillation (NAO), with its influence being particularly pronounced during winter months. Furthermore, under a milder scenario of global warming projecting a temperature increase of 1.5–2°C by the end of the 21st century, forecasts for the European part of Russia indicate contrasting trends in river flow patterns. Specifically, in winter, the flow of arctic rivers such as the Northern Dvina and Pechora is projected to increase. However, for southern rivers like the Don and Kuban, as well as for all mentioned rivers, a decrease in flow is anticipated during summer and autumn (Kalugin, 2023). Human interventions in watersheds pose significant challenges in determining the precise impact of climate change on river flow (Merz et al., 2012). Consequently, the effects of climate change are often more discernible in the mountainous regions of a basin, where human influence is relatively limited, compared to lowlands, where human activities are more pronounced (Mankin et al., 2015). A warming climate has triggered the retreat of glaciers and the reduction of snow cover worldwide (Zemp et al., 2015). This loss of snow and ice has disrupted the natural regulation of runoff, leading to increased river flow in downstream areas (Singh et al., 2016; Stoffel et al., 2016; Matti et al., 2017; Hernández–Henríquez et al., 2017).

Rivers across the Balkan Peninsula, including those in Serbia, exhibit a characteristic seasonal flow pattern, with lower flows during the summer and higher flows during the winter and early spring, rendering them susceptible to flooding. Papadaki and Dimitriou (2021) highlight that in recent decades, the flow of Balkan rivers has experienced a decline due to a combination of factors including reduced precipitation and anthropogenic influences such as mismanagement of water resources. Simulations, such as those conducted for the Drim River, indicate an anticipated significant decrease in water levels in the future. Pekarova et al. (2018) conducted an examination of changes in the flow of the Danube River, utilizing data obtained from the Ceatal Izmail hydrological station situated in Ukraine, near the river's mouth. Their analysis, spanning from 1840 to 2015, revealed that the average flow of the Danube did not undergo significant alterations over this period. However, the study identified a notable shift in the timing of spring high waters in recent years, occurring approximately 40 days earlier than historical norms. Using the emission scenarios RCP2.6 and RCP8.5, Probst and Mauser (2023) analyzed changes in several hydroclimatic elements, including temperatures, precipitation, soil moisture content, etc. They also examined the dynamics of runoff in the Danube River basin in the near (2031–2060) and distant future (2071–2100) compared to the base period of 1971–2000. The authors emphasize that "the impacts of climate change remain moderate for RCP2.6 and become serious for RCP8.5," but both scenarios predict an increase in winter runoff and a decrease in summer runoff. They also project an increased risk of major floods along the entire course of the Danube, while the risk of low flows will increase along the lower stretch of the river. The Sava River is the second longest tributary of the Danube (after the Tisza), but it contributes the largest amount of water - the average annual flow of the Sava River just before it joins the Danube near Belgrade is about 1700 m^3/s (Komatina & Grošelj, 2015). For the period 1971–2010, as well as for the longer period from 1931–2010, it has been determined that the Sava River shows a significant negative trend in mean annual flow (Lutz et al., 2016; Orešić et al., 2017). Changes in the regime of the Sava River largely occur due to human influence (Trenc et al., 2018).

One of the longer tributaries of the Danube is the Velika Morava (along with its longer tributary, the West Morava, with the length of the Velika Morava being 493 km). This river contributes an average of 297 km^3/s of water into the Danube annually. The results of the trend for the period 1926–2005 show that the flow of the Velika Morava slightly increases during winter and spring, and decreases in summer and autumn (Stojković et al., 2014). The Velika Morava is formed by the joining of the South Morava and West Morava near Stalać and is the national and largest river of Serbia. Its watershed has a total area of 38,207 km^2, and 97% of the basin is located in Serbia. In other words, the Velika Morava basin covers 42.38% of the territory of Serbia. The drainage area of the South Morava and West Morava is about 31,500 km^2 (Dukić & Gavrilović, 2002). For the period 1946–2020, the South Morava registers a significant decrease in mean annual flow (Langović et al., 2022), but its tributary, the Toplica River, for the period 1957–2018 registers a positive flow trend Martić–Bursać et al., 2022). When it comes to the West Morava, it should be pointed out that the largest part of renewable internal freshwater resources in Serbia is located precisely in the basin of this river (Simić & Matic, 2017).

Taking into account the significance of the West Morava River for Serbia, the main objective of this study is to analyze daily, monthly, seasonal, and annual flows from the hydrological station (HS) Jasika. This HS was chosen because the empirical flow (Q) data are most compact, and it is closest to the confluence of the West Morava and South Morava, thereby representing the flow regime dynamics of the West Morava throughout its course. Flow is primarily influenced by precipitation, but also by temperature (via evaporation), thus changes in average monthly temperatures and precipitation will be examined at the Jasika HS site using data from the nearest meteorological station (MS) in Kruševac. Finally, the aim is to investigate the correlation between 15 indicators of atmospheric and oceanic oscillations (teleconnections) with the fluctuation of monthly flow values, temperature, and precipitation based on data from the Jasika HS and Kruševac MS. Flow calculations were conducted for the period from 1948 to 2023, while temperature and precipitation data spanned from 1949 to 2023. For consistency, the influence of teleconnections on the mentioned hydroclimatic parameters was examined for the period from 1949 to 2023. The significance of this study lies in considering the entire instrumental period (76 years) for the first time and utilizing proven methods (trend analysis, percentiles, standardized deviations, 10–year moving averages). In order to enhance the understanding of hydrological processes in the context of contemporary climate change, the impact of atmospheric and oceanic oscillations on the hydroclimate of the observed area will also be investigated for the first time.

2. MATERIALS AND METHODS

2.1 Study area

The study area focuses on the West Morava River with the aim of identifying changes in flow patterns in the context of contemporary climate change. Flow data were collected from the Jasika Hydrological Station, located near the confluence of the West Morava with the South Morava. The Jasika HS is situated 18 km from the confluence with the Južna Morava, which marks the beginning of the Velika Morava. The drainage area of the West Morava at the Jasika HS profile is 14,721 km^2, with the gauge datum set at 138.56 m above sea level in relation to the Adriatic Sea. The closest meteorological station to this site is in Kruševac (at an elevation of 166 m), providing temperature and precipitation data (Figure 1).

FIGURE 1 The position of the West Morava River in Serbia, along with the locations of the Jasika Hydrological Station (HS Jasika) and the Kruševac Meteorological Station (MS Kruševac).

The West Morava is a river in Central Serbia formed in the Požega Valley by the confluence of three rivers: Golijska Moravica, Đetinja, and Skrapež (Penjišević, 2022). From its origin to the confluence with the South Morava, the river spans 210 km, while its total length from the source of its longest tributary, the Golijska Moravica, located at an elevation of 1350 meters above sea level, to its confluence with the South Morava, measures 308 km. The river flows eastward through a diverse valley landscape. Within the relief of the West Morarava valley, there exists a substantial variation in elevation, ranging from 144 to 1,321 meters above sea level (Milosavljević et al., 2023). This valley of the West Morava River holds significant economic importance for Serbia (Lukić et al., 2018). Varied mineral compositions of rocks, coupled with deep faults, have led to the formation of notable deposits of minerals and thermal-mineral waters within the West Morava River valley (Gulan et al., 2020). In accordance with the Köppen climate classification, the upper reaches of the West Morava basin, situated in southwest and west Serbia above 1000 meters, exhibit characteristics of a moderately cold climate (D climate), while lower regions experience a moderately warm climate (C climate). Annual precipitation averages around 1100 mm in the western part of the basin, gradually decreasing downstream to approximately 650 mm in the eastern direction. Likewise, the average annual temperature ranges from approximately 6–7^0C in the western basin, increasing to around 10–11^0C in the eastern region.

2.2 Data and Methods

As previously mentioned, data on daily flows of the West Morava from the Jasika HS were utilized, and based on these data, average monthly, seasonal, and annual flows were computed. Throughout the entire time series, 3% of the data for mean daily flow were missing. To address this, missing data were estimated as the arithmetic mean of the daily flow values of the preceding and following days. Since the Jasika HS is nearest to the Kruševac MS (refer to Figure 1), mean monthly temperature and monthly precipitation data from that station were employed. These data were sourced from the Republic Hydrometeorological Institute of Serbia (RHMIS, 2024), covering the period from 1948 to 2023 for flow data, and from 1949 to 2023 for precipitation and temperature data. Temperature and precipitation data were employed to investigate their correlation with teleconnections, as they are meteorological variables exerting the most significant influence on river flow. The interrelation between the aforementioned hydroclimatic parameters (flow, precipitation, temperature) was explored using 15 indicators of atmospheric and oceanic variations (Table 1).

TABLE 1 Used indices of teleconnections with sources and based parameters.

Index	**Source**	**Unit**	**Institution^1**	**Period**
North Atlantic oscillation (NAO)	http://www.cru.uea.ac.uk/cru/data/nao/nao.dat	hPa	UAE-CRU	1949-2022
Summer North Atlantic Oscillation (SNAO)	https://climexp.knmi.nl/data/isnao_ncepncar.dat	hPa	UAE-CRU	1949-2023
Atlantic multirate oscillation (AMO)	https://www.esrl.noaa.gov/psd/data/correlation/amon.us.data	^{0}C	NOAA-ESRL	1949-2022
Arctic oscillation (AO)	https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii.table	hPa	NOAA-CPC	1950-2023
Mediterranean oscillation (MOI-1)	http://www.cru.uea.ac.uk/cru/data/moi/moi1output.dat	hPa	UAE-CRU	1949-2022
Mediterranean oscillation (MOI-2)	https://crudata.uea.ac.uk/cru/data/moi/moi2output.dat	hPa	UAE-CRU	1949-2022
Western Mediterran osc. (WeMO)	http://www.ub.edu/gc/documents/Web_WeMOi-2020.txt	hPa	UB-GC	1949-2020
El Niño-Southern Oscillation (ENSO-NINO3.4)	https://www.cpc.ncep.noaa.gov/data/indices/ersst5.nino.mth.91-20.ascii	^{0}C	NOAA-CPC	1949-2023
Southern Oscillation Index (SOI)	https://crudata.uea.ac.uk/cru/data/soi/soi_3dp.dat	hPa	UAE-CRU	1949-2022
East Atlantic oscillation (EA)	https://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/ea_index.tim	gpm	NOAA-CPC	1950-2023
East Atlantic-West Russian osc.(EAWR)	https://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/eawr_index.tim	gpm	NOAA-CPC	1950-2023
Scandinavian oscillation (SCAND)	https://ftp.HYPERLINK ”ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/scand_index.tim”cpc.ncep.NOAA.gov/wd52dg/data/indices/scand_index.tim	gpm	NOAA-CPC	1950-2023
Polar-Eurasian oscillation (POLEUR)	https://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/nao_index.tim	gpm	NOAA-CPC	1950-2023

North Atl. Osc. (NAO-500hPa)	HYPERLINK "ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/nao_-index.tim"https://ftp.cpc.ncep.NOAA.gov/wd52dg/data/indices/NAO_-index.tim	gpm	NOAA-CPC	1950-2023
North Sea-Caspian Pattern (NCP)	https://crudata.uea.ac.uk/cru/data/ncp/ncp.dat	gpm	UAE-CRU	1949-2005
^{1}hPa – Mean Sea Level Pressure (mb); gpm - geopotential; UAE–CRU: University of East Anglia – Climatic Research Unit; NOAA–ESRL (CPC): National Oceanic and Atmospheric Administration – Earth System Research Laboratory's (Climate Prediction Center); UB–GC: University of Barcelona-Climatology Group	^{1}hPa – Mean Sea Level Pressure (mb); gpm - geopotential; UAE–CRU: University of East Anglia – Climatic Research Unit; NOAA–ESRL (CPC): National Oceanic and Atmospheric Administration – Earth System Research Laboratory's (Climate Prediction Center); UB–GC: University of Barcelona-Climatology Group	^{1}hPa – Mean Sea Level Pressure (mb); gpm - geopotential; UAE–CRU: University of East Anglia – Climatic Research Unit; NOAA–ESRL (CPC): National Oceanic and Atmospheric Administration – Earth System Research Laboratory's (Climate Prediction Center); UB–GC: University of Barcelona-Climatology Group	^{1}hPa – Mean Sea Level Pressure (mb); gpm - geopotential; UAE–CRU: University of East Anglia – Climatic Research Unit; NOAA–ESRL (CPC): National Oceanic and Atmospheric Administration – Earth System Research Laboratory's (Climate Prediction Center); UB–GC: University of Barcelona-Climatology Group	^{1}hPa – Mean Sea Level Pressure (mb); gpm - geopotential; UAE–CRU: University of East Anglia – Climatic Research Unit; NOAA–ESRL (CPC): National Oceanic and Atmospheric Administration – Earth System Research Laboratory's (Climate Prediction Center); UB–GC: University of Barcelona-Climatology Group

In summary, each teleconnection is defined by an index, represented by a single number, indicating the distribution of pressure or oceanic water temperature over a broader area. AMO and ENSO are oceanic oscillations, while the others are atmospheric oscillations. Variability in atmospheric oscillations entails changes in the intensity and position of low and high-pressure systems, which exert stronger or weaker influences on weather conditions or climate element values. NAO pertains to atmospheric oscillation variations over the northern Atlantic, AO represents the polar vortex, MO and WeMO denote regional atmospheric circulation patterns over the Mediterranean and the western part of the basin, while AMO and ENSO refer to changes in sea surface temperatures in the Atlantic north of the equator and the tropical Pacific. The indices of all oscillations considered in this study are presented as standardized (normalized) deviations relative to their respective baseline periods. For oscillations related to variability in geopotential height at the 500-hPa level, the baseline period is 1981–2010, while for those teleconnections associated with changes in sea level pressure and sea surface temperature in the Atlantic and Pacific, the baseline periods vary – NAO uses 1950–2000, WeMO uses 1961–1990, etc. However, it's essential to note that the baseline period for standardizing deviations is entirely irrelevant when calculating the correlation coefficient because the coefficient's value remains consistent. Further details regarding these and other global and regional teleconnections can be found in the study by Burić and Stanojević (2020). To assess the relationship between monthly teleconnection values and hydroclimatic parameters, a straightforward Pearson's correlation coefficient was computed, and its significance was verified using the t-test at the 95% ($p < 0.05$) and 99% ($p < 0.01$) confidence levels.

For the study's purposes, various methods were employed, including trend analysis, standardized deviations, 10-year moving averages, the percentile method, and correlation analysis. Trend calculation and significance assessment were conducted using the non-parametric Sen's slope estimator and the Mann–Kendall test (Kendal, 1975, Hirsh & Slack, 1984) at significance levels of 99.9% ($p < 0.001$), 99% ($p < 0.01$), 95% ($p < 0.05$), and 90% ($p < 0.10$). Quantitative and qualitative evaluation of flow deviations compared to the corresponding normal were performed using standardized deviations (SD) and percentiles (PC) methods. The SD method was applied to monthly, seasonal, and annual values, while the PC method was utilized to determine the frequency of days with large (75th percentile) and small (25th percentile) flows, as well as very large (91st percentile) and very small (9th percentile) flows. Essentially, both methods categorize deviations for a given time unit (refer to Table 2), and their main advantage lies in their calculation based on the same empirical distribution, allowing for comparison of results across different regions worldwide.

TABLE 2 Categorization of flow anomalies based on standardized deviation (SD) and percentiles (PC).

Regime of flow	**Rannge of SD values**	**Rannge of PC values**
Extremely large water	> 3	> 98th percentile
Very big water	$2 - 3$	91-98th percentile
Big water	$1 - 2$	75-91th percentile
Normally	$-1 - 1$	25-75th percentile
A little water	$-1 - (-2)$	9-25th percentile
Very little water	$-2 - (-3)$	2-9th percentile
Extremely little water	< -3	< 2th percentile

It's worth noting that the 91st and 9th percentiles were selected because they consider somewhat more moderate extremes, allowing for the identification of potentially more hazardous phenomena within the observed time unit. The procedure involves initially calculating percentile thresholds separately for each month from a sample of all daily flows (1948–2023) for that particular month. For instance, when determining the threshold for the 91st (9th) percentile for the month of January, the number of days with flows above (below) the obtained threshold during the period 1949–2023 is counted. Consequently, four sets of time series were generated for the mentioned percentiles (9th, 25th, 75th, and 91st), with 12 time series formed for each month, totaling 48. Subsequently, trend analysis was conducted to observe the direction in which the annual and monthly number of days featuring high and low water levels, including those with significantly high or low water levels, is moving.

3. RESULTS

3.1 Average water flow pattern throughout the year

The average annual flow of the West Morava at the Jasika HS, observed from 1948 to 2023, is 105.1 m^3/s. The lowest average monthly flow occurs in September, at 43.1 m^3/s, while the highest is in March, at 187.2 m^3/s (Table 3). The flow regime of the West Morava river is primarily influenced by precipitation and temperature within its watershed. The watershed area of the West Morava exhibits a continental precipitation regime. June typically sees the highest rainfall, for example, with 76.6 mm recorded at the Kruševac MS, while February records the lowest, with 40.4 mm at the Kruševac MS. In January and February, precipitation often falls as snow, especially in the upper mountainous regions of the watershed, with low temperatures and minimal evaporation. March marks the snowmelt period, accompanied by increased rainfall compared to February, resulting in heightened runoff, hence the highest average water levels are typically observed in March. During the summer, temperatures are high (averaging around 21°C), leading to significant evaporation, coupled with increased water usage for irrigation and other human needs, resulting in the lowest average flow, typically observed in September. On a seasonal basis, the lowest flow occurs in autumn (57.4 m^3/s), while the highest occurs in spring (170.8 m^3/s).

TABLE 3 Average monthly and annual flow values (Q), standardized deviations (SD), coefficient of variation

(Cv), and coefficient of skewness (Cs) of the West Morava River at the Jasika Hydrological Station for the period 1948–2023.

Parameters	**Jan**	**Feb**	**Mar**	**Apr**
Q (m^3/s)	110.4	147.4	187.2	181.4
SD (m^3/s)	57.2	76.0	96.6	87.6
Cv (%)	51.9	51.5	51.1	48.8
Cs	0.89	0.93	0.96	0.74
Winter: Q = 119.5 m^3/s;	Winter: Q = 119.5 m^3/s;	Winter: Q = 119.5 m^3/s;	Spring: Q = 170.8 m^3/s;	Spring: Q =

On an annual basis, the normal fluctuation (SD) of the average flow of the West Morava at the Jasika HS is ±31.0 m^3/s. The largest fluctuation occurs in March, at 96.6 m^3/s, while the smallest SD is in September, at 26.3 m^3/s. Therefore, the greatest and smallest fluctuations are precisely in the months with the highest and lowest average flows. A more realistic picture of flow fluctuations is provided by the coefficient of variation (Cv), as this parameter represents the extent to which the standard deviation deviates from the average flow. According to Tošić and Crnogorac (2005), rivers are classified into four groups based on the value of Cv: Group I - rivers with low fluctuations (Cv <0.5), Group II - rivers with moderate fluctuations (0.51–0.65), Group III - rivers with higher fluctuations (0.65–0.80), and Group IV - rivers with large fluctuations (Cv >0.80). Based on these threshold values, the West Morava has low fluctuations in April, moderate fluctuations occur during December–March and in May, June, and September. In July, August, and November, the West Morava has higher fluctuations, while based on the Cv value for October (80.7%), it falls into the group of rivers with large fluctuations. This month (October) also shows pronounced asymmetry of fluctuations (Cs), with a coefficient of up to 3.46. Positive Cs values indicate a dominance of negative deviations. Therefore, comparing the regime of average monthly flows with the regime of precipitation and temperature (Figure 2), a certain non-parallelism is observed. The highest flow is recorded in March due to snow melting, rainfall, and minimal evaporation (relatively low temperatures), while the lowest flow is typically in September due to pronounced evapotranspiration during the summer and insufficient precipitation to replenish the water loss, partly caused by human needs (primarily for irrigation).

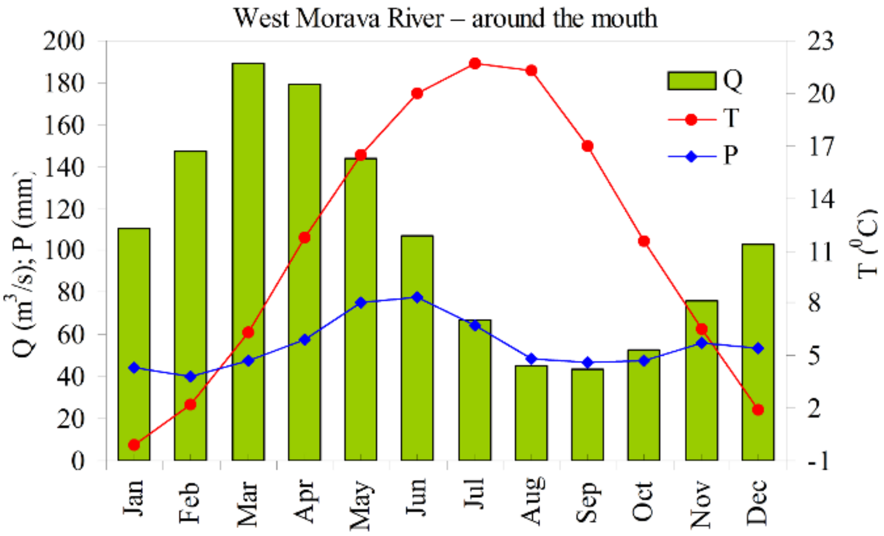

FIGURE 2 Average monthly values of flow (Q), precipitation (P) and temperature (T) at the HS Jasika (1949–2023).

3.2 The trend of mean flows

Based on the obtained results, the changes in the average flows of the West Morava at the HS Jasika profile are not significant throughout the period from 1948 to 2023, both on a monthly and annual as well as seasonal basis, statistically speaking. However, it should be noted that the flow values during seven months, as well as on an annual level, and particularly in winter, spring, and summer, exhibit a slight downward trend. To more precisely assess the changes in river flow at the mentioned profile, the 76-year period was divided into two concurrent periods of 38 years each (1948–1985 and 1986–2023). In the first half of the observed period, significant increases in average flow are observed in August, September, and December, while in the second half (1986–2023), only the month of May shows a significant positive trend (Table 4). In all other cases, the changes are insignificant.

TABLE 4 Trend and significance of average flows (Q) of West Morava, precipitation (P) and temperature (T).

Trend Q (m^3s^{-1}/decade)	**Trend Q (m^3s^{-1}/decade) 1948-2023**
Jan	-1.1
Feb	-1.6
Mar	2.7
Apr	-0.1
May	-3.1
Jun	-0.9
Jul	-1.0
Aug	1.4
Sep	1.1
Oct	0.7
Nov	-0.1
Dec	1.8
Year	-0.6
Winter	-0.7
Spring	-0.5
Summer	-0.4
Autumn	0.8
^{1}Signific.: *** $p < 0.001$**, $p < 0.01$, * $p < 0.05$ and $^{+}$ $p < 0.1$	^{1}Signific.: *** $p < 0.001$**, $p < 0.01$, * $p < 0.05$ and $^{+}$ p

When analyzing precipitation data from the vicinity of MS Kruševac, it is observed that changes are statistically insignificant, although a predominant positive trend is evident. Notably, only the month of March shows a significant increasing trend in precipitation (2.64 mm/decade). This underscores the initial indicator of the correlation between precipitation and flow: when precipitation changes are insignificant, flow changes tend to follow suit. Conversely, air temperature exhibits a consistent positive trend across all time intervals—months, seasons, and annually. Significant temperature increases are observed in February, March, May, throughout the summer months (June, July, and August), as well as seasonally in winter, spring, and summer, and annually. Essentially, the rise in evapotranspiration due to temperature escalation is offset by increased precipitation, resulting in no significant alterations in the average flow of the West Morava river overall. However, these assessments are based on average monthly, seasonal, and annual values. Thus, to gain a comprehensive understanding, it is imperative to examine the fluctuations in daily flows.

3.3 Categorization of mean flow deviations

The classification of average flows of the West Morava at the HS Jasika profile was conducted at monthly, seasonal, and annual levels using standardized deviations (SD). Normal fluctuations, falling between −1 and +1 SD, are considered within the expected range (Figure 3). Positive SD values indicate flows higher than the average, while negative values signify lower flows. Additionally, the method of 10-year moving averages with a one-year shift (step +1) was also applied to observe changes at the decadal level. This approach helps mitigate short-term fluctuations and identify potential decadal variations over a longer timeframe.

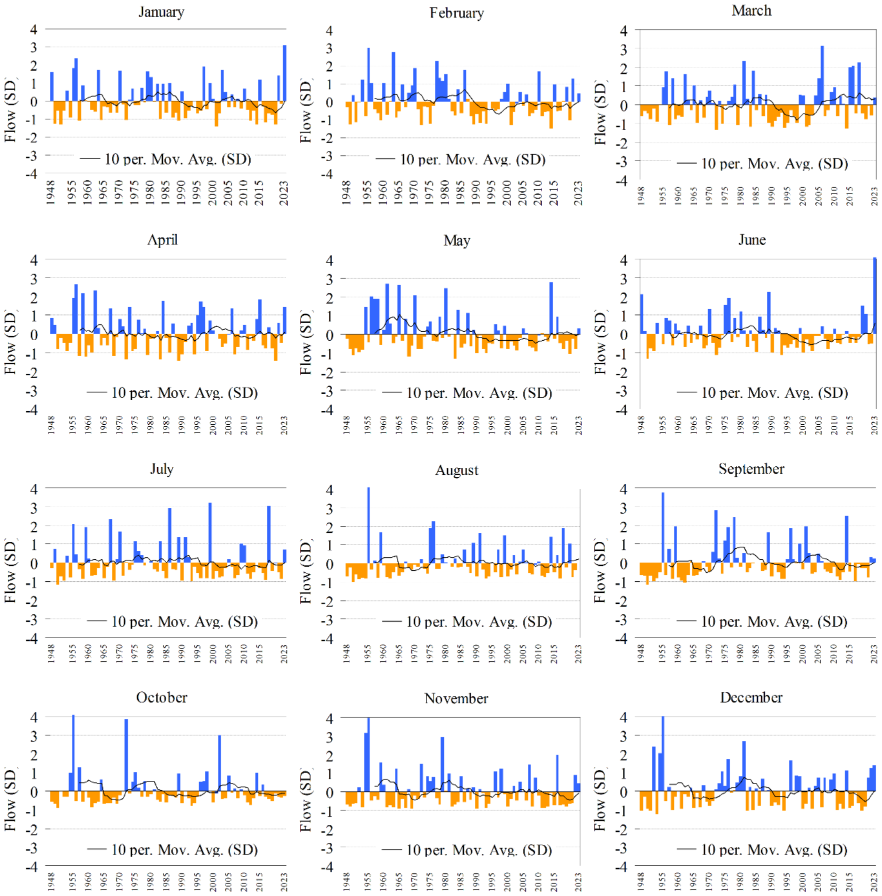

FIGURE 3 Monthly values of standardized deviations (SD) and 10-year moving averages of the West Morava flow on the HS Jasika profile (1948–2023).

Positive values of the asymmetry coefficient (Cs) were previously mentioned, indicating the prevalence of negative deviations. For instance, over the observed 76-year period (1948–2023), the average monthly flow in January experienced negative deviations 47 times, while in 29 years, the flow exceeded the normal value for this month. Normal deviations (± 1 SD) occurred in January for 52 years, representing 68.4% of cases. The average January flow fell into the high water category for 10 years (13.2% of cases), with only one instance (2.3%) classified as very high water. Extremely high waters (deviation $>$ 3 SD) were classified only once, specifically in January 2023. Conversely, there were 12 instances of January flows falling into the category of small waters, with no occurrences of very small waters. Notably, no January had a mean flow deviating $<$ –3 SD, indicating the absence of extremely large waters. Analyzed at the 10-year level, with a shift of +1, it is evident that the moving 10-year averages remained within the normal range, not exceeding ±1 SD. Similar observations can be made for other months as well.

Similar results were obtained at the seasonal and annual levels (Figure 4). For instance, over 41 years, the mean annual flow experienced negative deviations, while positive deviations were observed 35 times. Mean annual flow fell into the category of small waters for 10 years, while there were no occurrences of very small or extremely small flows in the observed 76-year period. The categories of large and very large flows were observed for 7 and 2 years, respectively, while an extremely large annual flow was recorded once (in 1955).

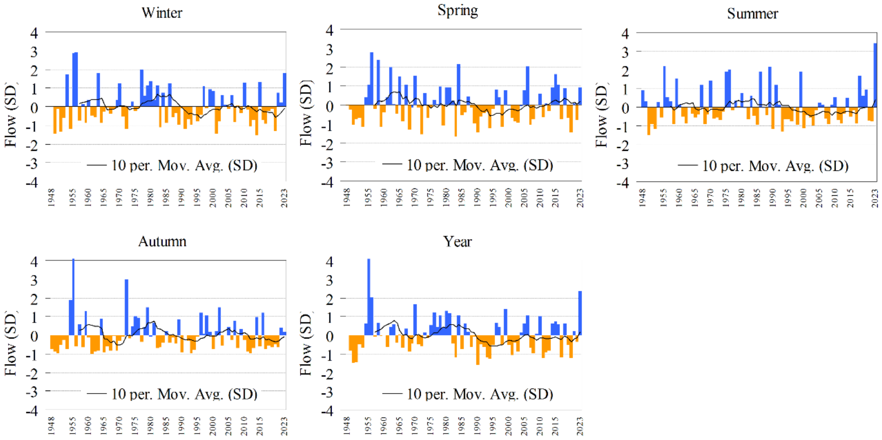

FIGURE 4 The seasonal and annual values of standardized deviations (SD) and 10-year moving averages of the West Morava flow on the HS Jasika profile for the period 1948–2023:

When examining all time units (months, seasons, and years), two common characteristics emerge. Firstly, over the analyzed 76-year period (1948–2023), there is an overwhelming prevalence of negative deviations, signifying that occurrences of low water levels are far more frequent, with no instances of very small or extremely small flows. Secondly, at least once or twice, flows classified as very large water were recorded across almost all time units, with nearly every category experiencing at least one instance of extremely large flow. Thus, the prevalence of "dry" flows, alongside those categorized as very large and extremely large waters, primarily suggests the influence of contemporary climate changes. To better understand this impact, further examination of daily flows is necessary.

3.4 Changes in daily flows

Based on the available data, the period of instrumental measurements at HS Jasika revealed notable extremes in the water regime of the West Morava. The absolute lowest flow recorded was a mere 14 m^3/s, documented on September 11, 2017, at 1:30 p.m. In contrast, the absolute maximum flow peaked at 2150 m^3/s, occurring three years earlier on May 14, 2014, at 1:00 a.m. This vast disparity illustrates an absolute fluctuation amplitude of 2136 m^3/s (Table 5), corresponding to a ratio of 1:154. Such a significant fluctuation amplitude underscores the torrential nature of the West Morava. To mitigate these extremes and ensure a more balanced flow, it is imperative to implement measures within the basin to enhance the river's suitability for various water management purposes.

TABLE 5 The absolute maximum and minimum flows of the West Morava river at the HS Jasika profile for the period 1948–2023

Flow (m^3/s)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Aps. max	1060.0	1061.0	1300.0	911.0	2150.0	1330.0	759.0	497.0	357.0	425.0	1120.0	670.0
Aps. min	15.5	24.0	29.4	36.4	22.5	22.5	16.0	14.3	14.0	16.0	15.0	15.3
Amplituda	1044.5	1036.0	1270.6	874.6	2127.5	1307.5	743.0	482.7	343.0	409.0	1105.0	654.7

Based on the average daily flows (Qd) for the period 1948–2023, four percentile indices (thresholds) were calculated for each month separately: 9th, 25th, 75th, and 91st (Table 6). Subsequently, the number of days with flows above the 75th and 91st percentiles, as well as below the 9th and 25th percentiles, was calculated. Days with daily flows below the 25th and 9th percentiles were labeled as dry (low water) and very dry (very low water), while days with daily flows above the 75th and 91st percentiles were defined as wet (high water) and very wet days (very high water). Finally, the annual number of these days was summarized, the trend was calculated, and its significance was examined.

TABLE 6 Average values of percentile thresholds based on daily flows of the West Morava at the HS Jasika profile for the period 1948–2023: low water (Qd $<$ 9th), very low water (Qd $<$ 25th), high water (Qd $>$ 75th), and very high water (Qd $>$ 91st) percentiles.

Percentile (m^3/s)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Qd9th	38.0	48.7	68.4	62.2	51.8	40.4	23.8	18.1	18.9	22.0	25.9	32.6
Qd25th	57.8	76.6	98.0	95.8	75.4	56.0	32.4	24.5	24.9	28.0	32.0	41.3
Qd75th	134.0	179.0	236.0	228.0	162.0	122.3	77.5	50.2	46.0	55.1	81.1	134.0
Qd91th	216.0	295.1	376.0	355.0	270.0	205.8	138.0	81.8	80.0	101.0	173.0	208.0

The trend analysis showed a decrease in the annual number of all observed days. During the period 1948–2023, the most intense decrease was observed in the days with low waters: Qd25th = –5.5 days per decade (Figure 5). The results of statistical significance indicate that the trend rates are insignificant for all four indicators. However, under the conditions of contemporary climate change, it was not expected that the annual number of days with low, very low, high, and very high waters would decrease; quite the opposite.

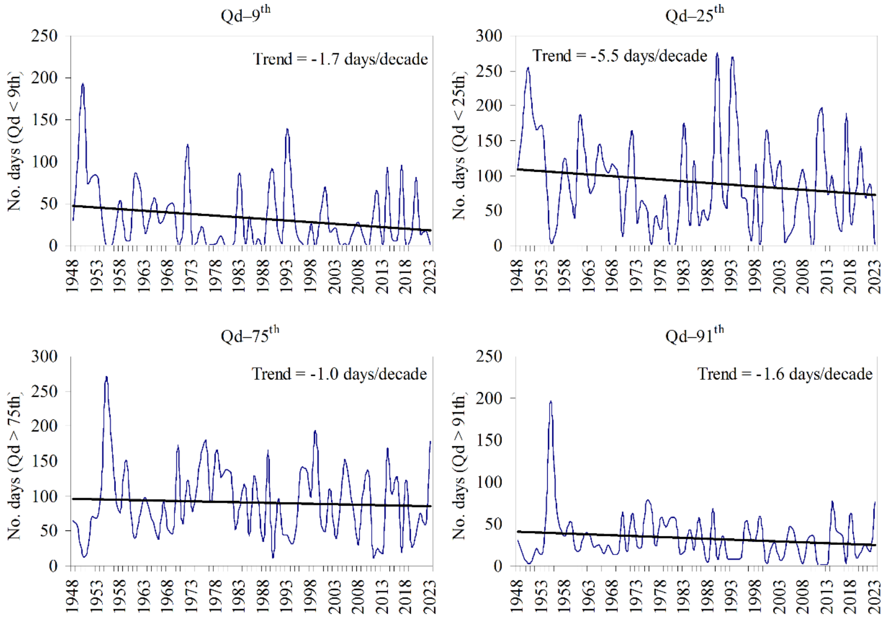

FIGURE 5 The trend of the annual number of days with low, very low, high, and very high waters (9th, 25th, 75th, and 91st), West Morava, HS Jasika profile (1948–2023).

In order to more precisely determine the changes in flow, trend calculations were performed for each month separately. In this case, too, the changes were negligible, as the trend value for all four percentile indices at the monthly level did not exceed ±0.3 days per decade. However, it should be noted that the number of days increases with: very low waters (Qd9th) in January, March, and April, low waters (Qd25th) in January and June, high waters (Q75th) in March, August, September, October, and December, and very high waters (Qd91st) in March and June. Regardless of the insignificance of the changes, it should be emphasized that the increase in the number of moderately extreme cases in these months is not favorable for the environment.

To better discern the potential impact of climate change on the fluctuations of the West Morava flow, trend calculations were conducted for the recent portion of the 21st century, specifically for the period 2001–2023.

The findings from the 23-year observation period revealed a trend of increasing days with very high water (Qd91th) at a rate of 7.7 days per decade (Figure 6), meeting significance conditions at the $p < 0.1$ level (90% confidence level). Statistically insignificant changes were observed for the other three percentile indices.

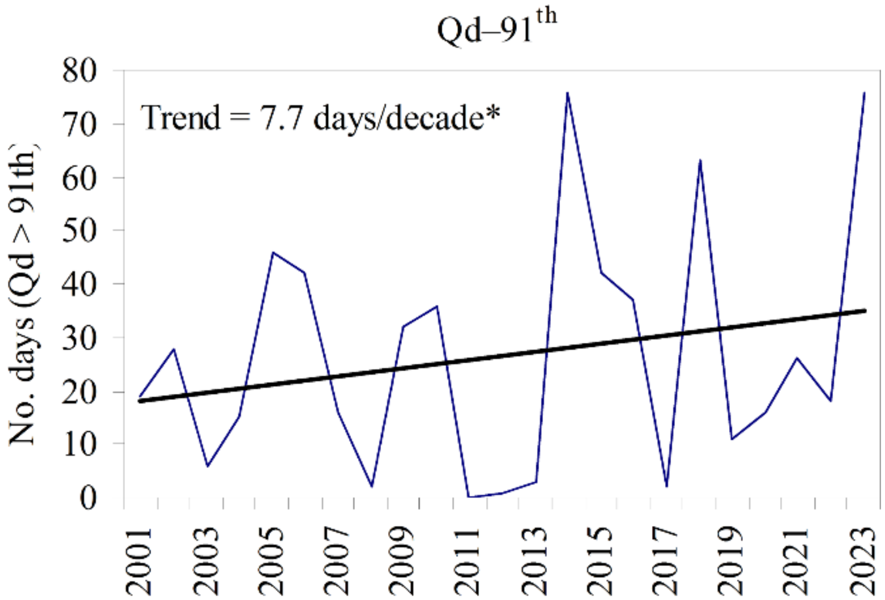

FIGURE 6 The trend in the annual count of days with very high water (91st percentile) for the period 2001–2023, observed at the HS Jasika profile of the West Morava river (* $p < 0.05$).

Similarly, for the same period (2001–2023), insignificant changes were observed in the percentile indices at the monthly level (Table 7), but it is notable that a greater number of months exhibit a positive tendency. The positive trend is most prominent in Qd91th and Qd9th, indicating an increase in extreme cases – the number of days with very high waters and very low waters is increasing.

TABLE 7 Monthly trend analysis of the occurrence of days with small, very small, large, and very large water flows (9th, 25th, 75th, and 91st percentiles) at the HS Jasika profile on the West Morava River (2021-2023).

Trend Q (No. days/decade)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Qd<9th	0.5	-1.1	-2.8	2.1	0.4	-1.7	1.7	1.4	1.9	0.8	-0.5	0.5
Qd<25th	0.1	-2.2	-3.2	2.3	-1.1	-2.3	-0.9	2.7	1.5	0.1	3.3	0.3
Qd>75th	-1.0	2.6	0.2	2.4	0.8	3.1	2.4	-0.3	-2.4	-4.2	-2.9	2.0
Qd>91th	1.5	0.1	-0.1	0.9	0.2	3.7	1.7	0.2	0.1	-2.6	0.9	1.4

3.5. Possible causes of variability in flow (Q), precipitation (P) and temperature (T)

Variations in atmospheric and oceanic oscillations play a crucial role in shaping weather and climate patterns (Sheridan and Lee, 2012). As previously noted, river flow is influenced by precipitation and temperature. In this specific context, the correlation between river flow (Q) and temperature (T) is statistically insignificant only during the period from November to January. In all other months, especially from May to September, significant correlations are observed, with coefficient values ranging from 0.40 to 0.52. On the other hand, the correlation between river flow (Q) and precipitation (P) is significant throughout all months, with correlation coefficients reaching up to 0.74 during spring, summer, and autumn. Regarding the connection with teleconnections, the analysis revealed that the North Atlantic Oscillation (NAO) pattern at sea level (NAO-slp) exhibits a significant relationship with all three hydroclimatic parameters (Q, P, and T) in January, February, and March. In September, the connection is significant with river flow (Q) and precipitation (P), while in June and July, it is significant with temperature (T). In December, a significant connection is observed only with river flow (Q). However, for the months of April, May, and August, none of the considered parameters show statistical significance with NAO-slp. Qualitatively similar results were obtained for NAO-500 (Table 8).

Also, the summer variant of NAO (SNAO) in January shows a significant connection with all three parameters. The SNAO index is defined to better identify the influence of NAO in the summer months, as the calculations have shown, resulting in a stronger correlation with two out of three parameters compared to NAO. Correlation coefficient calculations have shown statistically significant results for AMO only with T in the three summer months and in November, at the 99% ($p < 0.01$) and 95% ($p < 0.05$) significance levels, respectively. ENSO was considered through two indicators, NINO3.4 and SOI, but of all teleconnections, this phenomenon showed the weakest influence on the three hydroclimatic parameters. Namely, correlation coefficient values satisfy significance conditions only in November and December with T (NINO3.4 and SOI) and in December with Q (NINO3.4). On the other hand, the influence of NCP is present in January and February on all three hydroclimatic parameters, and in July, August, October, and December on two each. EA showed the strongest connection with T, especially in February, April, and August, with correlation coefficients ranging from 0.61 to 0.71. Oscillations over the Mediterranean basin (MOI-1, MOI-2, and WeMO) mostly influence some of the considered parameters in winter, and similar results were obtained for EAWR. The influence of the SCAND pattern is mostly felt on T, as well as POLEUR, but the influence of POLEUR is only present in February, July, and November.

TABLE 8 Correlation coefficients between the index of teleconnections and monthly flows (Q), temperature (T) and precipitation (P) according to data from HS Jasika and MS Kruševac.

Teleconnection	**Parameter**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**N**
NAO-slp (1949-2023)	Q	-0.36**	-0.42**	-0.29*						-0.27*		
	T	0.26*	0.32*	0.33**			-0.30*	-0.34**				
	P	-0.26*	-0.50**	-0.33**						-0.39**		
SNAO (1949-2023)	Q	-0.25*							0.36**	0.25*		
	T	-0.45**	-0.71**	-0.27*	-0.52**		-0.44**	-0.35**	-0.40**	-0.41**	-0.50**	- 0
	P	-0.28*		-0.29*			0.34**	0.26*				
AMO (1949-2022)	Q											
	T						0.41**	0.52**	0.37**			0
	P											
AO (1950-2023)	Q	-0.36**	-0.47**	-0.31*				0.25*	0.25*			- 0
	T			0.31*								
	P	-0.45**	-0.47**							-0.33**	-0.27*	- 0
MOI-1	Q	-0.31*	-0.36**							-0.28*		
	T				-0.27*							- 0

(1949-2022)	P		-0.36**	-0.29*				-0.30*		-0.36**		
	Q	-0.30*	-0.33**							-0.31*		
MOI-2	T					0.38**						
(1949-2022)	P		-0.28*							-0.32*		
	Q											
WeMO	T	0.26*	0.39**								0.32*	0
(1949-2020)	P	0.43**										
	Q	-0.32*	-0.47**					0.36**	0.36**			
NCP	T	-0.27*	-0.48**		-0.44**				-0.38**	-0.29*	-0.45**	-0
(1949-2005)	P	-0.60**	-0.36**	-0.41**				0.38**			-0.51**	
ENSO	Q											
(NINO3.4)	T											0
(1949-2023)	P											
	Q											
SOI	T											
(1949-2022)	P											
	Q						-0.31*			-0.27*		
EA	T	0.43**	0.71**	0.32*	0.61**	0.51**	0.39**	0.47**	0.61**	0.42**		0
(1950-2023)	P					-0.30*	-0.32*			-0.35**	-0.25*	
	Q											
EAWR	T	-0.43**	-0.27*							-0.25*	-0.33**	
(1950-2023)	P	-0.36**	-0.38**								-0.33**	
	Q								0.25*			
SCAND	T		-0.36**	-0.36**	0.25*		-0.34**		-0.37**			0
(1950-2023)	P						0.27*	0.26*		0.25*		
	Q											
POLEUR	T		-0.31*					0.26*				0
(1950-2023)	P										-0.37**	
	Q	-0.25*	-0.44**	-0.38**					0.29*			
NAO-500	T	0.29*		0.29*			-0.30*	-0.29*			-0.30*	-0

(1950-2023)	P	-0.25*	-0.34**	-0.25*			0.25*					
* $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	** $p < 0.01$, * $p < 0.05$	* < 0 * < 0

4. DISCUSSION AND CONCLUSIONS

The Earth's climate system is intricate and ever-changing, with its primary driver being the hydrological cycle (Wu et al., 2013). The detrimental effects of climate change on water resources are being witnessed globally. Evidence of global warming is undeniable (Burić & Penjišević, 2023), leading to diminished water supplies due to rising temperatures and alterations in precipitation patterns. Concurrently, heightened anthropogenic activities and more frequent, intense rainfall exacerbate water quality issues and elevate the risk of flooding. These shifts, alongside other phenomena like droughts, heatwaves, and heavy precipitation events, pose significant challenges to human livelihoods, public health, and ecosystems. Projections suggest that water resources will face even greater pressures from climate change and human activities in the future compared to the present (van Vliet et al., 2023). The demand for clean water is escalating, yet the availability is diminishing. Therefore, preserving the world's water resources stands as the foremost imperative for both present and future generations. However, freshwater reservoirs face vulnerabilities not only from climate change but also from direct human interventions and the expanding global population (Vörösmarty et al., 2000). Wang et al. (2024) examined alterations in average monthly river flows across 10,120 hydrological stations spanning from 1965 to 2014. Their findings revealed that climate change is disrupting seasonal flow patterns, particularly in the higher latitudes of America, Russia, and Europe. The authors contend that the escalating air temperatures are fundamentally altering natural river flow patterns. Their research reveals a troubling decline in seasonal flows across most rivers, directly linked to anthropogenic greenhouse gas emissions. Ultimately, they conclude that continued temperature increases could lead to a permanent and significant reduction in seasonal flows. Nevertheless, uncertainties persist regarding the impact of global warming on precipitation patterns and consequent river flow changes. While some regions experience increased precipitation and river flow, others witness decreases, with some areas facing alternating floods and droughts (Koutroulis et al., 2018). Predictions through 2050 indicate a 10–40% runoff increase in eastern equatorial Africa, the La Plata basin, and higher latitudes of Eurasia and North America. Conversely, southern parts of Africa and Europe, alongside the Middle East and mid-latitudes in western North America, are anticipated to see a runoff reduction of 10–30% (Milly et al., 2005).

The impact of anthropogenic climate change on hydroclimate has been extensively documented in numerous studies (e.g. Andualem et al., 2020; Sharma et al., 2020; Daba et al., 2020; Nikzad Tehrani et al., 2020; Malede et al., 2024). It is widely believed that global warming accelerates the hydrological cycle, leading to increased water evaporation (resulting in more water vapor in the atmosphere) and altering precipitation patterns (Chen & Grasby, 2014). However, when considering the drivers of contemporary climate changes, it is imperative to account for the influence of natural factors, such as fluctuations in solar activity, volcanic eruptions, and variations in atmospheric and oceanic oscillations. For instance, research has established connections between the flow of major rivers that discharge into the Arctic Ocean (such as the Mackenzie, Ob, Lena, and Yenisei rivers) and phenomena like ENSO, AO, NAO, and the Pacific Decadal Oscillation (PDO) (Ahmed et al., 2021). Additionally, other studies have demonstrated the relationships between hydroclimatic parameters and teleconnections (e.g. Xiao et al., 2014; Shi et al., 2021).

In the context of Serbia, it is important to emphasize the significant economic, social, and ecological value of the catchment area of the West Morava River. This region holds particular importance for the country due to its abundance of renewable domestic freshwater resources, with the majority located within the catchment of this river. Previous research conducted for the periods 1965–2014 (Langović et al., 2017) and 1961–2015 (Milanović–Pešić, 2020) indicated an insignificant trend of decreasing annual flows in the West Morava. Despite its strategic water resources, Serbia ranks among the countries with lower water availability in Europe, with an average of around 1700 m^3 per inhabitant per year (Dašić et al., 2020). Given these circumstances, this study aimed to analyze changes in the flow of the West Morava River based on data from HS Jasika, situated near the confluence of the West Morava with the South Morava, where the Velika Morava begins. Furthermore, the study aimed to explore the potential impact of various teleconnections on hydroclimatic changes in the observed area.

An in-depth examination of the flow patterns of the West Morava at the HS Jasika profile spanning from 1948 to 2023 reveals significant fluctuations across all temporal scales (monthly, seasonal, yearly), indicating the river's torrential nature. While the trends in monthly, seasonal, and annual flows are deemed statistically insignificant, it is noteworthy that a prevailing negative trend persists, aligning with previous studies (Langović et al., 2017, Milanović–Pešić, 2020). However, during the latter half of the observed period (1986–2023), there is evidence of an increasing trend in mean annual and seasonal flows, except for autumn, where a negative trend is observed. Throughout the 76-year duration under scrutiny (1948–2023), negative standardized deviations dominate (>50% of occurrences), signifying a higher frequency of low-flow episodes.

Upon examining mean daily flows, it was observed that the annual count of observed days is declining, contrary to expectations. However, there is an increase in the monthly count of days exhibiting various characteristics: very low water (Qd9th) in January, March, and April; low water (Qd25th) in January and June; high water (Q75th) in March, August, September, October, and December; and very high water (Qd91th) in March and June. Notably, in the recent period (2001-2023), there has been a significant increase in the annual count of days with very high water (Qd91th). These findings suggest a slight trend towards drier conditions in flow patterns, alongside an uptick in the number of days featuring very high water, indicating the influence of climate change. This underscores the concern that such fluctuations are unfavorable for the environment.

Indeed, hydroclimatic variables are influenced by changes in atmospheric and oceanic oscillations, and some studies suggest that climate change also impacts teleconnections (e.g., Gillett et al., 2003; Cohen & Barlow, 2005; Rind et al., 2005; Givati et al., 2013). The findings of this study reveal that NAO and NCP exert an influence on the fluctuations of flow, precipitation, and air temperature (Q, P, and T) in the observed area, particularly during colder months. Additionally, all three hydroclimatic parameters show a connection with SNAO, albeit only in the summer months. The AMO significantly affects T during the summer months overall. ENSO indicators suggest an influence on T only in November and December. EA variability has a statistically significant effect on T in February, April, and August, with correlation coefficients ranging between 0.61 and 0.71. Indicators of atmospheric oscillations over the Mediterranean (MO and WeMO), as well as EAWR, exhibit a significant correlation with the hydroclimate of the analyzed location, primarily during winter. The impact of SCAND and POLEUR oscillations is noticeable only on T.

Based on the findings, it is evident that there is currently little to moderate concern regarding the hydroclimatic conditions. However, there is significant cause for concern regarding the future, given the accelerating pace of climate change. Therefore, it is imperative to proactively develop plans for flow equalization and sustainable water resource management in the West Morava basin. Additionally, measures for both mitigating and adapting to present and, more importantly, future climate changes need to be defined and implemented promptly.

ACKNOWLEDGEMENTS

The study was supported by the Ministry of Science, Technological Development and Innovation of Republic of Serbia (451-03-65/2024-03/200123)

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Ahmed, R., Prowse T., Dibike, Y. & Bonsal, B. (2021). Effects of Climatic Drivers and Teleconnections on Late 20th Century Trends in Spring Freshet of Four Major Arctic–Draining Rivers. *Water,13* (2), 179.*https://doi.org/10.3390/w13020179*

Andualem, T. G., Malede, D. A. & Ejigu, M. T. (2020). Performance evaluation of integrated multi–satellite retrieval for global precipitation measurement products over Gilgel Abay watershed, upper Blue Nile basin, Ethiopia. *Modeling Earth Systems and Environment* , *6,* 1853–1861.*https://doi.org/10.1007/s40808-020-00795-w*

Burić, D. & Stanojević, G. (2020). Trends and possible causes of cloudiness variability in Montenegro in the period 1961–2017.*Climate Research,* 81, 187–205.*https://doi.org/10.3354/cr01615*

Burić, D. & Penjišević, I. (2023). Southern Hemisphere temperature trend in association with greenhouse gases, El Niño Southern Oscillation, and Antarctic Oscillation. *IDOJARAS, 127* (1), 23–42. http://doi.org/10.28974/idojaras.2023.1.2

Chen, Z. & Grasby, S. E. (2014). Reconstructing river discharge trends from climate variables and prediction of future trends. *Journal of Hydrology, 511* (16), 267–278.*https://doi.org/10.1016/j.jhydrol.2014.01.049*

Cohen, J. & Barlow, M. (2005). The NAO, the AO, and Global Warming: How Closely Related?. *Journal of Climate* , *18,* 4498–4513.*https://doi.org/10.1175/JCLI3530.1*

Daba, M.H., Ayele, G.T. & You, S. (2020). Long– term homogeneity and trends of hydroclimatic variables in the upper Awash River basin, Ethiopia. *Advances in Meteorology* , *2020,*8861959.*https://doi.org/10.1155/2020/8861959*

Dašić, T., Đorđević, B. & Plavšić, J. (2020). Water Management in Climate Change Conditions. *Zbornik radova VODA 2020, Trebinje, 2020,* 1–8.*https://hdl.handle.net/21.15107/rcub_ grafar_ 2534*

Givati, A. & Rosenfeld, D. (2013). The Arctic Oscillation, climate change and the effects on precipitation in Israel. *Atmospheric Research* , *132 − 133,* 114– 124.*https://doi.org/10.1016/j.atmosres.2013.05.001*

Gillett, N. P., Graf, H. F. & Osborn, T. J. (2003). Climate Change and the North Atlantic Oscillation. *Geophysical Monograph Series* ,*134* , 193– 209.*https://doi.org/10.1029/134GM09*

Gavrilović, Lj. & Dukić, D. (2002). *Reke Srbije* . Zavod za udzbenike i nastavna sredstva, Beograd (eng. Rivers of Serbia. Institute for textbooks and teaching aids, Belgrade).

Gulan, Lj., Penjišević, I., Stajić, M. J., Milenković, B., Zeremski, T., Stevanović, V. & Valjarević, A. (2020). Spa environments in central Serbia: Geothermal potential, radioactivity, heavy metals and PAHs.*Chemosphere, 24,*125171.https://doi.org/10.1016/j.chemosphere.2019.125171

Hernández–Henríquez, M. A., Sharma, A. R. & Déry, S. J. (2017). Variability and trends in runoff in the rivers of British Columbia's Coast and Insular Mountains. *Hydrological Processes, 31,*3269–3282. https://doi.org/10.1002/hyp.11257

Hirsch, R. M. & Slack, J. R. (1984). A nonparametric trend test for seasonal data with serial dependence. *Water Resources Research* , 20(6), 727–732. https://doi.org/10.1029/WR020i006p00727

Hu, D., Xu, M., Kang, S., Chen, J., Yang, C. & Yang, Q. (2023). The Effects of Discharge Changes in Siberian Rivers on Arctic Sea–Ice Melting. *Remote Sensing, 15* , 3477.*https://doi.org/10.3390/rs15143477*

Kalugin, A. (2023). Climate Change Effects on River Flow in Eastern Europe: Arctic Rivers vs. Southern Rivers. *Climate* , *11* , 103.*https://doi.org/10.3390/cli11050103*

Kendall M. G. (1975) Rank Correlation Methods. Charles Griffin, London

Koutroulis, A. G., Papadimitriou, L. V., Grillakis, M. G., Tsanis, I. K., Wyser, K., Caesar, J. & Betts, R. A. (2018). Simulating Hydrological Impacts under Climate Change: Implications from Methodological Differences of a Pan European Assessment. *Water* , *10* , 1331.*https://doi.org/10.3390/w10101331*

Komatina, D. & Grošelj, S. (2015). Transboundary Water Cooperation for Sustainable Development of the Sava River Basin. In: Milačič, R., Ščančar, J., Paunović, M. (eds) The Sava River. The Handbook of Environmental Chemistry, 31, 1–25, Springer, Berlin, Heidelberg.*https://doi.org/10.1007/978-3-662-44034-6_1*

Kwadijk, J., Arnell, N. W., Mudersbach, C., de Weerd, M., Kroon, A. & Quante, M. (2016). Recent Change—River Flow. In: Quante, M., Colijn, F. (eds) North Sea Region Climate Change Assessment. Regional Climate Studies. Springer, Cham, 137–146.*https://doi.org/10.1007/978-3-319-39745-0_4*

Langović, M., Manojlović, S. & Čvorović, Z. (2017). Trends of mean annual river discharges in the West Morava river basin. *Bulletin of the Serbian Geographical Society* , *97* (2), 19–45.*https://doi.org/10.2298/GSGD1702019L*

Langović, M., Dragićević, S. & Živković, N. (2022). Determination of Discharge Cycles of the South Morava River (Serbia). *International Scientific Conference GEOBALCANICA* , 45–57.*https://doi.org/10.18509/GBP22045l*

Lukić, T., Dunjić, J., Đerčan, B., Penjišević, I., Milosavljević, S., Bubalo-Živković, M. & Solarević, M. (2018). Local Resilience to Natural Hazards in Serbia. Case Study: The West Morava River Valley.*Sustainability, 10* (8), 2866. http://www.mdpi.com/2071-1050/10/8/2866

Lutz, S. R., Mallucci, S., Diamantini, E., Majone, B., Bellin, A. & Merz, R. (2016). Hydroclimatic and water quality trends across three Mediterranean river basins. *Science of The Total Environment, 571* , 1392–1406.*https://doi.org/10.1016/j.scitotenv.2016.07.102*

Mankin, J. S., Viviroli, D., Singh, D., Hoekstra, A. Y. & Diffenbaugh, N. S. (2015). The potential for snow to supply human water demand in the present and future. *Environmental Research Letters, 10* , 114016.*https://doi.org/10.1088/1748-9326/10/11/114016*

Malede, D. A., Andualem, T. G., Yibeltal, M., Alamirew, T., Kassie, A. E., Demeke, G. G. & Mekonnen, Y. G. (2024). Climate change impacts on hydroclimatic variables over Awash basin, Ethiopia: a systematic review. *Discover Applied Sciences, 6* , 27.*https://doi.org/10.1007/s42452-024-05640-8*

Merz, B., Vorogushyn, S., Uhlemann, S., Delgado, J. & Hundecha, Y. (2012). HESS Opinions "More efforts and scientific rigour are needed to attribute trends in flood time series". *Hydrology and Earth System Sciences, 16* , 1379–1387.*https://doi.org/10.5194/hess-16-1379-2012*

Matti, B., Dahlke, H. E., Dieppois, B., Lawler, D. M. & Lyon, S.W. (2017). Flood seasonality across Scandinavia – Evidence of a shifting hydrograph?. *Hydrological Processes, 31* , 4354–4370, https://doi.org/10.1002/hyp.11365

Martić–Bursać, N. M., Radovanović, M. M., Radivojević, A. R., Ivanović, R. D., Stričević, Lj. S., Gocić, M. J., Golubović, N. M. & Bursać, B. L. (2022). Observed climate changes in the Toplica river valley – Trend analysis of temperature, precipitation and river discharge.*IDŐJÁRÁS, 126* (3), 403–423.*HYPERLINK "https://doi.org/10.28974/idojaras.2022.3.8"http://doi.org/HYPERLINK "https://doi.org/10.28974/idojaras.2022.3.8"10.28974/idojaras.2022.3.8*

Milly, P., Dunne, K. & Vecchia, A. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature, 438* , 347–350.*https://doi.org/10.1038/nature04312*

Milanović–Pešić, A. (2020). Water Regime and Discharges Trends of the Rivers in the Šumadija Region (Serbia). Conference: International Scientific Symposium "New Trends in Geography" At: Ohrid, North Macedonia. PROCEEDINGS, 3–13.*https://www.researchgate.net/publication/340237441*

Milosavljević, S., Penjišević, I. & Lukić, T. (2023). Hypsometrical distribution of settlements as a factor of regional differentiation of the gender-age structure of the populaion of West Morava valley.*Bulletin of the Serbian Geographical Society, 103* (1), 1–26.*https://doi.org/10.2298/GSGD2301001M*

Nikzad Tehrani, E., Sahour, H. & Booij, M. J. (2019). Trend analysis of hydro–climatic variables in the north of Iran. *Theoretical and Applied Climatology, 136,* 85–97.*https://doi.org/10.1007/s00704-018-2470-0*

Orešić, D., Čanjevac, I. & Maradin, M. (2017). Changes in discharge regimes in the middle course of the Sava River in the 1931–2010 period.*Prace Geograficzne, 151* , 93–119.*https://doi.org/10.4467/20833113PG.17.024.8036*

Papadaki, C. & Dimitriou, E. (2021). River Flow Alterations Caused by Intense Anthropogenic Uses and Future Climate Variability Implications in the Balkans. *Hydrology, 8* (1), 7.*https://doi.org/10.3390/hydrology8010007*

Pekarova, P., Gorbachova, L., Bacová Mitkova, V., Pekar, J. & Miklanek, P. (2018). Statistical Analysis of Hydrological Regime of the Danube River at Ceatal Izmail Station. IOP Conference Series: Earth and Environmental Science, World Multidisciplinary Earth Sciences Symposium (WMESS 2018) 3–7 September 2018, Prague, Czech Republic, *221,*012035.*https://doi.org/10.1088/1755-1315/221/1/012035*

Penjišević, I. (2022). *Zapadno Pomoravlje – regionalni razvoj. Istorijski institut, Kraljevo, Srbija* (eng. Western Pomoravlje - regional development. Institute of History, Kraljevo, Serbia).

Pratap, S. & Markonis, Y. (2022). The response of the hydrological cycle to temperature changes in recent and distant climatic history. *Progress in Earth and Planetary Science, 9,* 30.*https://doi.org/10.1186/s40645-022-00489-0*

Probst, E. & Mauser, W. (2023). Climate Change Impacts on Water Resources in the Danube River Basin: A Hydrological Modelling Study Using EURO–CORDEX Climate Scenarios. *Water, 15* (1), 8.*https://doi.org/10.3390/w15010008*

Rawlins, M., Yang, D. & Ge, S. (2021). Regional and Basin Streamflow Regimes and Changes: Climate Impact and Human Effect. In: Yang, D., Kane, D.L. (eds), *Arctic Hydrology, Permafrost and Ecosystems,*159–186. *https://doi.org/10.1007/978-3-030-50930-9_6*

RHMIS (2024). Hydrological and Meteorological Yearbooks, Belgrade.*https://www.hidmet.gov.rs/data/*

Rind, D., Perlwitz, J., Lonergan, P. & Lerner, J. (2005). AO/NAO response to climate change: 2. Relative importance of low– and high– latitude temperature changes. *Journal of Geophysical Research: Atmospheres, 110* (12), D12108.*https://doi.org/10.1029/2004JD005686*

Singh, S., Kumar, R., Bhardwaj, A., Sam, L., Shekhar, M., Singh, A., Kumar, R. & Gupta, A. (2016). Changing climate and glacio–hydrology in Indian Himalayan Region: A review. *WIREs Climate Change, 7,*393–410. https://doi.org/10.1002/wcc.393

Simić, Z. & Matic, B. B. (2017). Low flow conditions evaluation within the western Morava river basin. *European Water* , 60, 293–298.*https://www.ewra.net/ew/pdf/EW_2017_60_40.pdf*

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., van Lanen, H. A. J., Sauquet, E., Demuth, S., Fendekova, M. & Jódar, J. (2010). Streamflow trends in Europe: evidence from a dataset of near–natural catchments. *Hydrology and Earth System Sciences, 14* , 2367–2382.*httpsHYPERLINK "https://doi.org/10.5194/hess-14-2367-2010"://HYPERLINK "https://doi.org/10.5194/hess-14-2367-2010"doiHYPERLINK "https://doi.org/10.5194/hess-14-2367-2010".HYPERLINK* *"https://doi.org/10.5194/hess-14-2367-2010"orgHYPERLINK "https://doi.org/10.5194/hess-14-2367-2010"/10.5194/HYPERLINK "https://doi.org/10.5194/hess-14-2367-2010"hessHYPERLINK "https://doi.org/10.5194/hess-14-2367-2010"-14-2367-2010*

Stahl, K., Tallaksen, L. M., Hannaford, J. & van Lanen, H. A. J. (2012). Filling the white space on maps of European runoff trends: estimates from a multi–model ensemble. *Hydrology and Earth System Sciences, 16,* 2035–2047.*httpsHYPERLINK "https://doi.org/10.5194/hess-16-2035-2012"://HYPERLINK "https://doi.org/10.5194/hess-16-2035-2012"doiHYPERLINK "https://doi.org/10.5194/hess-16-2035-2012".HYPERLINK "https://doi.org/10.5194/hess-16-2035-2012"orgHYPERLINK "https://doi.org/10.5194/hess-16-2035-2012"/10.5194/HYPERLINK "https://doi.org/10.5194/hess-16-2035-2012"hessHYPERLINK "https://doi.org/10.5194/hess-16-2035-2012"-16-2035-2012*

Stojković, M., Plavšić, J. & Prohaska, S. (2014). Long–term changes of annual and seasonal flows: A case of the Sava River. *Vodoprivreda, 46,* 39–48.*https://grafar.grf.bg.ac.rs/handle/123456789/572*

Stoffel, M., Wyżga, B. & Marston, R. A. (2016). Floods in mountain environments: A synthesis. *Geomorphology, 272* , 1–9. https://doi.org/10.1016/j.geomorph.2016.07.008

Sharma, T., Vittal, H., Karmakar, S. & Ghosh, S. (2020). Increasing agricultural risk to hydro–climatic extremes in India Increasing agricultural risk to hydro–climatic extremes in India.*Environmental Research Letters, 15,* 034010.*https://doi.org/10.1088/1748-9326/ab63e1*

Sheridan, S. & Lee, C. C. (2012). Synoptic Climatology and the Analysis of Atmospheric Teleconnections. *SAGE Journals, 36* (4), 548–557.*https://doi.org/10.1177/030913331244*

Shi, X., Huang, Q. & Li, K. (2021). Decomposition–based teleconnection between monthly streamflow and global climatic oscillation.*Journal of Hydrology, 602,* 126651.*https://doi.org/10.1016/j.jhydrol.2021.126651*

Tošić, R. & Crnogorac, Č. (2005). *Praktikum iz hidrologije (I –dio – Potamologija*). Banja Luka: Geografsko društvo Republike Srpske, Bosna i Hercegovina (eng. Practicum in hydrology (Part I – Potamology). Banja Luka: Geographical Society of the Republic of Srpska, Bosnia and Herzegovina).

Trenc, N., Duplić, A., Topić, R., Matoš, B., Velić, J. & Ćaleta, M. (2018). Human induced change of the natural geomorphological system and its consequences for the biodiversity of the Sava River west of Zagreb. Conference: 3rd international conference on integrative sciences and sustainable development of large rivers I.S. Rivers 2018 At: Lyon. pp. 3.*https://www.researchgate.net/publication/326440622*

van Vliet, M. T. H., Thorslund, J., Strokal, M., Hofstra, N., Flörke, M., Macedo, H. E., Nkwasa, A., Tang, T., Kaushal, S. S., Kumar, R., van Griensven, A., Bouwman, L. & Mosley, L. M. (2023). Global river water quality under climate change and hydroclimatic extremes. *Nature Reviews Earth & Environment, 4,* 687–702.*https://doi.org/10.1038/s43017-023-00472-3*

Vörösmarty, C. J., Green P., Salisbury, J. & Lammers R. (2000). Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science, 289,* 284–288.*https://doi.org/10.1126/science.289.5477.284*

Wang, H., Liu, J., Klaar, M., Chen, A., Gudmundsson, L. & Holden, J. (2024). Anthropogenic climate change has influenced global river flow seasonality. *Science , 383,* 1009–1014.*https://doi.org/10.1126/science.adi9501*

Wu, P., Christidis, N. & Stott, P. (2013). Anthropogenic impact on Earth's hydrological cycle. *Nature Climate Change, 3* , 807–810.*https://doi.org/10.1038/nclimate1932*

Xiao, M., Zhang, Q. & Singh, V. P. (2014). Influences of ENSO, NAO, IOD and PDO on seasonal precipitation regimes in the Yangtze River basin, China. *International Journal of Climatology, 35* (12), 3556–3567.*https://doi.org/10.1002/joc.4228*

Zemp, M., Frey, H., Gärtner–Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Càceres, B. E., Casassa, G., Cobos, G., Dàvila, L. R., Delgado Granados, H., Demuth, M. N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C. A., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurdsson, O., Soruco, A., Usubaliev, R. & Vincent, C. (2015). Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology, 61,*745–762. https://doi.org/10.3189/2015JoG15J017