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Seasonal variability changes and trends in minimum discharge for Western Balkan rivers

Igor Leščešen [a,*], Slobodan Gnjato [b], Duško Vujačić [c], Ana M. Petrović [d], Ivan Radevski [e]

[a] Institute of Hydrology SAS, Dúbravská cesta 9, Bratislava 841 04, Slovak Republic
[b] University of Banja Luka, Faculty of Natural Science and Mathematics, Mladena Stojanovića 2, Banja Luka 78000, Bosnia and Herzegovina
[c] University of Montenegro, Faculty of Tourism and Hospitality, Stari Grad, 320, Kotor 85330, Montenegro
[d] Geographical Institute "Jovan Cvijić" of the Serbian Academy of Sciences and Arts, Đure Jakšića 9, Belgrade 11000, Serbia
[e] Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University, Arhimedova 3, Skopje 1000, North Macedonia

A R T I C L E I N F O

Keywords:
Low flow
Hydrology
Non-stationarity
Trend
Western Balkan

A B S T R A C T

Study region: This study focuses on the Western Balkans, specifically analyzing river basins across Bosnia and Herzegovina, Serbia, Montenegro, and North Macedonia.
Study focus: The objective is to investigate long-term trends in minimum river discharges from 1961 to 2020, with an emphasis on low-flow events and their seasonal dynamics. Minimum discharge magnitudes were categorized as M1 (lower) and M2 (higher) based on the 1961–1990 baseline period. Seasonal Mann–Kendall trend tests were applied to detect significant changes in low-flow frequency and intensity across a representative network of gauging stations.
New hydrological insights for the region: The results reveal a statistically significant increase in the frequency of M1 low-flow events during summer, indicating more severe low-flow conditions. This trend is especially prominent across central and southern stations. Winter season analyses also suggest rising minimum discharge values, albeit with spatial variability. Conversely, M2 events, indicative of relatively higher minimum flows, show a consistent and statistically significant decline across nearly all stations during summer. These opposing trends reflect a regional intensification of summer low-flow conditions and a possible shift in the seasonal flow regime. The findings underscore the growing vulnerability of Western Balkan river systems to hydrological droughts, likely driven by climate change and local watershed pressures. These insights hold practical relevance for water resource management, highlighting the urgency of adaptive strategies for drought mitigation and ecological flow preservation.

1. Introduction

Hydrological drought is a major natural hazard characterized by prolonged water deficit in rivers, lakes or groundwater compared to normal levels, leading to significant negative impacts on the environment and human activities (Sutanto et al., 2024; Van Loon, 2015). Understanding the mechanisms behind the occurrence and evolution of droughts has become increasingly important due to the

* Corresponding author.
E-mail addresses: lescesen@uh.savba.sk (I. Leščešen), slobodan.gnjato@pmf.unibl.org (S. Gnjato), duskov@ucg.ac.me (D. Vujačić), a.petrovic@gi.sanu.ac.rs (A.M. Petrović), ivan.radevski@pmf.ukim.mk (I. Radevski).

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increasing pressure that population growth is placing on global water resources and the uncertainties brought about by climate change and the intensification of the hydrological cycle (Raczyński and Dyer, 2022). The increasing frequency of drought risks, exacerbated by both human activities and global climate change, has profound implications for environmental health, economic prosperity and social stability (Vicente-Serrano et al., 2020, Stoyanova et al., 2022; Milovanović et al., 2023). Hydrometeorological factors such as precipitation, evapotranspiration and runoff play a crucial role in controlling the occurrence and progression of droughts, making their assessment complex and challenging (Mishra and Singh, 2010). The complexity of characterizing the severity and risk of droughts arises from their far-reaching impacts over large areas and long periods, sometimes spanning months, years, or even decades (Peña-Angulo et al., 2022). Managing future water supplies requires an understanding of the spatial and temporal patterns of historical droughts, which is a common challenge in hydrology (Van Loon et al., 2024). As a result, research on hydrological droughts has greatly increased worldwide in the last decade (Shi et al., 2022; Haile et al., 2020; Hasan et al., 2019; Wanders and Wada, 2015; Prudhomme et al., 2014). While much of this global research has focused on continental or national scales, there is a growing recognition that regional-scale analyses are necessary to capture the nuances of local hydrological regimes and their responses to climate change. This recognition has particular importance for regions such as the Western Balkans, where complex topography, transboundary river systems, and diverse climate zones interact to produce unique drought dynamics.

The minimum flow data are important for several reasons. They determine water availability and guide the allocation of water resources for various uses such as irrigation, drinking water supply and industrial needs, especially during dry periods (Depetris, 2021). Understanding minimum flows is essential for maintaining the health of aquatic ecosystems and protecting sensitive species that depend on specific flow regimes, as low flows can stress aquatic life and degrade habitats (Depetris, 2021). Furthermore, minimum discharge information is necessary for planning and operating hydropower projects, as it determines the reliable power generation capacity of a river (Depetris, 2021). Analyzing minimum discharge trends aids in predicting and managing droughts and in designing appropriate mitigation strategies. River discharge data reflects changes in precipitation patterns, temperature, and evaporation rates, all of which are directly influenced by climate change. Analyzing discharge trends helps identify shifts in water availability and seasonal flow patterns, essential for understanding the broader impacts of climate change on water resources (Däll and Zhang, 2010). Climate change is expected to modify river flow regimes across Europe, including Southeast Europe. Factors such as rising temperatures, changes in precipitation patterns, and declining snow cover will interact variably across different climate zones, potentially leading to increased water stress in southern regions while northern areas may experience more stable water resources (Schneider et al., 2013). Despite this broader European perspective, the Western Balkans remain underrepresented in many studies on streamflow droughts, particularly with respect to minimum discharge trends. This lack of region-specific knowledge is problematic given the area's sensitivity to hydroclimatic extremes and its reliance on rivers for hydropower, water supply, and agriculture. Our study addresses this gap by providing a detailed and seasonally resolved analysis of minimum discharge trends at multiple hydrometric stations across the Western Balkans. By focusing on the frequency and intensity of minimum discharge events, this study offers new hydrological insights into the evolving drought risk in a climate-vulnerable region, where integrated water resource management is increasingly urgent.

In Southeast Europe, the Drina and Lim River Basins, part of the larger Sava River Basin, have been identified as sub-hotspots for climate change vulnerability. These basins face risks from flooding, hydropower disruption, and pollution as temperatures keep rising (Rüttinger et al., 2021). Recent studies highlight changing patterns of minimum river discharge in Europe. For example, Vlach et al. (2020) found a significant increase in summer low flows in Central European headwaters, particularly in catchments at altitudes of 800 – 1000 m above sea level. Šimor and Ľupták, (2021) observed changes in minimum and average annual discharges in Slovak rivers, raising concerns about environmental and aquatic life impacts. Alecci and Rossi (2020) discussed these issues within the context of Italian legislation, while Hagemann et al. (2020), emphasized the need for high-resolution discharge simulations to accurately capture these changes, particularly in climate change studies. Regional and local hydrological studies are crucial for presenting the spatial and temporal variability of runoff characteristics, despite their relatively small scale (Cammalleri et al., 2020; Valiya Veettil and Mishra, 2020). Assessing streamflow extremes on a local scale should start with identifying typical seasonal variations over time (Mishra and Singh, 2010). With the changing climate, these patterns may either intensify or weaken over longer periods (Raczyński and Dyer, 2022). The increasing frequency, intensity, and duration of streamflow droughts in mid-latitudes of the Northern Hemisphere are some of the predicted effects of climate change (Van Loon, 2015). The severity of droughts in Europe over the last decade suggests that climate change will likely affect runoff seasonality, variability of discharge, and the risk of extreme streamflow drought occurrence (Langhammer and Bernsteinová, 2020). Under conditions of rising air temperatures, increasing evaporation rates, decreasing soil moisture (Hanel et al., 2018), and decreasing snow cover in Central Europe (Blöschl et al., 2019), droughts are more likely to occur and escalate into multiyear events.

Given the importance of understanding hydrological droughts and their impacts on river basins in the Western Balkans, this paper provides a detailed analysis focusing on minimum discharge events. First, we introduce the significance of hydrological droughts, the escalating pressures from climate change, and the necessity of understanding drought mechanisms (Section 1). We emphasize the need for an in-depth examination of minimum discharge data and its environmental and socio-economic implications. Next, we describe the study area, detailing the geographical, climatic, and hydrological characteristics of the Western Balkans (Section 2). This section highlights the diversity of landscapes and climate influences in the region. In Section 3, we outline the data collection and methods used in our analysis. This includes the hydrometeorological data sources, the time span of the data (1961–2020), and the statistical methodologies employed to analyze minimum discharge trends. We also discuss the sensitivity analyses conducted to address data gaps and ensure result reliability. Section 4 is dedicated to seasonal analysis, differentiating between winter and summer minimum discharges. We explore the distinct meteorological and hydrological factors influencing each season and their implications for drought events. In Section 5, we perform a trend analysis using advanced statistical tests to detect and validate trends in minimum discharge events over the study period. This section provides insights into the regional and seasonal variability of hydrological extremes. The Results and Discussion section (Section 6) presents our findings, highlighting significant trends in occurrence rates and their implications for water resource management. We discuss the practical implications of our results for future hydrological assessments and climate change adaptation strategies in the Western Balkans. Finally, Section 7 concludes with a summary of key findings and their relevance for future research and policy-making in the context of hydrological droughts in the Western Balkans.

2. Study area

The term "Western Balkans" (WB) was introduced by European Union authorities in the early 2000s to describe a group of Southeast European countries that were neither members nor official candidates of the EU at the time but were considered to have potential for future accession (Dabrowski and Myachenkova, 2018). Geographically, this region is situated between Hungary to the north and Greece to the south, bordered by Croatia and the Adriatic Sea to the west and by Romania and Bulgaria to the east. The Western Balkans, as defined here, encompass the nations of Serbia, Bosnia and Herzegovina, Montenegro, Albania, and North Macedonia. The region's physiography is dominated by the rugged terrain of the Balkan Peninsula, with extensive mountainous zones such as the Dinaric Alps and the Balkan Mountains. In contrast, the northern part of Serbia extends into the Pannonian Plain, introducing considerable geographical diversity. The study area spans approximately 153,300 km^2, comprising of Serbia covering 88,361 km^2 (Milošević et al., 2021), Bosnia and Herzegovina 51,129 km^2 (Đug and Drešković, 2012), Montenegro 13,812 km^2 (Fabris and Zugic, 2012) and North Macedonia 25,713 km^2 (Radevski et al., 2018) with a combined population of roughly 13 million (Milošević et al., 2021) (Fig. 1). Climatically, the region exhibits a high degree of variability. While much of the area experiences a continental or temperate continental climate, mountainous regions are characterized by alpine conditions. The Adriatic coast and its hinterland are influenced by sub-Mediterranean and Mediterranean climates, adding to the region's hydrometeorological complexity. This climatic heterogeneity, coupled with the geographical diversity, makes the Western Balkans particularly sensitive to climate-induced hydrological extremes such as floods and droughts.

Fig. 1. Geographical location of gauging stations and countries in the Western Balkans.

3. Data and methods

3.1. Data set

The data used in this study come from various hydrometeorological services from several countries and include the monthly minimum discharges for several rivers and stations from 1961 to 2020 (2015 for stations in North Macedonia), as shown in Fig. 2. Data sources include the Hydrometeorological Service of the Republic of Srpska, the Hydrometeorological Service of the Republic of Serbia, the Hydrometeorological Service of North Macedonia and the Hydrometeorological Institute of Montenegro. Monthly low-flow conditions is an important metric for assessing water availability and managing drought risks (Bodner et al., 2015; Gnjato et al., 2024; Vogt et al., 2018), which is particularly important given global water stress scenarios where freshwater bodies are essential for human consumption (Van Beek et al., 2011). Analyzing the severity and duration of annual maximum river flows helps to understand the spatial and temporal variability of drought (Niaz et al., 2021). These insights, coupled with threshold level methodologies and pooling techniques, facilitate drought characterization and mitigation strategies (Fleig et al., 2006).

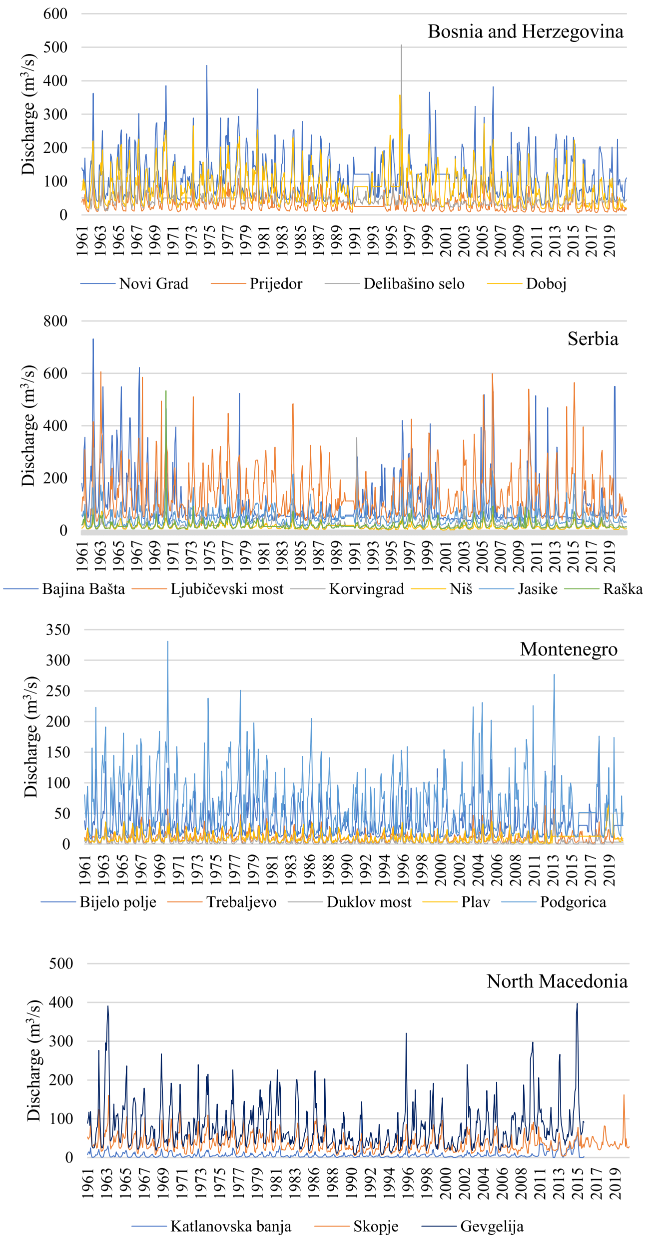

Fig. 2. The minimum monthly discharges of the rivers used in this study.

Table 1
Information about the data used in this study.

River	Station	Country	Data Period	Missing data
Una	Novi Grad	Bosnia and Herzegovina	1961–2020	1991,1992, 2000, 2001
Sana	Prijedor		1961–2020	1991,1992,1993, 1994
Vrbas	Delibašino Selo		1961–2020	No missing data
Bosna	Doboj		1961–2020	No missing data
Drina	Bajina Bašta	Serbia	1961–2020	1973, 1975,1990
Velika Morava	Ljubičevski most		1961–2020	1990
Zapadna Morava	Jasika		1961–2020	1990
Nišava	Niš		1961–2020	1990
Južna Morava	Korvingrad		1961–2020	1975,1990
Ibar	Raška		1961–2020	1981, 1982, 1990
Lim	Bijelo Polje	Montenegro	1961–2020	2016
Tara	Trebaljevo		1961–2020	2020
Zeta	Duklov most		1961–2020	2016, 2019, 2020
Lim	Plav		1961–2020	2013, 2014, 2015
Morača	Podgorica		1961–2020	2016, 2017
Vardar	Skopje	North Macedonia	1961–2020	No missing data
Pčinja	Katlanovska Banja		1961–2015	No missing data
Vardar	Gevgelija		1961–2015	No missing data

Hydrological datasets often have gaps, outliers or erroneous entries which, if not treated appropriately, can significantly affect statistical rigor and lead to erroneous interpretations of the phenomena studied (Łopucki et al., 2022). To assess the sensitivity of our study results to the completeness of the data, we performed a rigorous sensitivity analysis comprising three hypothetical scenarios: (b1) assuming that all missing months contained magnitude 1 (M1) events, (b2) assuming that all missing months contained magnitude 2 (M2) events, and (b3) assuming that no events occurred in the missing months. To fill these gaps, a method was used in which the mean discharge values were used, with values below the average maximum discharge for the entire period being used in scenario b1 and values above this average being used in scenario b2. Evaluation of results indicated that scenario b2 exhibited marginally higher means, lower standard errors, and slightly reduced skewness compared to scenarios b1 and b3. This meticulous approach underscores the importance of handling missing data comprehensively to uphold the integrity and reliability of hydrological analyses and subsequent interpretations.

In the hydrological assessment of the rivers in Bosnia and Herzegovina, scenario b1 was considered suitable for the Sana River. This decision was based on the fact that b1 has competitive mean discharge values, a reasonable range, consistent interquartile ranges and lower standard errors over several months. Overall, these factors indicate that b1 provides a stable and reliable estimate of the minimum flows required to maintain the hydrologic integrity of the Sana River. Importantly, the Sana River is characterized by moderate baseflow contributions from karstic springs, leading to less extreme variability during dry periods. This hydrological behavior aligns well with the more conservative assumptions of scenario b1, which favors lower discharge values and thus provides a realistic estimation of minimum flow conditions for this type of catchment.

In contrast, scenario b2 was chosen for the Una, Vrbas and Bosna rivers. The decisive factor for this decision was that b2 showed consistently higher mean discharge values throughout the year, indicating potentially better sustained flow conditions. In addition, b2 had a balanced range of discharge values and acceptable standard errors, ensuring reliable estimates that are crucial for effective water resource management and conservation of ecology in these river basins. These rivers exhibit more dynamic hydrological regimes, including substantial snowmelt inputs and stronger seasonal fluctuations. Such regimes are more consistent with the assumptions embedded in scenario b2, which uses higher infill values that better capture the elevated discharge levels typical of these basins during snowmelt and wet seasons. This approach ensures that seasonal hydrological dynamics are not underestimated in flow reconstruction.

Based on the statistical measures, scenario b2 is the most suitable for the Nišava River's minimum discharge. It consistently shows higher mean discharge values across all months, indicating better sustained flow conditions. The range of discharge values in b2 is comparable to b1 but lower than b3, suggesting greater stability and fewer extreme variations. The interquartile range (IQR) values for b2 are comparable to b1, indicating consistent flow conditions. Despite slightly higher standard errors, b2's benefits of higher mean discharge and manageable variability make it the best choice for ensuring reliable minimum discharge levels in the Nišava River. Hydrologically, the Nišava River exhibits both rainfall and snowmelt influences, resulting in a relatively flashy response. Scenario b2, by imputing higher discharge values during missing periods, better reflects this variability, ensuring that the analysis does not underestimate the flow regime's responsiveness to precipitation inputs.

In Montenegro, scenario b1 is identified as the optimal solution for addressing data gaps in river discharge measurements across several key stations. For the Podgorica station on the Morača River and Bijelo Polje stations on the Lim River, b1 demonstrates moderate mean values and low standard error, ensuring reliable mean estimates and aligning well with hydrological conditions. Similarly, for the Trebaljevo station on the Tara River, b1 offers a balanced approach with moderate variability. The Zeta River also benefits from b1's consistent and reliable data representation. Lastly, at the Plav station on the Lim River, b1's moderate variability and reliable mean estimates make it the best choice for accurate data representation. The rivers in this region often display a relatively stable baseflow sustained by snowmelt and groundwater contributions, particularly from karstic aquifers. Scenario b1, with its moderate discharge imputations, is more appropriate for these stable flow regimes, as it avoids overestimating discharge during missing periods while still accounting for expected flow continuity in these systems.

3.2. Seasonal analysis

It is crucial to differentiate between winter and summer minimum discharges due to the unique meteorological and hydrological factors influencing each season. By analyzing the seasonal variations, we can gain valuable insights into the mechanisms and conditions driving hydrological drought events. Understanding these distinct seasonal patterns helps in identifying the contributing factors to droughts, which often transcends seasonal boundaries. This comprehensive analysis can aid in developing more effective hydrological drought management strategies and improve our understanding of the underlying causes of this hydrological extreme throughout the year.

Hisdal et al. (2001) and Hannaford and Buys (2012) found that short-term trends in the magnitude and direction of river discharge are strongly influenced by multi-decadal variability, often obscuring long-term patterns. Vicente-Serrano et al. (2021) found the absence of statistically significant long-term trends in meteorological droughts in Western Europe, while Masseroni et al. (2021) found a significant decrease in annual runoff volumes in the Mediterranean regions. These findings highlight the critical importance of longer-term datasets for accurately assessing and understanding the variability and trends in river flows and drought events across Europe. Conducting seasonal assessments of minimum flows in Europe remains crucial for understanding the hydrological dynamics in the region.

The data set was divided into two categories: the hydrological summer (April to September), which is mainly influenced by intense precipitation, and the hydrological winter (October to March), which is influenced by a combination of precipitation and snowmelt. The distinction between winter and summer minimum flows is crucial due to their different meteorological and hydrological characteristics. This distinction is essential to gain comprehensive insights into the patterns and causes of hydrological droughts. It is important to recognize that minimum flows can extend beyond certain seasons, which underscores the need for this distinction to fully understand the dynamics of hydrological droughts. To investigate temporal variations in minimum river flows and identify significant trends, we employed kernel estimation with associated confidence bands. This non-parametric method uses a Gaussian kernel function to assign weights to observed extreme event data $T_{(i)}$, where $i = 1,2,\ldots, N$, and estimates the time-varying frequency $\lambda_{(t)}$ of these events, as defined in Eq. 1.

$$\lambda_{(t)} = \sum_i K((t - T_{(i)}) \Big/ h) \tag{1}$$

The bandwidth parameter h, which governs the smoothness of the estimated trend, was set to 20 years based on cross-validation to ensure an optimal balance between bias and variance. This approach allows for a flexible, data-driven assessment of trends in the frequency of low-flow events over time, without assuming a predefined functional form. The resulting time series of $\lambda_{(t)}$ facilitates the identification of periods with elevated or diminished frequencies of minimum flows, thereby supporting a nuanced analysis of temporal dynamics in hydrological extremes. To ensure statistical robustness, we constructed 90 % confidence bands around $\lambda_{(t)}$ by applying a bootstrap resampling procedure with 5000 iterations, generating empirical percentile-based confidence bounds. Our investigation also included trend detection in a non-stationary framework, using advanced kernel techniques to estimate time-varying occurrence rates. Bootstrap confidence bands were constructed following the methodology of Mudelsee (2020) to ensure a rigorous assessment of the significance of trends amid the temporal variations in the occurrence of extreme events.

3.3. Trend analysis

To assess the significance of the estimated curves for the frequency of occurrence, we used the Cox-Lewis test, a statistical method developed by Mudelsee et al. (2004) specifically for the analysis of extreme events. This approach rigorously examines the presence of upward or downward trends in event rates. We applied this test to validate the trends observed from 1961 to 2020 by contrasting the null hypothesis (H0) of a constant event rate with the alternative hypothesis (H1) of an increasing event rate. This robust statistical framework allowed us to thoroughly analyze the temporal changes in the frequency of extreme events and determine their significance over the specified study period.

$$u = \left[\sum \frac{T(i)}{n} - \frac{(t_2 + t_1)}{2} \right] \Big/ \left[(t_2 - t_1)(12n)^{-\frac{1}{2}} \right] \tag{2}$$

As the sample size (n) increases, the test statistic u quickly converges to a standard normal distribution. In this context, T(i) (with i = 1, …, n) stands for the data of the extreme events, n for the size of the data set and [t1, t2] for the observation interval Mudelsee (2020). This statistical model illustrates that as the number of data points increases, the distribution of the test statistic u converges to a standard normal distribution. This convergence enhances the reliability of interpreting significance levels in studies of extreme event occurrences over time.

In our study, we examined two categories of events based on different thresholds. First, we used the 30-year average minimum flow (1961–1990) as a threshold, a standard criterion established by the World Meteorological Organization (WMO) for both the summer (April-September) and winter (October-March) seasons. We have also divided the minimum flows into two levels: Magnitude 1 (M1), representing extreme events where minimum flows were below the threshold, and Magnitude 2 (M2), representing severe events where flows exceeded the threshold (see Table 2). This classification allowed us to distinguish between different intensities of extreme hydrological events based on established thresholds and provided a systematic framework for analyzing and interpreting the patterns of minimum river flow occurrence across different seasons.

4. Results

The analysis of streamflow data from various gauging stations across the Western Balkan region reveals significant insights into the hydrological behavior and variability within the area. Table 3 presents the descriptive statistics for all gauging stations used in this study, encompassing measurements such as mean discharge, median discharge, standard error, standard deviation, kurtosis, and skewness. These statistics provide a comprehensive overview of the flow characteristics at each station, highlighting both central tendencies and variability in discharge rates.

The values of skewness indicate asymmetry in discharge distributions, while kurtosis provides information on the peakedness of the distribution. Together, these descriptors characterize the statistical shape of discharge variability, providing context for understanding flow regimes across sites.

4.1. Trend analysis

Non-stationary trend analysis to detect trends in minimum flows is an important area of research, especially in the context of climate change and its impact on water resources. In the context of hydrological trend analysis, statistically significant values ($p < 0.05$) indicate that the observed changes in low-flow conditions are unlikely to be due to random variability alone and instead reflect meaningful alterations in the hydrological regime most commonly attributable to climatic change or other anthropogenic influences. The results of the seasonal Mann-Whitney *U* test and Cox-Lewis tests provide valuable insights into the regional and seasonal variations in minimum flows and offer a nuanced understanding of how these extremes evolve under changing climatic conditions.

The Cox-Lewis tests at various stations show different trends between the summer and winter seasons. At the Novi Grad station on the Una River, non-significant p-values are observed for both seasons. At the Prijedor station on the Sana River, on the other hand, significant deviations in M2 are observed for both seasons. The Delibašino Selo station on the Vrbas River shows the most significant trends, with all p-values being highly significant (except for M1 events). The Doboj station on the Bosna also shows significant deviations. During the summer season, M1 events show a weak upward trend at most stations, with only the Doboj station showing a statistically significant increase. In contrast, M2 events show a statistically significant downward trend at three stations: Prijedor on the Sana River, Delibašino Selo on the Vrbas River and Doboj on the Bosna River. Significant trends are also observed at the Bajina Bašta station on the Drina River. The stations Ljubičevski most on the Velika Morava River and Jasika on the Zapadna Morava River show non-significant p-values. At the Niš station on the Nišava River, significant changes are observed in both the summer and winter seasons. The Korvingrad station on the Južna Morava River and Raška station on the Ibar River show non-significant p-values. At the Skopje station on the Vardar River, significant deviations in M2 are observed for both seasons. At the Bijelo Polje station on the Lim River, M2 events have a statistically significant decreasing trend. The Trebaljevo station on the Tara River shows significant winter trends in both M1 and M2 events as well as a significant decrease in summer M2 events. The Duklov most station on the Zeta River displays statistically significant increasing (M1 events) and decreasing (M2) events, while during the summer season, no changes were

Table 2
Threshold levels applied to dataset to determine the magnitude of the event (in m^3/s).

No*	River	Station	Country	Threshold level	
				Summer season	Winter season
1	Una	Novi Grad	Bosnia and Herzegovina	110.2	121.2
2	Sana	Prijedor		36	37.8
3	Vrbas	Delibašino Selo		51.9	48.8
4	Bosna	Doboj		81.8	87.5
5	Drina	Bajina Bašta	Serbia	118	89
6	Velika Morava	Ljubičevski most		142	149.2
7	Zapadna Morava	Jasika		51.9	55.4
8	Nišava	Niš		16.6	15.9
9	Južna Morava	Korvingrad		25.9	26.6
10	Ibar	Raška		21.5	19.9
11	Lim	Bijelo Polje	Montenegro	44.5	29.9
12	Tara	Trebaljevo		12.3	9.5
13	Zeta	Duklov most		5.9	4.6
14	Lim	Plav		14.7	7.3
15	Morača	Podgorica		63.8	74.1
16	Vardar	Skopje	North Macedonia	40.01	38.4
17	Pčinja	Katlanovska Banja		5.1	6.5
18	Vardar	Gevgelija		75.6	86.7

* No represents the location of the station in Fig. 1

Table 3
Descriptive statistics of eighteen gauging stations in the Western Balkan region.

No*	Station	N	Mean minimum (m^3/s)	Median Minimum (m^3/s)	St. error	St. deviation	Kurtosis	Skewness
1	Novi Grad	720	112.8	99.8	2.37	63.65	0.885	1.395
2	Prijedor	720	32.4	24.9	0.89	23.97	0.769	1.842
3	Delibašino S.	720	45.35	39.8	1.05	23.97	0.769	7.694
4	Doboj	720	79.22	68.7	1.93	51.94	0.878	1.274
5	Bajina Bašta	720	98.69	57.2	3.68	99.23	0.580	2.793
6	Ljubičevski	720	135.1	106.5	3.56	95.72	0.788	1.829
7	Jasika	720	54.07	43.6	1.33	35.66	0.807	1.785
8	Niš	720	14.06	10.5	0.41	11.12	0.747	2.066
9	Korvingrad	720	26.63	19.3	1.01	27.35	0.727	5.242
10	Raška	720	20.03	15.05	0.88	23.70	0.751	14.619
11	Bijelo Polje	720	34.1	26.8	0.94	25.23	0.785	1.745
12	Trebaljevo	720	9.8	7.3	0.32	8.73	0.742	2.155
13	Duklov most	720	4.6	2.5	0.22	6.16	0.534	2.580
14	Plav	720	10.5	8.5	0.29	7.98	0.817	1.967
15	Podgorica	720	62.7	51.4	1.79	48.19	0.819	1.358
16	Skopje	720	35.68	29.63	0.82	22.06	0.831	1.501
17	Katlanovska	660	6.77	4.13	0.33	8.55	0.609	4.001
18	Gevgelija	660	78.41	60.9	2.32	59.52	0.776	2.041

* No represents the location of the station in Fig. 1

observed. At the Plav station on the Lim River, both summer and winter measurements indicate significant trends. The Podgorica station on the Morača River also shows significant results for both seasons, but in both cases, statistically significant decreases of M2 events are observed. The stations Katlanovska Banja on the Pčinja River and Gevgelija station on the Vardar River show stable conditions with non-significant p-values.

4.2. Occurrence rate and frequency

Understanding the dynamics of minimum river flows is essential for sustainable water resource management, ecosystem protection, infrastructure design and understanding the impacts of environmental change on river systems.

Fig. 3 illustrate the frequency of minimum discharges for four river stations: Doboj (Bosna River) and Bajina Bašta (Drina River), Podgorica (Morača River) and Skopje (Vardar River) during both the summer and winter seasons from 1961 to 2020. At the Doboj station (Vrbas River), there is a clear, statistically significant, increasing trend in the frequency of minimum flows in both summer ($u=1.775$, $p = 0.038$) and winter ($u=2.154$, $p = 0.015$). The data at the Bajina Bašta station (Drina River) also show a significant increase in the frequency of minimum flows. The graph for the summer season shows a significant increase ($u=1.938$, $p = 0.026$), and the winter season reflects a similar trend ($u=2.267$, $p = 0.011$). The data for the Podgorica station on Morača River also show a significant increase in the frequency of minimum flows both during summer ($u=1.840$, $p = 0.033$) and winter season ($u=2.075$, $p = 0.019$). The summer season results for the Skopje station on the Vardar River indicate a notable increase in the frequency of minimum flows, although this trend is not statistically significant ($u=1.452$, $p = 0.073$). During the winter season, the occurrence rates of minimum discharges also exhibit an increasing trend, which is marginally more significant ($u=1.568$, $p = 0.058$).

Fig. 4 shows the frequency of minimum discharges above the 1961–1990 threshold for the stations Doboj on the Bosna River, Bajina Bašta on the Drina River and Skopje on the Vardar River during the summer and winter seasons. At the Doboj (Bosna River) station, a significant downward trend in occurrence rates can be observed in both the summer and winter seasons, with p-values of 0.006 and 0.045, respectively. At the Bajina Bašta station (Drina River), the occurrence rates also decrease in both seasons, whereby the statistical significance is stronger in the summer season (p-value 0.031) than in winter (p-value 0.047). At the Morača River (Podgorica station), a significant downward trend in occurrence rates of M2 events is observed in both the summer and winter seasons, with p-values of 0.002 and 0.007, respectively. The Skopje station (Vardar River) also shows statistically significant decreasing trends in occurrence rates for both seasons, with p-values indicating statistical significance (0.016 for summer and 0.020 for winter).

4.3. Regional characteristics

Occurrence rate and frequency of minimum river discharges can vary significantly across different regions due to local climate, topography, or land use. Understanding these regional differences helps in developing tailored management strategies. local water resources, including public water supply, agriculture, and hydropower generation (Sutanto et al., 2024).

Fig. 5 provides a comprehensive visualization of the statistically significant increasing and decreasing trends in the frequency of magnitude 1 and 2 runoff minimum events for the summer and winter seasons, respectively, at different hydrological stations in the Western Balkans region. For the M1 events (Fig. 5A), there is a statistically significant increasing trend in the frequency and occurrence rate of discharges below the 1961–1990 threshold at several stations, including Doboj on the Bosna River, Bajina Bašta on the Drina River, Niš on the Nišava River, Duklov most on the Zeta River, Plav on the Lim River and Podgorica station on the Morača River during

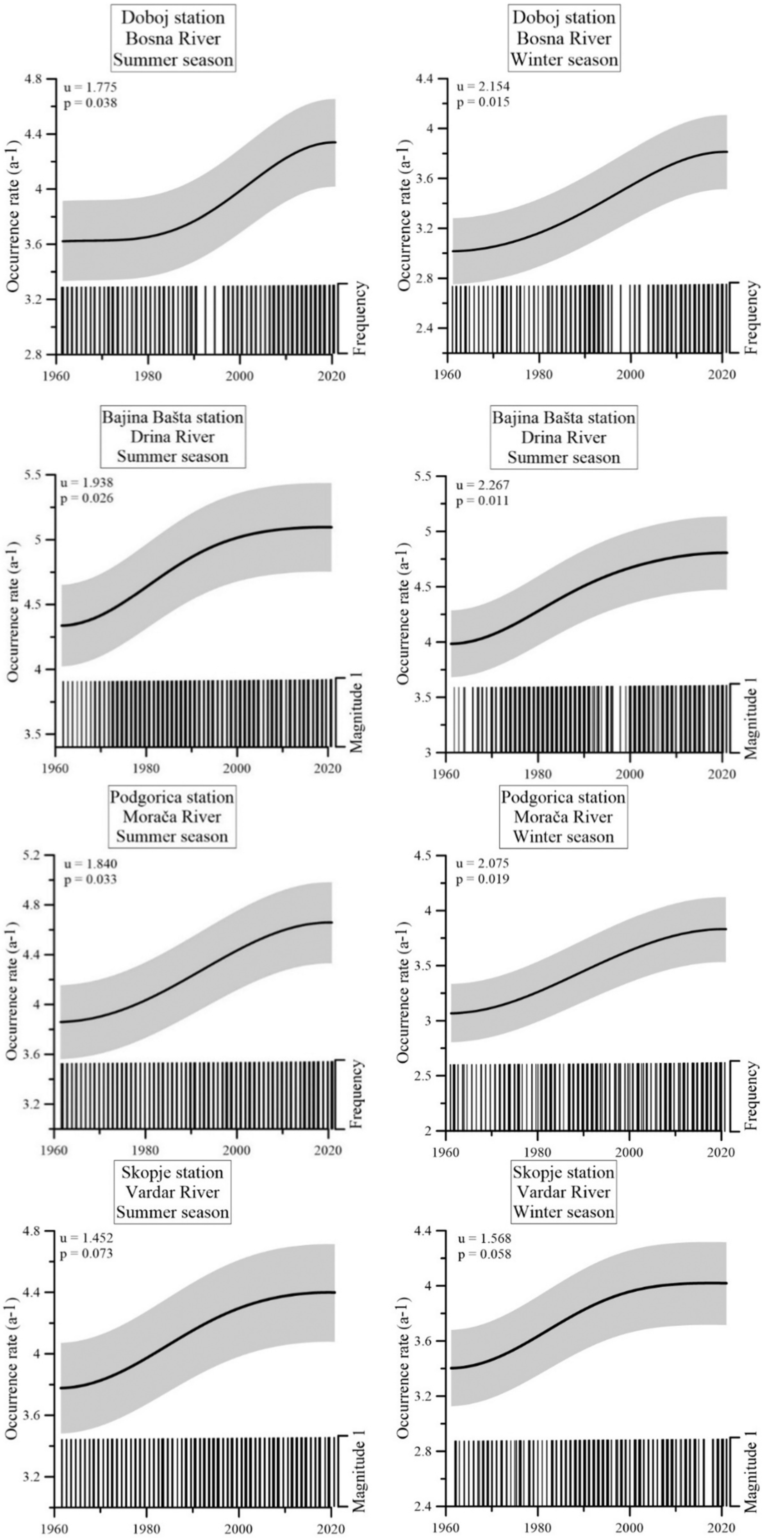

Fig. 3. Occurrence rates (solid lines) of M1 minimum discharges at four selected stations for two seasons with bootstrap 90 %confidence band (shaded). kernel estimation using a bandwidth of 20 years is applied to the flood dates with the cox and lewis test results for trend estimation (upper left-right corner of each graph).

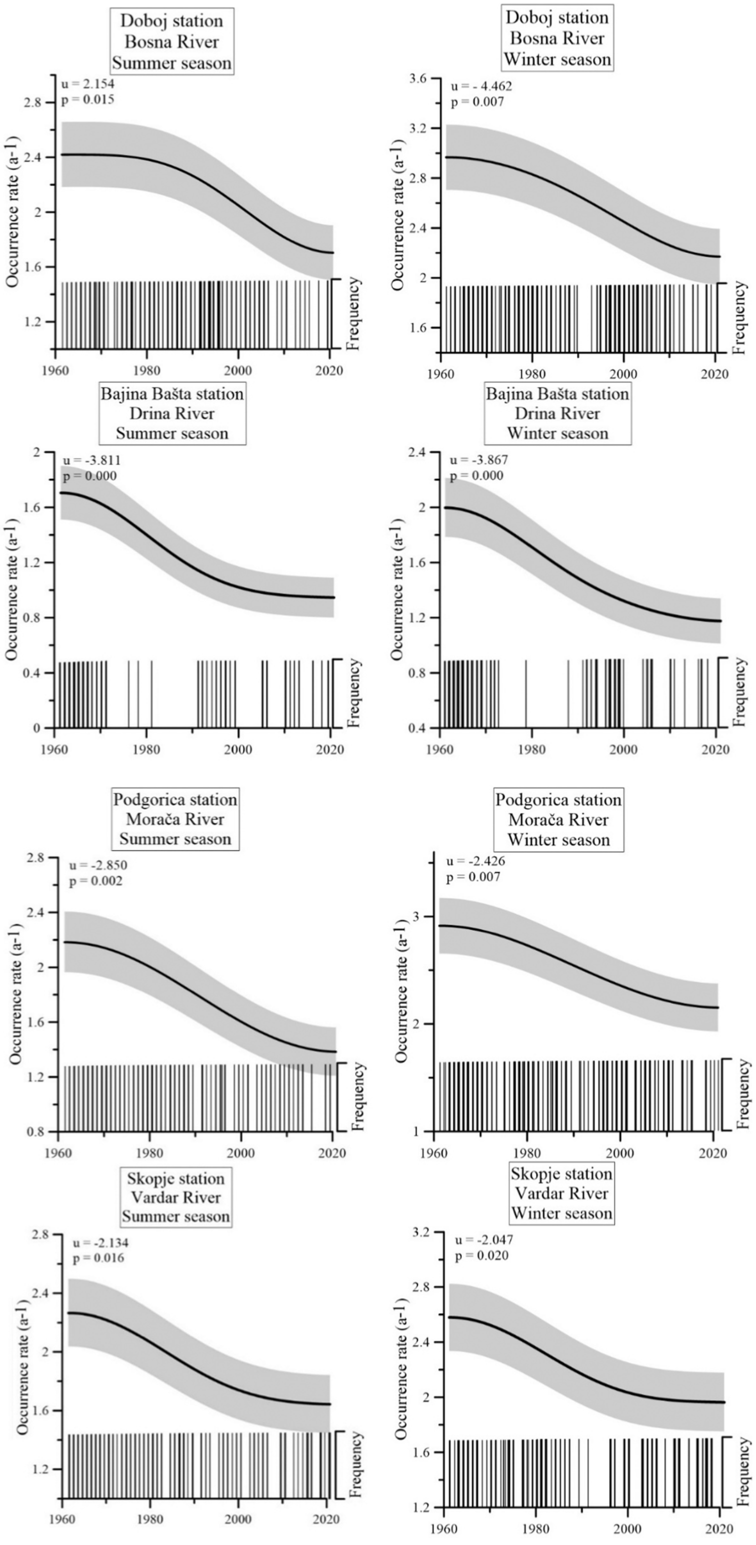

Fig. 4. Occurrence rates (solid lines) of M2 minimum discharges at four selected stations for two seasons with bootstrap 90 %confidence band (shaded). kernel estimation using a bandwidth of 20 years is applied to the flood dates with the cox and lewis test results for trend estimation (upper left-right corner of each graph).

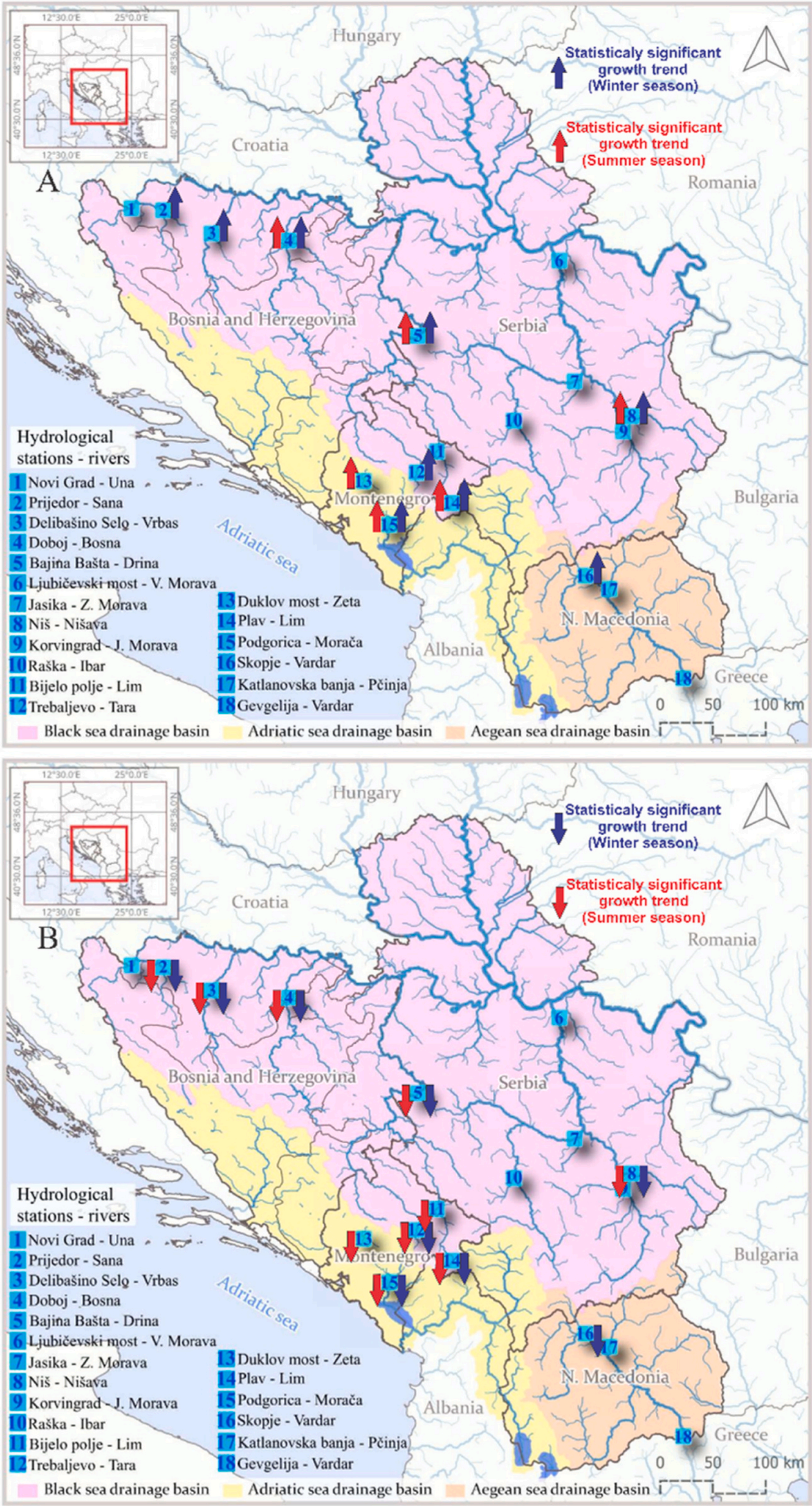

Fig. 5. Seasonal occurrence rates of magnitude 1 (A) and magnitude 2 (B) events. Summer season (Red Arrows) and winter season (Blue Arrows).

the summer season. In Bosnia and Herzegovina, an upward trend in M1 events was also observed for the remaining three stations (Novi Grad – Una River; Prijedor – Sana River and Delibašino Selo – Vrbas River). Increasing trends were also observed in winter (blue arrows) at stations such as Prijedor on the Sana River, Delibašino selo on the Vrbas River, Doboj on the Bosna River, Bajina Bašta on the Drina River, Niš on the Nišava River, Trebaljevo on the Tara River, Plav on the Lim River, Podgorica on the Morača River and Skopje on the Vardar River. For magnitude 2 events (Fig. 5B), the pattern of decreasing trends in the summer season is more pronounced than for magnitude 1 events, with 55 % of the stations showing significant decreases in minimum flows above the 1961–1990 threshold. In contrast, there are less significant trends in magnitude 2 discharges in winter than in summer. However, stations such as Skopje station on the Vardar River still show decreasing trends. The downward trends in magnitude 2 discharges in summer are more widespread and pronounced. The geographical distribution of these trends is scattered across the Western Balkans region, but certain areas such as Bosnia and Herzegovina (stations such as Novi Grad – Una River and Doboj – Bosna River), parts of Serbia (stations such as Bajina Bašta – Drina River and Niš – Nišava River), and Montenegro (e.g., Podgorica – Morača River, and Plav – Lim River) show consistent patterns of decreasing minimum flows.

5. Discussion

The statistical analyses and trend analyses of runoff in the Western Balkans region reveal complex and significant changes in the hydrological regimes of the last decades. The descriptive statistics presented in Table 3 provide a basic understanding of the runoff characteristics. The skewness is an important indicator of the asymmetry of the discharge distributions and helps to recognise whether low-flow or high-flow events dominate (Collischonn et al., 2017). A positive skewness observed at several stations indicates a higher frequency of low flows, which is crucial for drought risk assessment. A high kurtosis may indicate a higher probability of extreme events, either floods or droughts, which is essential for the development of robust water management strategies (Cao et al., 2013). This comprehensive statistical overview is crucial for effectively analysing the frequency of events and for understanding regional hydrological drought dynamics.

5.1. Trend analysis

Non-stationary trend analysis is crucial for recognising trends in minimum flows, especially with regard to the impact of climate change on water resources. In the hydrological trend analysis, statistically significant values ($p < 0.05$) indicate that the observed changes in low flow conditions are probably not due to random fluctuations, but reflect significant changes in the hydrological regime, usually due to climatic changes or other anthropogenic influences. The results of the individual stations in Table 4 illustrate the complex regional dynamics of hydrological extremes, which are influenced by geographical features, climatic variations and local hydrological conditions. Such spatial heterogeneity of low flow trends is a common feature across Europe, with southern and eastern regions showing predominantly decreasing annual minimum flows, while trends in central Europe are more mixed and spatially less coherent (Leščešen et al., 2022; Stahl et al., 2010). The observed nuanced differences underline the importance of localised hydrological assessments for understanding and managing risks associated with extreme hydrological events. Our finding that there are both rising and falling trends, depending on station and scale, is consistent with detailed regional studies in the neighbouring Danube catchment, which also show a complex mosaic of low flow trends rather than a simple, uniform pattern (Van Lanen et al., 2016).

Table 4
Seasonal Mann-Whitney *u* test results for discharge data at selected gauging stations in the Western Balkan region.

No*	Station	Summer season				Winter season			
		M1		M2		M1		M2	
		u	p-value	U	p-value	u	p-value	u	p-value
1	Novi Grad	0.85	0.1991	−1.14	0.1273	1.04	0.1491	−1.09	0.1381
2	Prijedor	1.57	0.0582	−2.60	**0.0051**	1.99	**0.0233**	−2.55	**0.0052**
3	Delibašino S.	1.49	0.0670	−3.67	**0.0001**	4.10	**0.0000**	−5.72	**0.0000**
4	Doboj	1.77	**0.0381**	−2.39	**0.0081**	2.15	**0.0153**	−4.46	**0.0071**
5	Bajina Bašta	1.94	**0.0263**	−3.81	**0.0002**	2.27	**0.0111**	−3.87	**0.0000**
6	Ljubičevski m.	1.12	0.1310	−1.57	0.0581	0.27	0.3954	−0.36	0.3593
7	Jasika	0.17	0.4311	−0.24	0.4063	0.28	0.3884	−0.36	0.3591
8	Niš	2.52	**0.0052**	−3.80	**0.0000**	1.86	**0.0312**	−2.63	**0.0043**
9	Korvingrad	−0.22	0.4122	0.33	0.3721	0.02	0.4911	−0.03	0.1561
10	Raška	0.58	0.2801	−0.97	0.1653	0.30	0.3812	−0.39	0.3472
11	Bijelo Polje	1.61	0.0532	−2.21	**0.0132**	0.47	0.3191	−0.57	0.2821
12	Trebaljevo	1.22	0.1104	−1.81	**0.0351**	1.73	**0.0421**	−2.14	**0.0161**
13	Duklov most	1.88	**0.0293**	−3.21	**0.0000**	1.10	0.1353	−1.53	0.0633
14	Plav	1.80	**0.0362**	−2.64	**0.0042**	−2.93	**0.0012**	3.10	**0.0000**
15	Podgorica	1.84	**0.0334**	−2.85	**0.0023**	2.07	**0.0194**	−2.43	**0.0074**
16	Skopje	1.45	0.0731	−2.13	**0.0161**	1.57	0.0583	−2.05	**0.0201**
17	Katlanovska B.	−0.45	0.3271	0.63	0.2634	−0.24	0.4052	0.29	0.3861
18	Gevgelija	−0.28	0.3882	0.40	0.3451	0.67	0.2521	−0.89	0.1874

* No represents the location of the station in Fig. 1

Recent projections for European river networks emphasise these spatial differences and show that intermittent drought events will increase in frequency and duration under all climate scenarios, particularly in southern Europe. For example, hybrid hydrological models applied to Croatian watersheds predict an increase in the frequency of droughts by 40–60 by 2100, even under moderate warming scenarios (Mimeau et al., 2025). Recent studies in Central Europe support these findings and show that runoff conditions in rivers are changing considerably due to both natural processes and anthropogenic activities. For example, a long-term analysis of 26 Slovakian rivers revealed considerable variability in the timing and magnitude of maximum and minimum flows, with maximum flows in several large rivers now occurring up to one month earlier than in the mid-20th century. This shift is attributed to changing precipitation patterns and rising temperatures, which reinforces the need for region-specific adaptation strategies (Bačová-Mitková et al., 2024). In general, the data from Table 4 emphasise the complexity and variability of hydrological extremes in different regions and highlight the need for adaptive water resource management strategies. In addition, hydrological modelling across the UK predicts a sharp decline in low flows (up to −90 % for low flows with a return period of 10 years by 2050–2080), with the most pronounced decreases in southern and western regions. These results, which are consistent with trends observed in continental Europe, highlight the growing risk of hydrological droughts and the importance of considering both the magnitude and timing of extreme events in future water management policies (Lane and Kay, 2021).

5.2. Occurrence rate and frequency

Understanding the dynamics of minimum flows is essential for the sustainable management of water resources, the protection of ecosystems and the design of infrastructures. The consistent upward trends in M1 events (more frequent extreme low flows) at all four stations in Fig. 3, both in summer and winter, emphasize a broader regional pattern of increasing frequency of low flow events. This consistent trend indicates a possible regional hydrological shift that may be influenced by climate change, temperature increase, changing precipitation patterns and human activities affecting river flow. This intensification in the frequency of hydrological droughts is consistent with large-scale projections for southern Europe, which expect more frequent and more severe drought events under future climate scenarios (Forzieri et al., 2014). These patterns indicate that both the summer and winter seasons in the Western Balkans region will experience an increase in runoff rates underthe set 1961–1990 threshold.

Conversely, the results for M2 events in Fig. 4 indicate a consistent pattern of decreasing frequency at different rivers and stations. This reflects broader hydrological changes likely driven by climate variability and other environmental factors, indicating that discharges moderately above the historical minimum are becoming less common. This could suggest a shift towards a more polarized flow regime, with a reduction in 'normal' low-flow conditions and an increase in more extreme events, a phenomenon also observed in parts of the Mediterranean (Tramblay et al., 2021). Similar trends have been documented in recent pan-European studies, which report that the frequency and severity of both high and low flow extremes are increasing in many river basins. For instance, Blauhut et al. (2022) found that Europe has experienced significantly warmer years associated with a decrease in runoff in several regions, leading to more frequent and severe low-flow events, particularly in southern and eastern Europe. These findings underscore the urgent need for improved monitoring and forecasting systems to manage the growing risk of hydrological extremes (Bačová-Mitková et al., 2024).

Additionally, the identification of hydro-hazard hotspots, areas where both flood and drought hazards are intensifying, has become a key focus in recent European hydrology research. Studies using national-scale hydrological models have shown that such hotspots are likely to expand under future climate scenarios, particularly in western and southern Europe, further emphasizing the need for integrated water resource management approaches (Lane and Kay, 2021)

5.3. Regional characteristics and implications

The trends shown in Fig. 5 are crucial for understanding the changing hydrological dynamics in the region and their potential impact. The overall increase in extreme low-flow (M1) events can be attributed to a striking warming tendency in the northern part (Peripannonian region) of Bosnia and Herzegovina, which is the highest in the country (Popov et al., 2018a). Mean annual air temperature trends in this area are in the range of 0.4–0.5 °C (Gnjato et al., 2023a), with the most prominent increase in summer (0.4–0.6 °C/decade). Both maximum (0.5 °C/decade) and minimum (0.3 °C/decade) air temperatures show a significant rise, particularly in summer (Leščešen et al., 2023; Popov et al., 2019). This is compounded by a significant positive trend in the Warm Spell Duration Index (5.5 days/decade). While overall precipitation trends were mainly insignificant (Gnjato et al., 2023b; Popov et al., 2018), summer precipitation decreased across the entire northern part of Bosnia and Herzegovina (Gnjato et al., 2021), and the number of consecutive dry days (CDD) increased (Popov et al., 2018). This combination of rising temperatures and drier summers directly contributes to the increased frequency of M1 events.

The increase in M1 events during winter, a traditionally wetter season, underlines the profound nature of hydrological changes. This can be linked to significant winter warming (0.4–0.5 °C/decade) (Gnjato et al., 2021) and, most importantly, a notable reduction in the number of snow cover days across Bosnia and Herzegovina (Gnjato, 2022). Snow cover trends in the northern region displayed a significant decrease in the range of 4.5–5.5 days/decade (Gnjato, 2022), which most certainly induced a significant increase in the frequency of M1 events during the winter season by reducing the snowmelt contribution to winter and spring river flows. This finding is critically important and mirrors results from the European Alps, where reduced snowpack depth and earlier snowmelt, driven by winter warming, have been identified as primary drivers of declining summer low flows and shifting seasonal streamflow patterns (Jenicek et al., 2018).

The more pronounced and widespread decreasing trends in M2 events during summer (Fig. 5B) highlight the more severe impact of low flows in this season. These increased low-water events are particularly worrying as they can lead to more pronounced water scarcity and stress for aquatic ecosystems and human activities, including public water supply, agriculture, and hydropower generation (Sutanto et al., 2024). The Vardar River basin, represented by the Skopje station, shows a significant decreasing trend during the winter season in both magnitudes, indicating that this basin is potentially vulnerable during this season, particularly in agricultural water supply and management. The vulnerability of such basins in Southern Europe is well-documented, with studies in Greece and Italy also showing that changes in precipitation and temperature regimes are increasing the pressure on water resources, especially in agricultural-heavy catchments (Zeitoun et al., 2013).

In the Croatian part of the Sava River, statistically significant descending trends of mean annual discharges were observed at all three hydrologic stations in the middle course of the river during the 1931–2010 period. The changes in discharge regimes have been predominantly linked to scientifically observed climate changes (Orešić et al., 2017). A comprehensive study covering 53 hydrological gauging stations in Croatia revealed a consistent decrease in summer discharge values. Furthermore, shifts in the timing of mean discharge maxima and minima were detected, largely attributed to changes in climatic parameters such as temperature, precipitation, and evapotranspiration (Čanjevac and Orešić, 2015). In Serbia, an analysis of 94 hydrological stations indicated that river discharge increased at 32% of stations and decreased at 68%, illustrating a strong spatial heterogeneity and dominant decreasing trends (Kovacevic-Majkic and Urosev, 2014; Urošev et al., 2016). In Bosnia and Herzegovina, negative discharge trends were detected across all seasons, with the most pronounced declines occurring in winter and spring. These changes in river discharge have been shown to be strongly associated with large-scale atmospheric circulation patterns over the Northern Hemisphere, including the Arctic Oscillation, the East-Atlantic pattern, the North Atlantic Oscillation, and the East Atlantic–West Russia pattern. A significant warming of the regional climate system, when combined with persistent downward discharge trends and decreasing summer precipitation, is projected to further reduce water availability in the Lower Vrbas River Basin. Consequently, adaptation measures addressing both current and projected climate changes are imperative across critical sectors in Bosnia and Herzegovina, including agriculture, energy (hydropower), and tourism (Gnjato et al., 2019). Results presented by Burić et al. (2025) for rivers in Montenegro, also show a significant increase in the annual number of days with low and very low flows, up to 19.0 days per decade, while the number of days with high and very high flows decreased by as much as 8.6 days per decade.

The geographical hotspots of decreasing minimum flows point to areas where water management strategies need to be particularly robust. These results indicate a broader regional pattern of increasing frequency and severity of low water events in the rivers of the Western Balkans. The implications for water resource management, ecological health, and socio-economic activities are significant. Understanding these trends is critical to developing effective mitigation and adaptation strategies to address the evolving hydrological challenges posed by climate change and other environmental pressures. The data highlights the need for continuous monitoring and detailed regional studies to better predict and manage future water resource scenarios in the face of increasing hydrological variability. These trends require adaptive management strategies to ensure the sustainability of water resources and the health of ecosystems in the Western Balkan region.

This study offers important insights into low-flow conditions in the Western Balkans; however, several limitations must be acknowledged. A major constraint lies in the uneven spatial and temporal coverage of discharge data. Many rivers in the region, particularly in mountainous or remote areas, lack continuous and well-maintained gauging stations due to longstanding logistical and financial challenges. This results in data discontinuities and significant gaps that hinder robust trend analysis and limit the regional representativeness of the findings. Methodologically, the application of statistical tools such as kernel estimation and trend analysis involve assumptions, particularly regarding parameter choices like bandwidth, which may influence outcomes and introduce uncertainty. Additionally, while the study highlights seasonal patterns, it does not investigate the underlying climatic or anthropogenic drivers of low-flow dynamics in detail. Finally, the absence of future projections restricts the study's utility for anticipating low-flow conditions under climate change. These limitations underscore the need for enhanced monitoring and further research.

6. Conclusion

The aim of this study was to analyze the monthly minimum flows of different rivers in the Western Balkans, focusing on seasonal fluctuations and long-term trends from 1961 to 2020. The geographical scope included Serbia, Bosnia and Herzegovina, Montenegro and North Macedonia and covered different climatic regions and hydrological conditions. By using a robust dataset from multiple hydrometeorological services and applying rigorous data processing techniques, the study provides valuable insights into the hydrological extremes in this region.

The main results of the study show significant seasonal and regional variations in minimum river flows. The distinction between hydrological summer (April to October) and winter (November to March) allowed a comprehensive understanding of the different meteorological and hydrological influences on minimum flows. The rigorous sensitivity analysis revealed that scenario b2, which assumes higher mean runoff values, provided the most reliable estimates for several rivers, indicating better sustainable runoff conditions, which are crucial for effective water resources management.

The results show a significant upward trend in the frequency of severe low-flow events (M1) at different stations, especially during the summer season. This trend indicates a potentially increasing frequency of hydrological droughts, which can severely impact water availability and ecosystem health. For example, stations such as Doboj station on the Bosna River, Bajina Bašta on the Drina River and Podgorica on the Morača River showed a statistically significant increase in the frequency of low water in both summer and winter. These findings are consistent with broader regional patterns of increasing hydrological extremes, which are likely due to climate change and anthropogenic influences.

Conversely, the occurrence rates of more moderate low flow events (M2) showed a consistent downward trend, particularly during the summer season. Stations such as Doboj station on the Bosna River, Bajina Bašta on the Drina River, and Skopje on the Vardar River reflected significant decreases in the frequency of these flows. This trend underscores the increasing severity and frequency of low water conditions, exacerbating water scarcity issues during critical periods.

The significance of these results lies in their implications for water resource management and adaptation strategies. The observed trends indicate a regional hydrological shift, necessitating tailored management approaches to mitigate the impacts of changing climatic conditions on river discharge patterns. The study emphasizes the importance of localized hydrological assessments to address the nuanced regional dynamics of hydrological extremes effectively.

Overall, this comprehensive analysis of minimum monthly discharges in the Western Balkans provides crucial insights into the hydrological behavior and variability within the region. The study highlights the increasing frequency of low discharge events and the severity of hydrological droughts, underscoring the need for adaptive water resource management strategies. These findings contribute to the broader understanding of hydrological extremes under changing climatic conditions, offering valuable guidance for future research and policy development in the region.

CRediT authorship contribution statement

Ivan Radevski: Resources. **Ana M. Petrović:** Writing – review & editing, Validation, Resources. **Igor Leščešen:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis. **Duško Vujačić:** Writing – review & editing, Validation, Resources. **Slobodan Gnjato:** Writing – review & editing, Resources, Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Igor Lescesen reports financial support was provided by NextGenerationEU Recovery and Resilience Plan of the Slovak Republic within the framework of project no. 09I03–03-V04–00186. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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