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Hydrological drought assessment of the Sava River basin in South-Eastern Europe

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ABSTRACT

Hydrological drought poses significant challenges to water resources, ecosystems, and human activities, necessitating comprehensive investigation. Monthly streamflow data from 12 monitoring stations across the Sava River basin were utilized to compute the streamflow drought index (SDI). The Mann–Kendall test evaluated trends, and the SDI's hydrological states were classified based on cumulative streamflow volumes. The study identified an alarming 83.3% of stations exhibiting statistically significant decreases in summer streamflow, indicating a widespread and concerning trend of declining water availability in the Sava River basin. Drought severity was particularly pronounced in tributaries such as the Vrbas and Bosna rivers, emphasizing the heterogeneous nature of hydrological changes. These findings underscore the urgent need for adaptive water resource management strategies in the face of escalating hydrological drought risks, especially given the far-reaching consequences on agriculture, industry, ecosystems, and social well-being. The study provides crucial insights for developing targeted resilience measures tailored to the specific challenges presented by the diverse hydrological conditions in the Sava River basin.

Key words: climate change, Europe, hydrological drought, Sava River, SDI

HIGHLIGHTS

- Comprehensive 60-year assessment.
- Localized hydrological insights.
- Streamflow drought index application.
- Interconnected hydrological systems.
- Future climate change projections.

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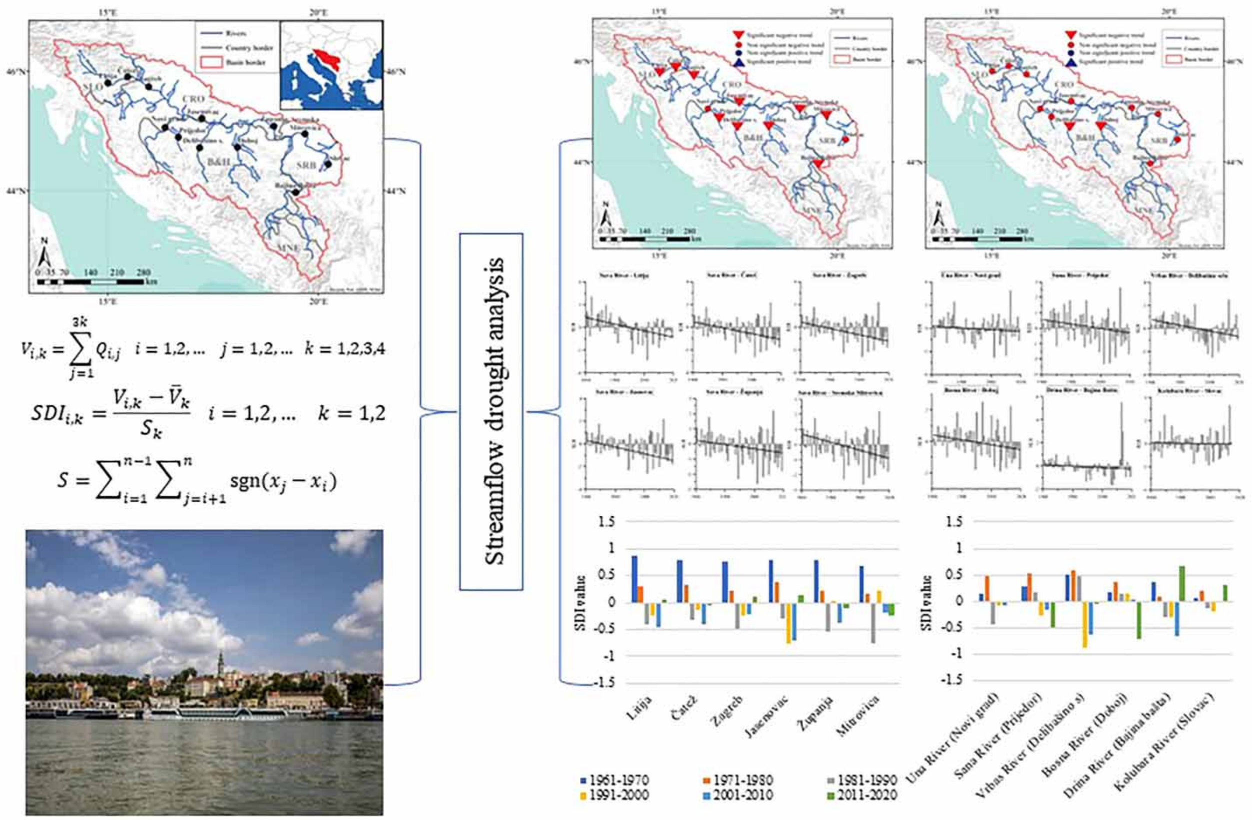
GRAPHICAL ABSTRACT



INTRODUCTION

Carbon emissions from production and consumption systems are the reasons for the extreme weather events such as drought and intensive rainfall (Abbas *et al.* 2021a, 2021b, 2022; Ehsan *et al.* 2024; Jiang *et al.* 2024). Hydrological drought is characterized by an insufficient presence of water in the hydrological system, leading to unusually low streamflow in rivers and diminished levels in lakes, reservoirs, and groundwater (Van Loon 2015). This precipitation deficit may accumulate swiftly or take months before manifesting as lowered lake levels, lowered river discharges, or deeper levels of groundwater. The far-reaching consequences of drought extend beyond its immediate hydrological impact, affecting human activities, lives, and Earth's ecosystems (Sardou & Bahremand 2014). This phenomenon has engaged interdisciplinary attention from scientists in geography, ecology, hydrology, meteorology, and agriculture, each contributing unique perspectives (Tigkas *et al.* 2015). Of several forms of droughts, the hydrological component is particularly critical due to its profound implications for hydropower production, water supply in urban areas, and industrial activity which significantly depend on surface water supplies (Vasiliades *et al.* 2011). Initiated by rainfall deficits, hydrological droughts are commonly associated with reservoirs/lake water levels within a basin, contributing to widespread impacts such as water supply reduction, deteriorating water quality, irrigation restrictions, agricultural failure, diminished energy production, disturbance of riparian habitats, limited outdoor activities, and disruptions to diverse social and economic endeavours (Mishra & Singh 2010). Despite European countries being generally considered to possess sufficient water resources, the increasing occurrence and spread of water scarcity and droughts have become evident. The period from 1980 to 2022 witnessed total economic losses due to weather- and climate-related events in 32 countries of the European Economic Area estimated at 650 billion euros, of which 52.3 billion euros in 2022 and 59.4 billion euros in 2021 (European Environment Agency 2023). The accumulating impacts of climate change, global warming, and human activities pose unprecedented challenges to exacerbate the drought problem (Asadieh & Krakauer 2015; IPCC 2021, 2021).

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The driving force behind droughts lies in the decrease in precipitation, resulting in diminished storage volumes and fluxes within the hydrological cycle (Mosley 2015). Essential for comprehending and monitoring drought events, drought indicators rely heavily on physical datasets encompassing river discharge, groundwater, precipitation, reservoir storage, and soil moisture. These indicators are categorized as hydrological, meteorological, and agricultural (Wable *et al.* 2019).

Streamflow is one of several hydrological variables used for drought characterization that holds paramount significance in determining water quantity. Hydrological droughts, identified by stream flow deficits relative to normal conditions, are characterized by severity, onset time, length, areal frequency, and areal coverage (Sardou & Bahremand 2014). The streamflow drought index (SDI) employs cumulative streamflow volumes to predict the onset, duration, and severity of droughts (Nalbantis & Tsakiris 2009). Recognized for fulfilling essential criteria for drought indices, the SDI has been globally applied, from Greece (Tigkas *et al.* 2012) and the Yangtze River in China (Li *et al.* 2012), Iran (Tabari *et al.* 2013) to the shared Diyala River Basin in Iraq and Iran (Al-Faraj *et al.* 2014). SDI has been instrumental in various studies across Europe, encompassing the Neman and the Vistula Basins in Eastern Europe (Rimkus *et al.* 2013; Kubiak-Wójcicka & Bąk 2018), in Croatia, this index was applied on the Cetina River basin (Ljubenkov & Kalin 2016), in UK it was applied on the 121 watersheds (Barker *et al.* 2016), and in Central Europe, on the Tisza (Leščešen *et al.* 2020), and in Lithuania it was applied on 15 catchments (Nazarenko *et al.* 2023).

The main goal of this research was to investigate the occurrence, frequency, and magnitude of hydrological droughts in the Sava River basin (SRB), the biggest basin in South-Eastern Europe, by employing the SDI. Discharge values from 12 monitoring stations along the Sava River and its affluents, located in Slovenia, Croatia, Bosnia & Herzegovina, and Serbia (Table 1), form the basis of our analysis.

STUDY AREA

The SRB, encompassing a vast area of approximately 97,000 km^2, stands as the largest river basin in South-Eastern Europe (SEE) (Figure 1). SRB is shared among six different countries, Serbia, Croatia, Bosnia and Herzegovina, Slovenia, Montenegro and Albania where only 0.2% of SRB is located (ICPDR 2014). Originating in Slovenia, the Sava River is formed by the convergence of two streams: Sava Bohinjka and Sava Dolinka. Noteworthy tributaries in the downstream direction are Una, Vrbas, Bosna, Drina, and Kolubara Rivers. The combined contribution of these rivers to the Sava River amounts to 1,149 m^3/s, constituting 68% of the Sava River flow at its convergence with the Danube River in Serbia. Among these tributaries, the Drina emerges as the most affluent, providing 371 m^3/s or 22% of the Sava's flow at its confluence with the Danube (Hrvatska Enciklopedija 2021). The Sava River stretches for 945 km until it joins the Danube River in Belgrade, and the basin is home to approximately 8 million people (Leščešen *et al.* 2022b).

Table 1 | Basic statistical characteristics of the selected rivers

Station	**River**	**Country**	**Mean annual discharge (m^3/s)**	**Standard error (m^3/s)**	**Median (m^3/s)**	**Minimum annual discharge (m^3/s)**	**Maximum annual discharge (m^3/s)**
Litija	Sava	Slovenia	163.4	4.4	160.7	97.4	267.2
Čatež	Sava	Slovenia	275.9	7.4	271.9	150.7	448.3
Zagreb	Sava	Croatia	302.4	6.1	301.3	199.5	464.1
Jasenovac	Sava	Croatia	7,334.2	23.6	711.4	372.4	1,123.0
Županja	Sava	Croatia	1,106.0	29.3	1,100.9	574.5	1,637.9
S. Mitrovica	Sava	Serbia	1,521.7	40.4	1,489.6	799.6	2,317.5
Novi grad	Una	BH	504.9	15.0	502.2	230.1	822.5
Prijedor	Sana	BH	79.7	2.2	78.9	36.6	120.3
Delibašino s.	Vrbas	BH	100.0	3.1	102.5	49.2	161.4
Doboj	Bosna	BH	160.9	5.3	156.1	63.6	259.2
Bajina bašta	Drina	Serbia	374.8	34.9	326.4	150.1	1,780.7
Slovac	Kolubara	Serbia	9.6	0.4	8.9	3.6	20.6

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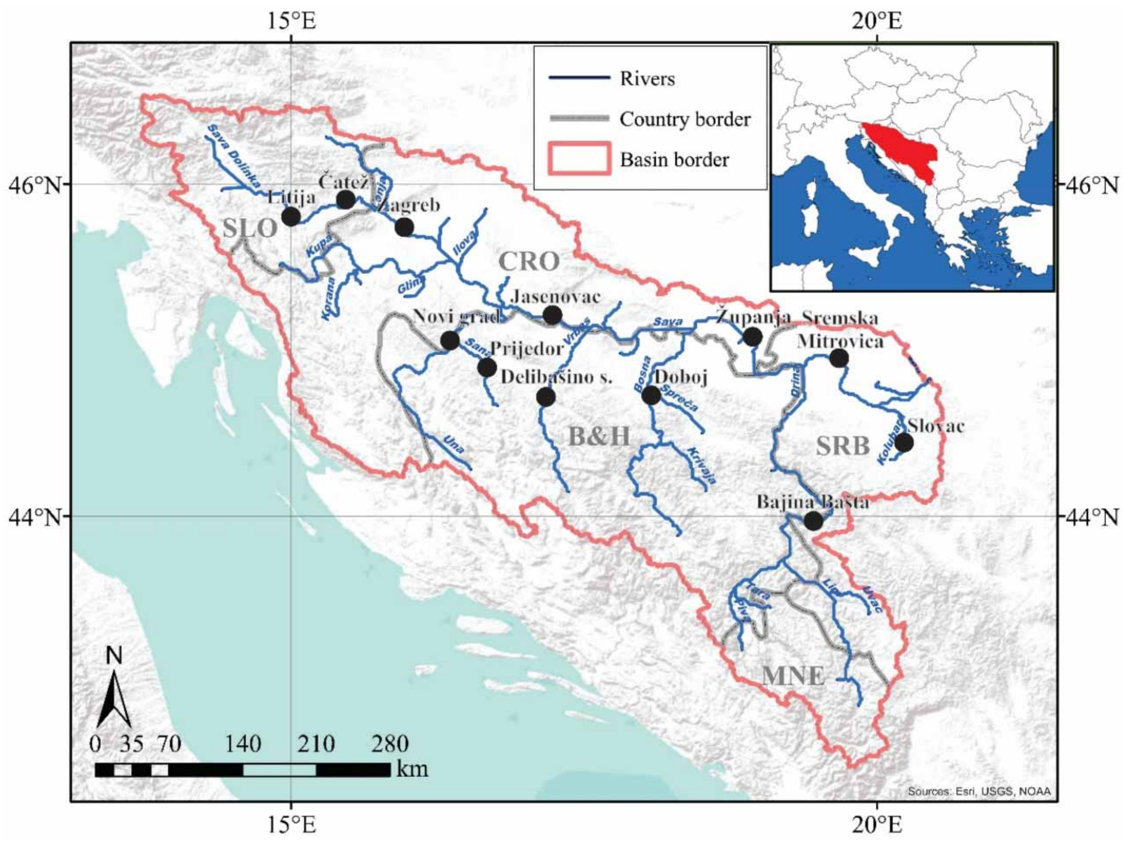

Figure 1 | Geographical position of the research basin and the stations used for this study.

SRB is under the influence of different river regimes, upriver parts, from the Litija station to the Četeš station, Alpine nival-pluvial regime is represented (Frantar *et al.* 2008). Downriver from the Čatež station, the regime shifts to an Alpine pluvial-nival regime (Ulaga *et al.* 2008). The Peripannonian pluvial-nival type is represented in the middle part of the SRB, from Zagreb to Jasenovac stations, and it includes Novi Grad, Prijedor, Delibašino selo, Doboj, Bajina bašta, and Slovac stations. Finally, Županja, and Sremska Mitrovica stations are under the Pannonian pluvial-nival type influence (Čanjevac & Orešić 2018; Leščešen *et al.* 2022a).

SEE, including the SRB, is a climate change hotspot characterized by above-average warming and highly vulnerable populations (Leščešen *et al.* 2023). Previous research that most commonly used the hydrological and meteorological data from the second half of the 20th century and first decades of the 21st century indicate that SEE has already experienced a significant increase in summer temperatures (Trbić *et al.* 2017), a decrease in summer precipitation (Milošević *et al.* 2021), and an increase in consecutive dry days (Popov *et al.* 2019), all of which contribute to increased overall dryness. The most important climate simulations predict a temperature increase of 3.5°C for the Western Balkans with moderate greenhouse gas emissions up to 8.8°C in the high emissions scenario (RCP 8.5) by the end of the century (IPCC 2021). There is very high confidence – indicating robust empirical evidence and high agreement between the reviewed studies – that summer temperatures in this region will increase more than the global terrestrial average, leading to more intense evapotranspiration that will further contribute to intensification of hydrological droughts during the warm period of the year (IPCC 2021). All of these results indicate that in the future a lack of water can be expected in the region, especially during the warm period of the year, when water is needed the most for agriculture, energy production, industries, and maintaining ecological balance.

DATA AND METHODS

In this paper, a 60-year (1961–2020) database of mean monthly streamflows for 12 selected stations that are located within the SRB (Figure 1) was utilized. This database can be considered satisfactorily long as usually a database of at least 50 years is

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necessary to differentiate variability from trends (Kundzewicz & Robson 2000). Streamflow data were obtained from four different national agencies (Slovenian Environment Agency; Meteorological and Hydrological Service, Croatia; Republic Hydrometeorological Service of Serbia; and the Republic Hydrometeorological Service – Republic of Srpska) (Table 1). The dataset was separated into hydrological summer (April–October) and hydrological winter (November–March).

Data quality control measures were rigorously implemented by each national organization responsible for the collection and maintenance of hydrological data. All organizations adhered to strict standards to ensure the accuracy and consistency of the data series used in this study. In doing so, they followed their internal instructions, but also the recommendations of the World Meteorological Organization (WMO). To ensure the homogeneity of the data, the Mann–Kendall (MK) and Pettitt tests, a non-parametric method often used to detect change points in time series data (Ferraz *et al.* 2022), was applied. The Pettitt test is particularly useful for detecting shifts in median values and thus assessing the consistency of hydrological data over time (Kocsis *et al.* 2020). The results of the MK and Pettitt tests can be found in Table 2.

Table 2 summarizes the results of the MK and Pettitt tests carried out with the data from the selected stations. It is noteworthy that all locations except Novi grad, Prijedor, and Slovac show a significant decreasing trend in streamflow, as evidenced by low *p*-values in the MK test. The results of the Pettitt test indicate that there are no significant changes at the 0.05 significance level at all sites, as the *p*-values are above 0.05, which in combination with the MK test results indicates homogeneity of the data for all sites. The data presented in Table 2 show a consistent downward trend in flow for most locations, with the Pettitt test revealing no significant changes. This consistency, combined with the classification of the data as homogeneous, indicates that the dataset is reliable for further analysis.

Obtained data were employed to establish the SDI of the Sava River and its main tributaries. The computation of SDI uses a time series of monthly streamflow volumes, denoted as $Q_{i,j}$, where i represents the hydrological year and j signifies the month in that year ($j = 1$ for October and $j = 12$ for September), $V_{i,k}$ can be calculated based on the equation (Nalbantis & Tsakiris 2009):

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \quad i = 1, 2, \ldots \quad j = 1, 2, \ldots \quad k = 1, 2, 3, 4$$

where k of the i-th hydrological year is defined based on the cumulative streamflow volumes ($V_{i,k}$). Here, $V_{i,k}$ represents the cumulative streamflow volume for the i-th hydrological year and the k-th reference period. The reference periods are categorized as follows: $k = 1$ for October to March, $k = 2$ for April to September. The calculation of SDI involves the assessment of cumulative streamflow volumes $V_{i,k}$ within these specified reference periods, allowing for a comprehensive characterization

Table 2 | MK and Pettitt test results for streamflow data homogeneity and trend analysis across various locations

	MK test		**Pettitt test**			
Location	**Trend**	***p*-value**	***K***	***p*-value**	**Change point at year**	**Data homogeneity**
Litija	Decreasing	0.000	24,102	0.071	1980	Homogeneous
Čatež	Decreasing	0.000	23,600	0.063	1988	Homogeneous
Zagreb	Decreasing	0.001	21,966	0.865	1981	Homogeneous
Jasenovac	Decreasing	0.000	24,786	0.104	1983	Homogeneous
Županja	Decreasing	0.005	18,784	0.694	1983	Homogeneous
S. Mitrovica	Decreasing	0.033	15,850	0.354	1982	Homogeneous
Novi grad	No trend	0.063	17,810	0.123	1980	Homogeneous
Prijedor	No trend	0.268	12,610	0.156	1980	Homogeneous
Delibašino s.	Decreasing	0.000	41,492	0.975	1987	Homogeneous
Doboj	Decreasing	0.010	18,228	0.865	2006	Homogeneous
Bajina bašta	Decreasing	0.050	39,415	0.202	1969	Homogeneous
Slovac	No trend	0.756	7,885	0.538	1969	Homogeneous

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of streamflow conditions across various hydrological cycles.

$$SDI_{i,k} = \frac{V_{i,k} - \bar{V}_k}{S_k} \quad i = 1, 2, \ldots \quad k = 1, 2$$

in which $\bar{V}_k$ and s_k represent the mean and the standard deviation of cumulative streamflow volumes of the reference period k as these estimations are conducted over the extended timeframe. This definition specifies that the truncation level is established at $\bar{V}_k$, however, it is worth noting that alternative values based on rational criteria could also be employed.

In the context of small basins, the streamflow in many cases displays a skewed probability distribution, which is aptly modelled by the family of gamma distribution functions. For ease of analysis and comparison, this distribution is transformed into a normal distribution. This transformation is achieved by employing the two-parameter log-normal distribution, where normalization entails reclaiming the natural logarithms of streamflow. The SDI is defined as:

$$SDI_{i,k} = \frac{y_{i,k} - \bar{y}_k}{S_{y,k}} \quad y = 1, 2, \ldots \quad k = 1, 2$$

where:

$$y_{i,k} = \ln(V_{i,k}) \quad i = 1, 2, \ldots \quad k = 1, 2$$

The natural logarithms of cumulative streamflow are calculated using the mean $\bar{y}_k$ and standard deviation s_y, with these statistical parameters estimated over an extensive period. The classification of drought states mirrors those used in meteorological drought indices, such as the standardized precipitation index. This classification encompasses five states, as outlined in Table 3 (Tigkas *et al.* 2015).

For SDI trend analysis the MK test, a non-parametric method relying on ranks, is applied. This test is commonly used for detecting trends in climatological and hydrological time series (Bezak *et al.* 2016; Leščešen 2022b). In the MK test, the null hypothesis (H_0) posits the absence of any trend in the series, while the alternative hypothesis (H_A) asserts the presence of a trend, which could be either positive or negative. In this study, a significance level of 5% is applied, indicating that statistical significance is acknowledged if the calculated *p*-value is less than or equal to 0.05. This approach helps to determine whether the observed trends in SDI data are statistically meaningful or simply a result of random variability.

RESULTS AND DISCUSSION

To determine possible changes in streamflow over the SRB, a MK test was applied, to show whether the observed change is positive or negative, and whether it can be considered statistically significant or not. Results of the MK test are presented in Figure 2 and Table 4, where it is shown that 83.3% of stations have recorded statistically significant decrease during the hydrological summer season (April–September). Decreasing water availability in rivers during the summer season can adversely impact agriculture by reducing crop yields and livestock productivity, while also affecting industries and public water supply. The resulting consequences extend to ecosystems, energy production, food security, and social well-being.

Table 3 | Description of hydrological drought based on the SDI

State	Description	Criterion	Probability (%)
0	Non drought	$SDI \geq 0.0$	50
1	Mild drought	$-0.99 \leq SDI < 0.0$	34.1
2	Moderate drought	$-1.49 \leq SDI < -1.0$	9.2
3	Severe drought	$-1.99 \leq SDI < -1.5$	4.4
4	Extreme drought	$SDI < -2.0$	2.3

From Tigkas *et al.* (2015).

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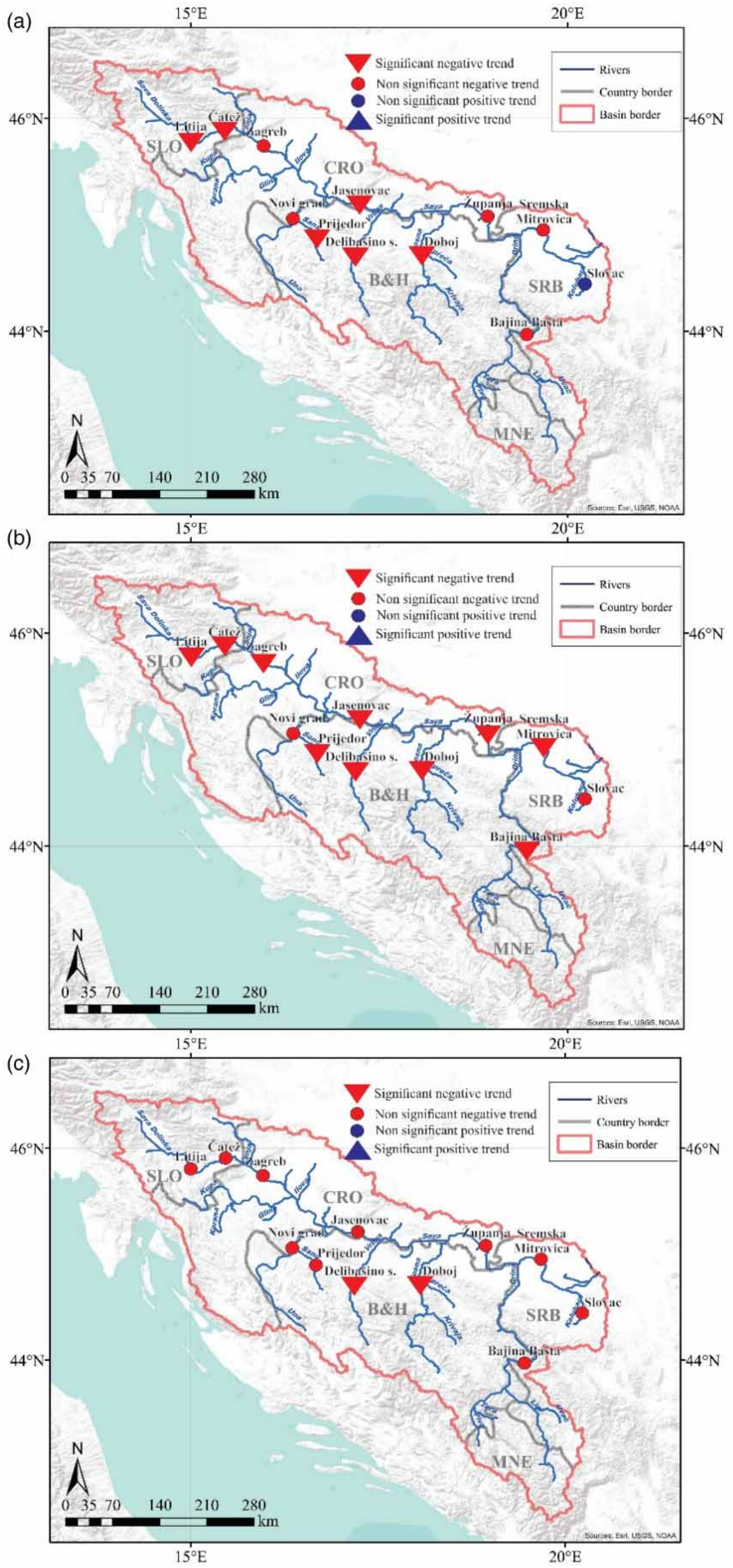

Figure 2 | Spatial distribution and statistical significance of long-term trends of SDI on: (a) annual; (b) summer; and (c) winter in SRB during the period 1961–2020.

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Table 4 | Mann–Kendall test results of the annual and seasonal streamflow over the SRB 1961–2020

		Annual		Summer		Winter	
Station	**River**	**Trend**	***p*-value**	**trend**	***p*-value**	**trend**	***p*-value**
Litija	Sava	−0.187	**0.035**	−0.293	**0.001**	−0.049	0.578
Čatež	Sava	−0.209	**0.018**	−0.279	**0.001**	−0.054	0.543
Zagreb	Sava	−0.145	0.103	−0.240	**0.007**	−0.012	0.885
Jasenovac	Sava	−0.214	**0.023**	−0.287	**0.001**	−0.079	0.377
Županja	Sava	−0.135	0.430	−0.221	**0.013**	−0.054	0.543
S. Mitrovica	Sava	−0.074	0.391	−0.227	**0.010**	−0.013	0.880
Novi grad	Una	−0.163	0.067	−0.093	0.277	−0.079	0.357
Prijedor	Sana	−0.177	**0.040**	−0.202	**0.019**	−0.072	0.399
Delibašino s.	Vrbas	−0.322	**0.000**	−0.254	**0.003**	−0.272	**0.001**
Doboj	Bosna	−0.1761	**0.041**	−0.179	**0.034**	−0.203	**0.018**
Bajina bašta	Drina	−0.121	0.159	−0.206	**0.017**	−0.027	0.753
Slovac	Kolubara	0.046	0.596	−0.001	0.985	−0.004	0.962

*Bold numbers highlight the statistically significant trends.

The results presented in Table 3 provide valuable insights into the hydrological dynamics of each station. Several stations along the Sava River, including Litija and Čatež, displayed significant negative trends in both annual ($p = 0.035$; $p = 0.018$, respectively) and summer streamflow ($p = 0.001$ at both stations), indicating a decline in water availability during the summer period. This consistent pattern was further emphasized by Jasenovac, corroborating the existence of a noteworthy negative trend in the SRB (annual $p = 0.023$; summer $p = 0.001$). Interestingly, Zagreb did not exhibit a significant annual trend, while a considerable negative trend in summer ($p = 0.007$) suggests potential seasonal variations impacting streamflow. Conversely, stations such as Županja and Sremska Mitrovica also did not show significant annual trends, yet both displayed a negative trend during summer ($p = 0{,}013$; $p = 0.010$, respectively). These findings further underscore the importance of considering seasonality in hydrological assessments. The most extreme drought on the annual level was recorded during 2011–2012 with an average SDI value of −2.48. Overall, from eight drought events with SDI values lower than −1, five were recorded after the year 2000.

Moving beyond the Sava River, the results along tributary rivers also revealed distinct trends. For instance, the Vrbas River showcased a significant negative trend at the annual level ($p = 0.000$) as well as at the seasonal (summer $p = 0.03$; winter $p =$ 0.01), indicating a consistent decline in streamflow during the observed period. The lowest annual SDI value on this river was recorded in 2006–2007 at −2.53. Similarly, the Bosna River displayed significant negative trends in annual ($p = 0.41$) and seasonal (summer $p = 0.034$; winter $p = 0.018$) streamflow, pointing to potential hydrological shifts in this region. At the Bosna River, the lowest SDI value was recorded in 2019–2020 with −3.04. At the Drina and Kolubara Rivers, no statistically significant trend was observed at the annual time scale, while only the summer season at the Drina River has shown a statistically significant decrease in SDI values ($p = 0.017$). Notably, the Kolubara River did not exhibit statistically significant trends in any analysed period, emphasizing the heterogeneity of hydrological patterns across different river basins. The reason for the absence of statistically significant trends on any time scale at the Kolubara River could be due to a lack of data since 2015, and as can be seen in Figures 3 and 4, during the last five years of the observed period negative SDI values were observed during the warm period at all stations within the study area.

As results in Table 2 indicate that only the summer season has shown statistically significant changes in SDI over the whole SRB, plots representing these changes were created and presented in Figures 3 and 4.

The SDI values fluctuate during the summer season over the observed period, reflecting the hydrological variability within the SRB. Notably, the findings reveal discernible patterns of hydrological drought intensity along the entire stretch of the river over this period, spanning from comparatively humid conditions at the outset to drier conditions in recent decades.

Commencing at the Litija station, positioned at the upriver location, positive SDI values dominate the early years, signifying periods of relative abundance in streamflow. However, a notable shift is discernible in the mid-1980s, marked by the

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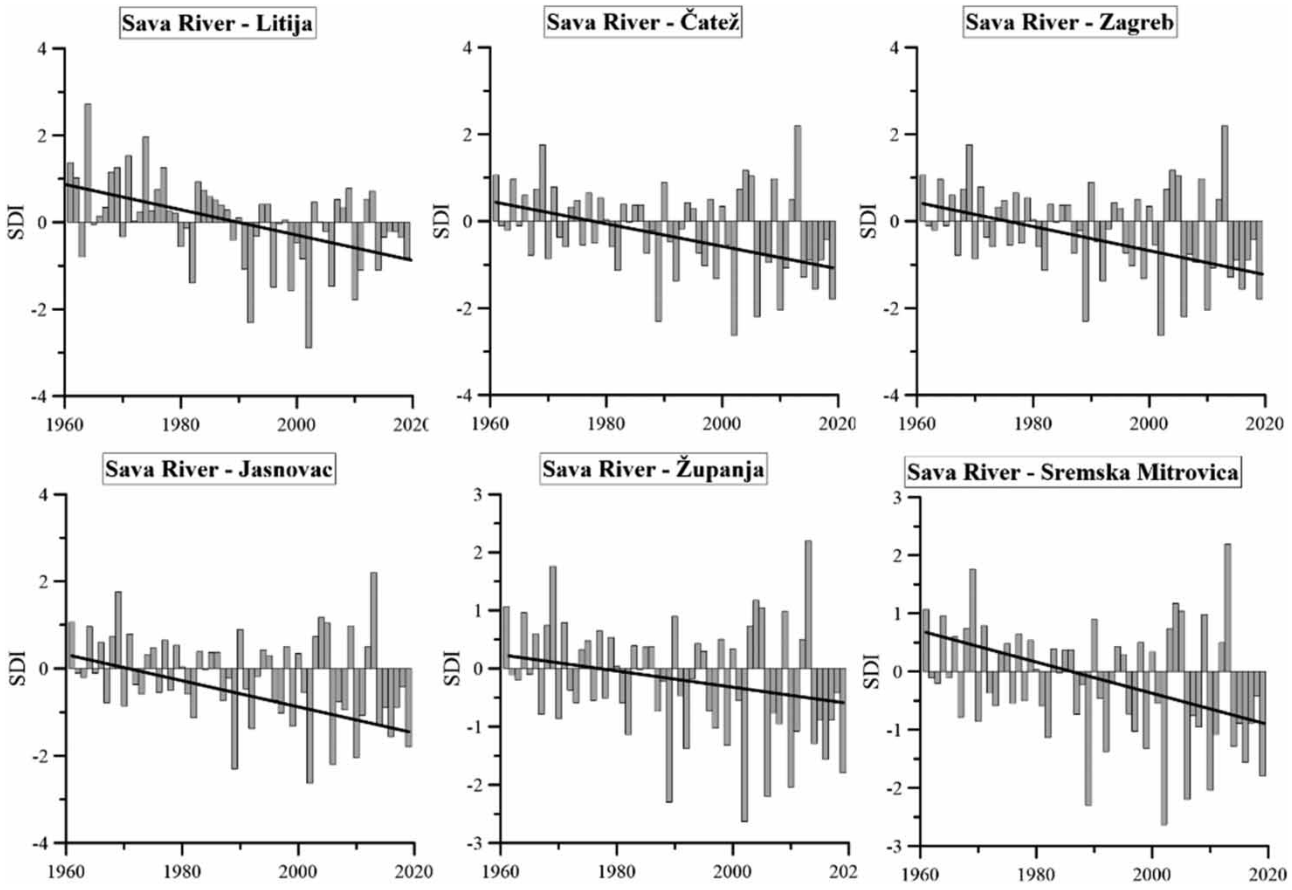

Figure 3 | Summer SDI values with linear trend line for the Sava River.

emergence of negative SDI values, indicating a transition towards more frequent and severe hydrological droughts. This pattern persists through subsequent decades, with occasional spikes in drought intensity. The downstream progression to Čatež maintains the negative trend in SDI values. These shifts underscore a basin-wide alteration in hydrological conditions, resulting in increased susceptibility to drought events. Continuing downstream to Zagreb, Jasenovac, and Županja, the negative trends in SDI values persist, signifying a consistent worsening of hydrological drought conditions. These collective trends along the upper and middle stretches of the Sava River emphasize the cumulative downstream intensification of hydrological drought severity. The downward trend in SDI values further intensifies upon reaching Sremska Mitrovica, the last station on the Sava River. Negative SDI values dominated the entire observation period, with again significant decreases in the late 1970s, indicating an increasing susceptibility to severe hydrological droughts. The persistence of negative SDI values at Mitrovica highlights the sustained impact of hydrological changes along the entire length of the Sava River. Examining the combined dataset, it becomes evident that there are periods of prolonged hydrological drought affecting all stations. Notably, the most extended dry period occurred between 2014 and 2020, where negative SDI values were widespread across all stations, signifying a basin-wide drought event (Figure 5). The drought period spanning 2014–2018 was observed across various regions in Europe, encompassing Western, Central, and Northern Europe. It commenced with the warmest winter since 1950, and the year 2014, in particular, stood out as exceptionally warm, marking the warmest on record. This warmth persisted across all seasons, with the most notable temperature anomaly occurring during spring, reaching up to 4°C (Moravec *et al.* 2021). Multi-scale fluctuations, a recurring phenomenon in the European hydroclimate, are frequently observed and can arise from the persistence of hydroclimatic processes (Markonis *et al.* 2018) or the recurrence of intra-annual extremes, such as severe summer droughts (Hari *et al.* 2020). These findings collectively underscore the escalating risk of prolonged and severe hydrological droughts impacting the SRB, emphasizing the urgency of adaptive water resource management strategies in the face of changing climate conditions. Over the last two decades, from 2001 to 2020, the trend in SDI values continues to

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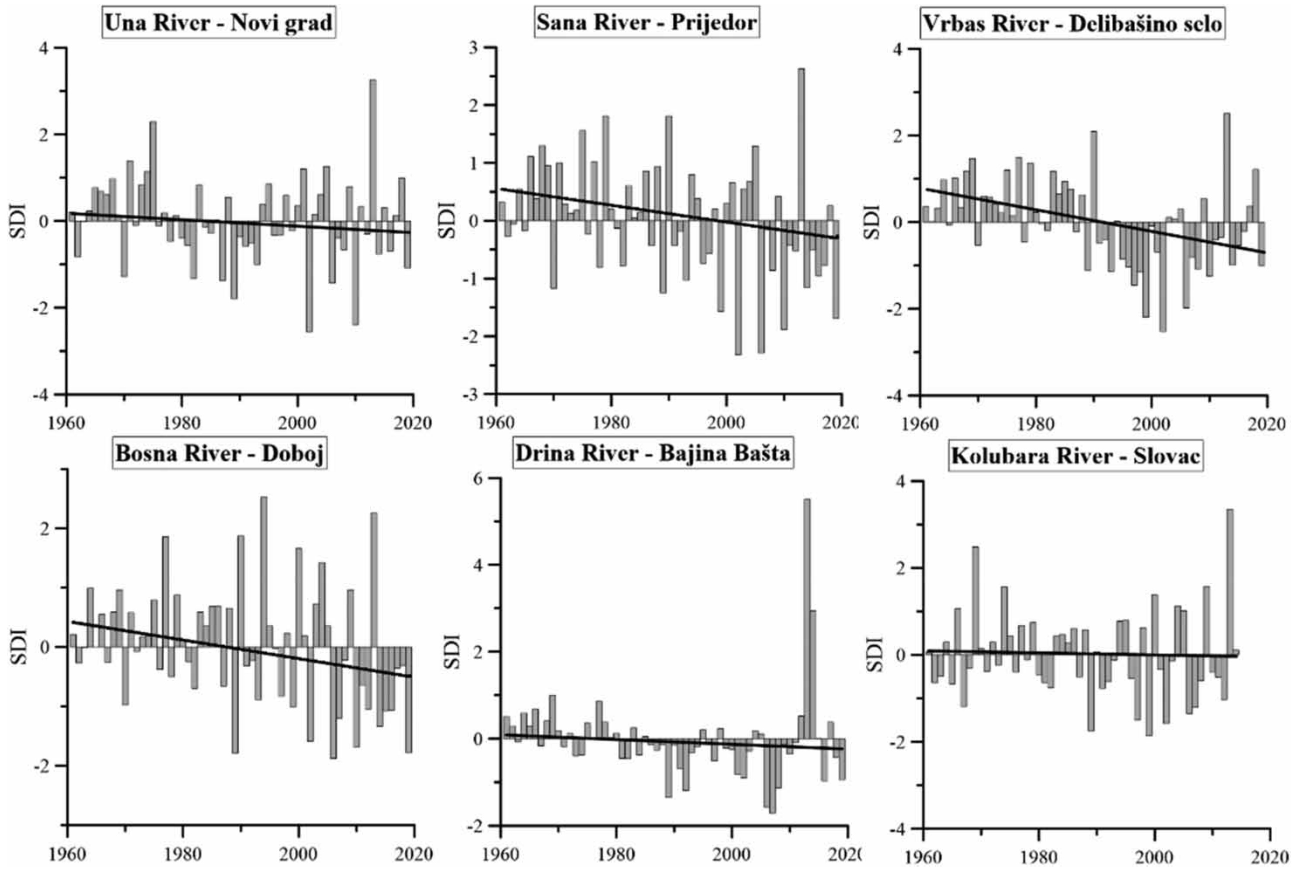

Figure 4 | Summer SDI values with linear trend line for right tributaries of the Sava River.

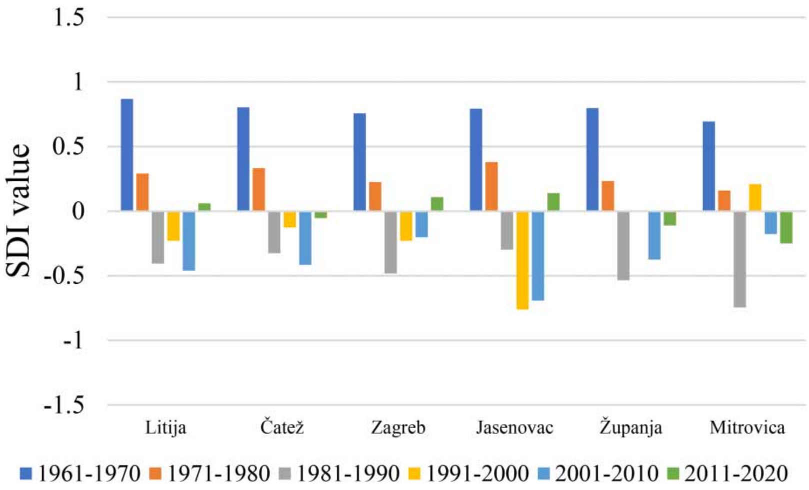

Figure 5 | Average decadal summer SDI values for the Sava River.

reflect an ongoing pattern of hydrological stress along the Sava River. The cumulative impact of negative SDI values along the entire river course reinforces the notion that the last two decades have not seen a significant improvement in hydrological conditions. Similarly, southern and central Europe are undergoing a discernible upward trend in hydrological drought events, as evidenced by a notable escalation in the severity of hydrological drought conditions (Peña-Angulo *et al.* 2022).

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The hydrological trends observed in the right tributaries of the Sava River, including the Una, Sana, Vrbas, Bosna, Drina, and Kolubara Rivers, provide valuable insights into the changing hydrological conditions in this region.

Starting with the Una River at the Novi Grad station, positive SDI values dominate the early years, indicating periods of relative abundance in streamflow (Figure 6). However, as observed on the Sava River, a notable shift occurred in the early 1970s, marked by the emergence of negative SDI values, signifying increased susceptibility to hydrological droughts. This pattern continues with fluctuations, suggesting varying degrees of hydrological stress over the subsequent years. The Sana River at the Prijedor station exhibits similar patterns, with both positive and negative SDI values throughout the observed period. The early 1970s again witnessed a notable increase in negative SDI values, indicating a heightened risk of hydrological drought. Despite occasional positive spikes, the overall trend highlights the vulnerability of this tributary to changing hydrological conditions. Moving to the Vrbas River at the Delibašino Selo station, a mix of positive and negative SDI values is observed, with significant decreases in the early 1980s. This shift suggests an alteration in hydrological patterns, potentially leading to increased occurrences of drought events. The subsequent years show a varying pattern, emphasizing the complex hydrological dynamics in this region. The Bosna River at the Doboj station exhibits diverse SDI values, with distinct negative trends in the early 1990s. This period coincides with significant negative values in other tributaries, indicating a basin-wide susceptibility to prolonged hydrological drought. The fluctuations in SDI values underscore the dynamic nature of hydrological conditions in this watershed. The Drina River at the Bajina Bašta station displays fluctuations in SDI values, with notable negative trends in the early 1990s. This aligns with similar patterns in other tributaries, emphasizing the interconnected nature of hydrological systems. The following years witnessed varying SDI values, reflecting the complex response of this river to changing climate conditions. Lastly, the Kolubara River at the Slovac station exhibits both positive and negative SDI values, with a significant decrease in the early 1980s. This suggests a period of increased hydrological stress and susceptibility to drought. The subsequent years show a mix of positive and negative values, highlighting the intricate hydrological dynamics within this watershed. Climate indices associated with drought are anticipated to notably rise across the region by the conclusion of the 21st century. Consistent with the projected escalation in aridity, an increase in consecutive dry days (CDD) during this summer season (Pongrácz *et al.* 2014). Southeast Europe is anticipated to witness a sustained intensification of drought conditions until the close of the century, with projections indicating an increase of up to 80% by the 2080s. This trend is substantiated by the majority of hydrological simulations, consistently portraying escalating streamflow drought conditions across the Iberian Peninsula, France, Italy, the United Kingdom, and the Balkan Peninsula throughout the 21st century (Forzieri *et al.* 2014).

The hydrological conditions across various tributaries of the Sava River, as exemplified by the Una River–Novi Grad station, the Sana River–Prijedor station, the Vrbas River–Delibašino Selo station, the Bosna River–Doboj station, the Drina River–Bajina Bašta station, and the Kolubara River–Slovac station, reveal intricate patterns of drought occurrences from 1961 to 2020. Examining the Una River, the data reflect a mix of drought states over the years. Notable periods of extreme drought, observed in 2002–2003 (SDI $= -2.55$) and 2010–2011 (SDI $= -2.39$), underscore the vulnerability of this

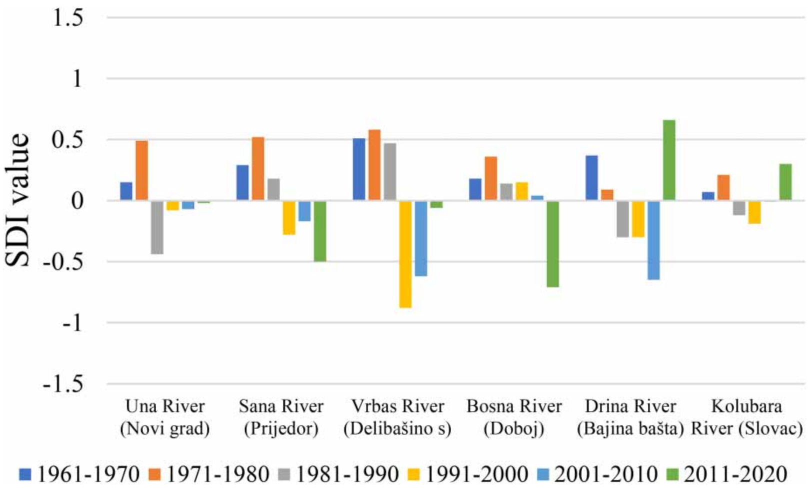

Figure 6 | Average decadal summer SDI values for the Sava River tributaries.

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station to severe hydrological stress. The Sana River exhibits a similar trend, with peaks of extreme drought aligning with regional drought events in 1999–2000 and 2002–2003. In contrast, the Vrbas River–Delibašino Selo station experiences more variability, with intermittent extreme drought events, such as those in 2002–2003 ($\mathrm{SDI} = -2.32$) and 2019–2020 ($\mathrm{SDI} = -1.69$). The Bosna River displays periods of extreme drought, particularly in 2002–2003 ($\mathrm{SDI} = -2.52$) and 1999–2000 ($\mathrm{SDI} = -2.19$), highlighting the shared vulnerabilities of these interconnected river systems. The 2003 drought is considered as the most widespread hydrological drought in Europe (Hanel *et al.* 2018). Analysing the Drina River, a pronounced drought period was observed from 2006 to 2012 with the lowest SDI value in 2007–2008 at -1.71. Finally, the Kolubara River station showcases a distinctive pattern, with a prominent spike in extreme drought during 1999–2000 ($\mathrm{SDI} = -1.86$), highlighting the localized nature of hydrological dynamics. The rise in the number of consecutive dry days in recent decades, with anticipated further increases in the future (Popov *et al.* 2018), highlights the potential for extended periods of meteorological droughts to transform into impactful hydrological droughts, affecting water supply significantly (Van Lanen *et al.* 2016). Furthermore, the amount of summer precipitation over the region has shown a statistically significant decrease in the recent period (Gajić-Čapka *et al.* 2015; Leščešen *et al.* 2022b). Precipitation analysis over the Sava River watershed in B&H revealed mainly insignificant trends in both signs, whereas a prominent decrease (especially in the north of B&H) was found in the summer season (up to 14 mm/decade). On the other hand, air temperature displayed prominent upward trends across the entire study area. The most pronounced warming (0.4–0.6 °C/decade) was present during the summer which further supports hydrological drought intensification in this part of the SRB (Gnjato *et al.* 2021). In the same study, authors emphasize a significant negative correlation between air temperature and river discharges and the strongest positive correlation between precipitation and river discharges, underpinning the worsening hydroclimatic conditions during the warmest part of the year.

The frequency distribution of hydrological drought events at various river stations elucidates distinctive patterns of hydrological stress, emphasizing the localized nature of these phenomena. Exploring the Litija station reveals a dynamic profile with significant occurrences of mild (20 events) and severe (7 events) drought conditions, contributing to a nuanced distribution. In contrast, the Čatež station exhibits a more concentrated distribution, featuring pronounced instances of moderate (16 events) and severe (12 events) drought conditions. The Zagreb station displays a unique pattern with a higher prevalence of non-drought periods (22 events) and a scarcity of moderate and severe drought events. Jasenovac, Županja, and Sremska Mitrovica stations each showcase varied profiles, with differing combinations of mild, moderate, and severe drought events (Figure 7). These results underscore the need for targeted, station-specific strategies in hydrological management and drought resilience to address the diverse challenges presented by the local hydrological context.

Examining the drought frequency of the tributaries, the Una River reveals a notable occurrence of mild drought events, with 19 instances, and a moderate frequency of non-drought periods (34 events). The Sana River displays a comparable pattern, with 19 occurrences of both mild and non-drought conditions. In contrast, the Vrbas River exhibits a slightly higher frequency of moderate drought events (8 instances) alongside 32 non-drought periods. The Bosna River presents a diverse distribution, with a substantial occurrence of both mild (19 events) and severe (5 events) drought conditions. The Drina River and the Kolubara River showcase a more balanced distribution, with notable instances of both mild and moderate drought conditions (Figure 8). Pronounced seasonal trends identified in this study are also observed in other European regions where an increase in summer drought frequency and intensity is observed (Böhnisch *et al.* 2021). These findings underscore the heterogeneity in hydrological vulnerabilities across the studied rivers, emphasizing the importance of localized strategies for drought resilience and water resource management.

The study has several potential limitations that should be considered when interpreting the results. One key limitation is the representativeness of the monitoring stations used, which may not adequately capture the spatial variability of hydrological conditions across the entire study area. This could lead to biases in the data and, consequently, the findings. Additionally, uncertainties in the data collection and processing methods, such as measurement errors, inconsistencies in data recording, and gaps in the time series, could further affect the reliability of the results. Another significant limitation is the methods' inability to account for intricate processes such as groundwater–surface water interactions, land use changes, and feedback mechanisms within the hydrological cycle.

Given these limitations, future research should focus on investigating the spatial analysis of droughts within SRB as well as the impact of anticipated climate variability on future drought scenarios and evaluating the effectiveness of various drought mitigation strategies to enhance our preparedness for and management of hydrological extremes. Furthermore, it is recommended to use hydrometeorological drought indices across various regions in the world to create more comprehensive

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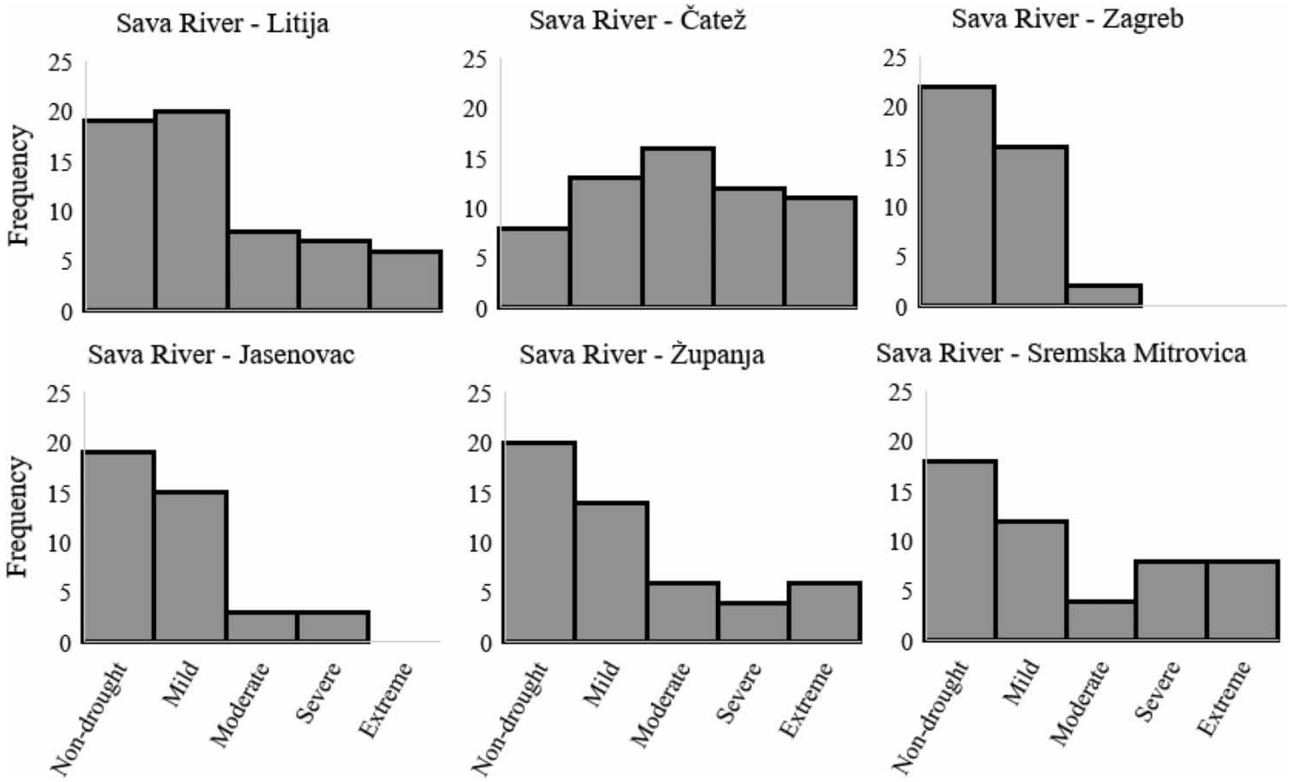

Figure 7 | Frequency of drought events based on the SDI for the Sava River.

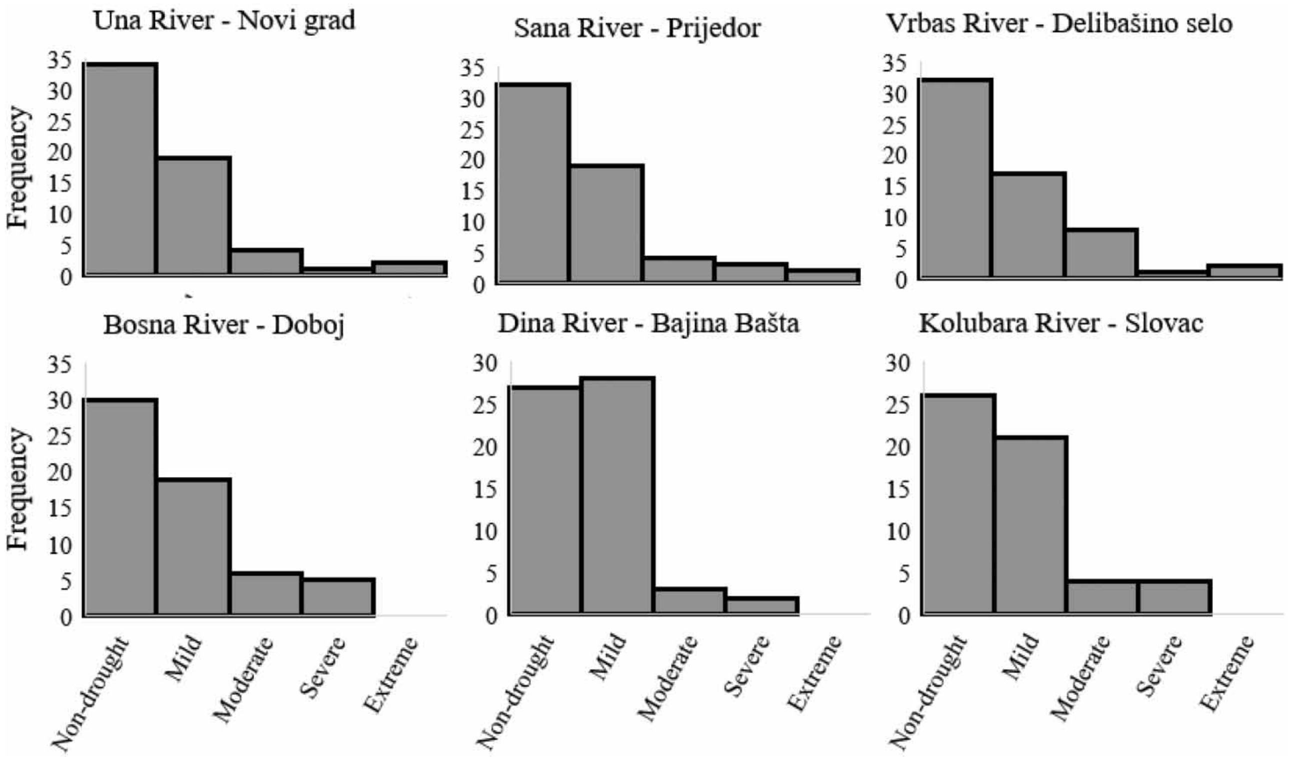

Figure 8 | Frequency of drought events based on the SDI for tributary rivers.

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systems for drought monitoring and prediction (Abbas *et al.* 2021a, 2021b), correlating hydrological with meteorological drought indexes (Sarwar *et al.* 2022). Additionally, incorporating anthropogenic information, such as changes in crop varieties, irrigation practices, and other adaptive measures, is essential for conceptualizing the full scope of drought impacts and designing effective mitigation plans (Waseem *et al.* 2022; Abbas *et al.* 2023). By addressing these research areas, we can develop more robust strategies to mitigate the effects of drought and improve water resource management in the face of climate change.

CONCLUSION

In conclusion, this study delves into the intricate dynamics of hydrological droughts in the expansive SRB, revealing significant trends and patterns that underscore the region's vulnerability to changing hydrological conditions. The observed decrease in streamflow, particularly during the critical summer season, has been a prevalent trend across numerous monitoring stations, indicating a heightened risk of hydrological droughts in the basin. The MK test results highlight that a substantial majority of stations, 83.3% during the hydrological summer season, recorded statistically significant decreases in streamflow, emphasizing the severity and widespread nature of this issue.

The findings elucidate the interconnectedness of hydrological systems within the SRB, emphasizing the cumulative downstream intensification of hydrological drought severity. The analysed tributaries, including the Una, Sana, Vrbas, Bosna, Drina, and Kolubara Rivers, exhibit diverse responses to changing hydrological conditions, reflecting the complex and localized nature of drought occurrences. Notably, the increased frequency and severity of hydrological droughts in recent decades, particularly evident in the last two, emphasize the escalating risk and sustained impact of prolonged drought events in the SRB.

Projected climate change, coupled with the compounding effects of global warming and human activities, poses unprecedented challenges that exacerbate the hydrological drought problem. The anticipated shifts in precipitation patterns and temperature, as indicated by climate change projections, are likely to further intensify the occurrence and severity of hydrological droughts in the SRB. This necessitates urgent attention to adaptive water resource management strategies to mitigate the potential socioeconomic and environmental consequences.

The implications of hydrological droughts extend far beyond reduced water availability, affecting agriculture, industries, public water supply, ecosystems, energy production, food security, and overall social well-being. As water scarcity becomes more prevalent, the livelihoods of the people living within the SRB are at stake. Agriculture, a cornerstone of the regional economy, faces challenges such as reduced crop yields and livestock productivity. Industries dependent on water resources are at risk, and public water supply may be compromised. Ecosystems, energy production, and food security are also threatened, highlighting the need for comprehensive and sustainable water management policies.

Given these findings, it is crucial for the inhabitants of the SRB to adopt proactive measures such as developing robust water management strategies, sustainable agricultural practices, and climate-resilient infrastructure. The implementation of advanced real-time monitoring systems and the enforcement of water use restrictions during critical drought periods can greatly improve water conservation efforts. Furthermore, encouraging the use of water-saving technologies and upgrading existing infrastructure will help to mitigate the effects of increasing hydrological droughts. Additionally, fostering international collaboration among the countries sharing the basin is crucial to addressing the transboundary nature of water resources. This study serves as a clarion call for timely and concerted efforts to enhance the region's resilience to the escalating challenges of hydrological droughts in the face of a changing climate.

Future studies in the SRB should delve into climate change impacts, integrated water resource management, and the ecological and socioeconomic repercussions of hydrological droughts. Investigating land use changes, water demand dynamics, and applying advanced monitoring techniques will be essential for informing adaptive measures and sustaining the region's water resources.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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