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Hydrological Shifts in the Carpathian Basin: Climate Change Impacts on Summer Low-flows

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KEYWORDS

- hydrological trends
- climate change impacts
- Carpathian Basin
- low-flow regimes
- regionalization

ABSTRACT

To assess hydrological shifts in the Carpathian Basin, this study analyzes a 90-year summer minimum discharge dataset from 12 river stations. We reveal widespread, significant declines, with the most pronounced trends on the Danube showing an average decrease of (-8.9% per decade). Critically, we identify a systemic regime shift using Pettitt tests, with most changepoints occurring between 1968-1990. Self-Organizing Maps (SOMs) regionalize these trends into two clusters: a high-variability group (Danube/Sava) and a vulnerable, low-flow group (Tisza/Drava). These findings prove the region's growing drought vulnerability and highlight the urgent need for adaptive water management.

Introduction

The discharge of rivers plays a fundamental role in the formation of natural and human environments and directly affects extremes of water such as flooding and drought. High-pressure events have devastating human and socio-economic effects (Paprotny et al., 2018), while low-pressure events exacerbate droughts and drought conditions, affecting water supply and ecosystem sustainability (Feyen & Dankers, 2009). Changes in average discharge patterns further affect long-term availability of water resources and affect ecological integrity and agricultural productivity (Calzadilla et al., 2013; Jana-Capdevila et al, 2019). Understanding the temporal trends of river discharge is therefore essential for effective water management and climate adaptation strategies, especially in areas vulnerable to climate change.

The scientific community has undertaken significant research efforts to understand how river discharge patterns will evolve in response to climate change. Global and regional climate projections show significant changes in the hydrological system due to warming temperatures and changes in rainfall patterns (IPCC, 2021). In southern Europe and the Carpathian basin, advanced climate models predict a global drought trend that will increase precipitation and appear as a reduction in river low-flows (Kilifarska et al., 2025). Such changes will not only affect water availability, but also increase the intensity and frequency of extreme water situations. The interaction between climate change and human pressures such as land use changes and water management practices make the hydrological response of river basins even more complicated (Droll, 2014). These evolving risks require a strong understanding of flows trends to inform adaptation water management strategies and mitigate the potential negative impacts on society and ecosystems.

Several publications examine the impact of climate change on hydrological cycles at different levels, from individual river basins to continental and global assessments. Although global hydrological models provide valuable insights, their application to the regional context poses significant challenges due to calibration efforts and

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data requirements. Studies on the long-term trends in the drainage of European rivers have revealed heterogeneous patterns throughout the continent. Many studies have shown that flows in southern and eastern Europe have declined, while flows in central and northern Europe have increased (Stahl et al. 2010, Caloiero & Veltri 2019). Some estimates suggest that river discharges in northern Europe have risen by 45% since 1962 (Tuling et al., 2019), while by 2050 the discharges in Northern parts of Europe will increase by 10% to 40% and while in Southern parts of Europe discharges will reduce by 10% to 30% under the A1B scenario (Milly et al., 2005). Likewise, Lehner et al. (2006), Feyen & Dankers (2009) project a significant reduction in drought-related emissions in southern and south-eastern Europe.

Seasonal discharge patterns have also been shown to be subject to substantial changes. In most European fisheries, a positive trend in discharge is observed in winter, while in spring and summer, a negative trend is evident (Bard and et al. 2015; Bormann & Pinter 2017; Leščešen et al., 2022; Gnjato et al., 2024). This trend reaches its peak in August, indicating an increase in the risk of summer droughts. Similarly, in the regions where the average monthly discharge is the lowest during the summer, the flow has declined, except in the areas where the groundwater reserves are substantial (Fleig et al. 2010; Laizé & Hannah 2010). A comprehensive review of European hydrological trends (Bates et al., 2008) confirmed these spatially explicit patterns, emphasizing the widespread reduction in summer discharge in Central and Eastern Europe.

Despite these extensive studies, significant research gaps remain with respect to robust detection of long-term discharge trends, especially in river basins in southern and southeastern Europe. Many existing studies are based on observational data from the second half of the 20th century (Piniewski, 2018; Fiala, 2010; Treuling, 2019), restricting the ability to capture extended historical trends. Furthermore, many studies focus on analysis of extreme event frequency data or validation of entire European hydrological models, but lack comprehensive studies to assess general trends in stream flows.

To address these shortcomings, our research aims to provide a long-term assessment of the trend in minimum monthly flow rates in the four main rivers in the Carpathia Basin during the summer of water (April to September). The aim of the study is to improve the understanding of the dynamics of regional flows, (i) to characterize monthly flows in the Carpathian basin with an extensive observation dataset, (ii) to conduct a detailed analysis of flows in the Carpathian basins, where water resources are increasingly under pressure due to climate change. (ii) Identification of potential inversion points in summer discharges using observation data; (iv) Comparing our results to existing literature to contextualize our results with wider European hydrological trends. This study uses long-term emission observations and robust statistical analyses to

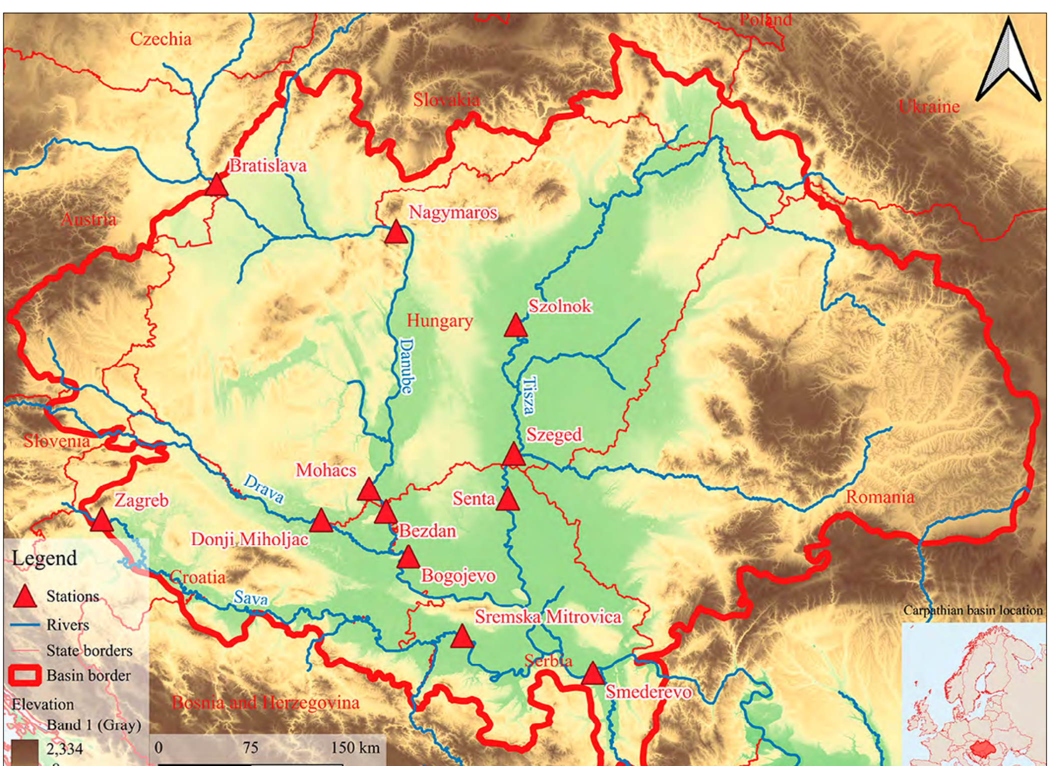

Figure 1. Study area of the Carpathian Basin, with the location of hydrological stations

Based on Gaudenyi & Mihajlovic (2022)

improve understanding of hydrological responses to climate change and inform water management strategies in vulnerable areas.

Study area

The Carpathian Basin, also known as the Pannonian Basin or Middle Danube Basin, is a large lowland basin in central and south-eastern Europe (Obreht 2019). Geographically, it is surrounded by the Alps to the west, the Carpathians to the north and east and the Dinaric Mountains, Šumadija, the Rhodope Mountains and the Balkans to the south (Gaudenyi & Mihajlović 2022). The basin stretches about 600 km from east to west and 500 km from north to south and forms a distinct geomorphologic and climatic region within the broader Alpine mountain belt in east-central Europe (Dolton, 2006). The hydrological characteristics of the region are influenced by three major climatic systems: the Atlantic, continental and Mediterranean climates. The presence of both humid oceanic and dry continental conditions further complicates the situation and leads to significant fluctuations in precipitation and temperature patterns (Mezősi, 2017). The basin is drained by four major rivers: the Danube, the Sava, the Tisza and the Drava. The Carpathian Basin spans multiple countries including Hungary, Croatia, Romania, and Serbia, extending into Austria, Slovakia, Ukraine, Bosnia and Herzegovina, and Slovenia. The present study focuses on the hydrological characteristics of Serbia, Croatia, Hungary, and Slovakia (Figure 1).

The Carpathian Basin is delineated by the ridges of mountain slopes that face the surrounding lowlands, including the Little Alföld, Alföld, Transylvanian Lowland, and Banat Plain (Gaudenyi & Mihajlović, 2022). This geomorphological configuration influences the basin's hydrology, affecting river discharge patterns, evapotranspiration, and regional water availability.

Data and methods

Data

In this work, a 90-year database (1931–2020) with daily discharge data for 12 stations in the Carpathian Basin is used (see Figure 1). The database is considered sufficiently extensive, as Kundzewicz & Robson (2000) point out that a minimum of 50 years of data is necessary to distinguish fluctuations from trends. The discharge data originate from four different national authorities (the Slovak Hydrometeorological Institute, the Meteorological and Hydrological Service of Croatia, the Hydrometeorological Service of the Republic of Serbia and the General Directorate for Water Management in Hungary). The data set was divided into hydrological summer (April–September) and hydrological winter (October–March) and the monthly minimum data for the summer season was used for further analysis. To ensure the integrity of the data, each national organization responsible for the collection and maintenance of hydrological data has taken strict measures to control data quality. These organizations adhered to stringent standards to guarantee the accuracy and consistency of the data series utilized 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 were applied.

Mann Kendall and Pettitt test

The Mann-Kendall (MK) test is a non-parametric statistical method that is very popular in the field of hydrological studies due to its efficiency in detecting trends in river discharge data. This approach has proven to be particularly valuable as it is highly resistant to non-normality and can effectively handle missing values. The MK test evaluates the monotonic trend in a time series by analyzing the ranks of the data points. This allows researchers to determine whether there is a significant upward or downward trend over time (Ferraz et al. 2022; Leščešen et al., 2024). Recent applications of the MK test have demonstrated its effectiveness in various contexts, including the analysis of long-term outflow trends in Afghanistan (Akhundzadah, 2024), Slovakia (Bačová Mitková et al., 2024), Serbia (Leščešen et al., 2022), Slovenija (Bezak et al., 2016). The MK test has also been used to assess trends in extreme floods and river fluctuations, providing important insights into hydrological changes under the influence of climate variability (Rydén, 2022). The ability of the MK test to detect trends at different confidence levels increases its usefulness in water resources management and planning and provides important information for adaptation to changing hydrological conditions (Bačová Mitková et al., 2024; Leščešen et al., 2022).

The Pettitt test is a non-parametric statistical method used to detect abrupt changes in time series data, which makes it particularly valuable for analyzing trends in river discharge (Pettitt, 1979). This test identifies points of change by comparing the ranks of observations before and after a potential change. This allows researchers to assess whether significant changes have occurred in the hydrological regime (Kocsis et al. 2020). The recent application of Pettitt tests has demonstrated its effectiveness in different water environments. For example, in a study of river flows in Ethiopia, the Pettitt test was used to identify significant changes in the pattern of monthly and seasonal river flows, and highlight changes that could affect water resource management (Woldemarim et al., 2023). In the same way, studies conducted in Iran combine the Pettitt test and the Mann-Kendall test to analyze stream flow data. This analysis revealed critical changes corresponding to climate changes and anthropogenic influences (Deb 2024). This combination of tests improves the robustness of trend analysis and provides a comprehensive understanding of time changes in river discharge. By incorporating Pettitt tests into hydrological assessment, researchers can effectively inform water management strategies and adapt to the hydrological conditions changing under climate change (Gholami et al., 2022).

Self-organizing map

Self-Organizing Map (SOM) is an effective tool for hydrological regionalization and analyzes complex data according to the principles of artificial neural networks. Typically, SOMs are used to identify patterns and clusters in spatial and temporal data and allow researchers to effectively visualize and interpret hydrological phenomena. In hydrology, SOM is especially useful for the aggregation and visualization of high-dimensional data, which is essential for understanding the relationship between different hydrological parameters in different regions (Kohonen, 2001). The unsupervised nature of this method facilitates the extraction of interdependent relationships between inputs and enables the classification of these patterns into low-dimensional grids in which similar inputs are closely related (Vesanto & Alhoniemi 2000). This capability is crucial for hydrological research, as understanding the spatial distribution of parameters can improve model accuracy and resource management.

SOM can be used for regionalization in two ways: by creating a series of maps representing clusters at different time steps, or by creating a single map containing all available data. The latter method allows a temporal change to be visualized by using continuous data to represent the pattern of water pattern over time on a training map (Agarwal and al., 2016a). Recent studies have highlighted the effectiveness of SOMs in identifying precipitation patterns and their impact on the hydroelectric performance of Brazil (Ferreira & Reboita, 2022) and the regionalization of precipitation periods in Senegal (Faye et al., 2024). In addition, SOMs have been successfully used in environmental studies to assess pollution patterns (Licen et al., 2023), demonstrating their versatility in various fields. By integrating SOM into the framework of water modeling, researchers can improve parameter estimates and better understand complex water systems undergoing change (Guntu et al., 2020). Overall, the application of SOMs in hydrological regionalization is a significant advance in the field, providing solid tools for the analysis and interpretation of data that are essential for effective management of water resources.

Results and discussion

As shown in Table 1, a comprehensive set of key statistical parameters for the discharge of selected hydrological stations along the Danube, Tisza, Sava and Drava rivers in the Carpathian Basin is presented. The analysis provides insights into the spatial variations of discharge characteristics, focusing on the trends in mean, median and extreme discharge values at different locations.

The results presented in Table 1 demonstrate a general pattern of increasing minimum discharge values in the downstream direction along the Danube, Tisza, and Sava rivers, reflecting the cumulative effects of tributary inflows and river network expansion. Along the Danube, minimum discharges rise from 676 m^3/s at Bratislava to 1400 m^3/s at Smederevo. Notably, the value at Nagymaros (668 m^3/s) is marginally lower than that observed upstream at Bratislava. This counterintuitive pattern is likely attributable to the operational influence of the Gabčíkovo hydropower system, which diverts a substantial portion of the Danube's flow through an artificial navigation canal, bypassing the natural riverbed that leads toward Nagymaros. During low-flow periods, the regulated discharge regime and reduced inflow to the side arm feeding Nagymaros can produce lower observed minimum discharges, despite the location being downstream. Continuing downstream, minimum values show a steady increase: 718 m^3/s at Mohács, 742 m^3/s at Bezdan, 926 m^3/s at Bogojevo, and reaching 1400 m^3/s at Smederevo. This pattern underscores the additive contributions of major tributaries such as the Drava, Tisza, and Sava, as well as the influence of regulated hydropower reservoirs and channel morphology on baseflow maintenance. A similar increasing trend is evident along the Tisza River. Minimum discharge values increase from 61.3 m^3/s at Szolnok to 73.3 m^3/s at Szeged, and further to 90.0 m^3/s at Senta. These increases reflect the progressive accumulation of runoff from sub-catchments and the moderating effect of upstream reservoirs, which tend to maintain a regulated low-flow regime to satisfy ecological and socioeconomic needs. Along the Sava River, the pattern is likewise pronounced, beginning with a minimum of 48.7 m^3/s at Zagreb and rising substantially to 203 m^3/s at Sremska Mitrovica. This marked increase can be attributed to major tributaries such as the Kupa and Una, as well as contributions from catchments with relatively high baseflow due to karstic and mountainous hydrological settings in the western Balkans. It is also noteworthy that despite urban water use and local ab-

Table 1. Statistical Characteristics of River Discharge at Selected Hydrological Stations in the Carpathian Basin

	Bratislava (Danube)	Nagymaros (Danube)	Mohacs (Danube)	Bezdan (Danube)	Bogojevo (Danube)	Smederevo (Danube)
Mean (m³/s)	1747.9	1968.3	2054.1	2028.5	2615.9	4444.1
Median (m³/s)	1690	1903	1943.5	1913	2448	4094
Std. Dev. (m³/s)	535.6	626.4	681.7	732.4	905.6	1905.9
Variance	286898.4	392417.5	464775.5	536524.5	820212.2	3632371
Skewness	1.288	0.999	1.119	1.269	1.075	1.06
Kurtosis	4.299	1.883	1.973	3.193	1.863	1.025
Range	4807	4868	5122	5939	6731	10700
Minimum (m³/s)	676	668	718	742	926	1400
Maximum (m³/s)	5483	5536	5840	6681	7657	12100
	Donji Miholjac (Drava)	**Szolnok (Tisza)**	**Szeged (Tisza)**	**Senta (Tisza)**	**Zagreb (Sava)**	**Sremska Mitrovica (Sava)**
Mean (m³/s)	448.2	480.7	579.3	557.7	147.8	938.2
Median (m³/s)	422.5	247	428	420	130	746.5
Std. Dev. (m³/s)	152.9	424.7	471.3	452.1	70.3	658.2
Variance	23397.9	180403.9	222182.4	204392.6	4947.8	433304.5
Skewness	1.308	0.789	1.978	2.014	1.549	1.686
Kurtosis	3.634	-0.934	4.299	4.509	3.808	3.251
Range	1208	1848.7	2686.7	2745	528.3	3755
Minimum (m³/s)	188	61.3	73.3	90	48.7	203
Maximum (m³/s)	1396	1910	2760	2835	577	3958

stractions, the increasing trend remains robust, indicating that natural and semi-regulated hydrological processes dominate the observed extremes.

Figure 2 presented here shows the temporal variability of minimum summer flows (April–September) at several hydrological stations along the Danube, Tisza, Sava

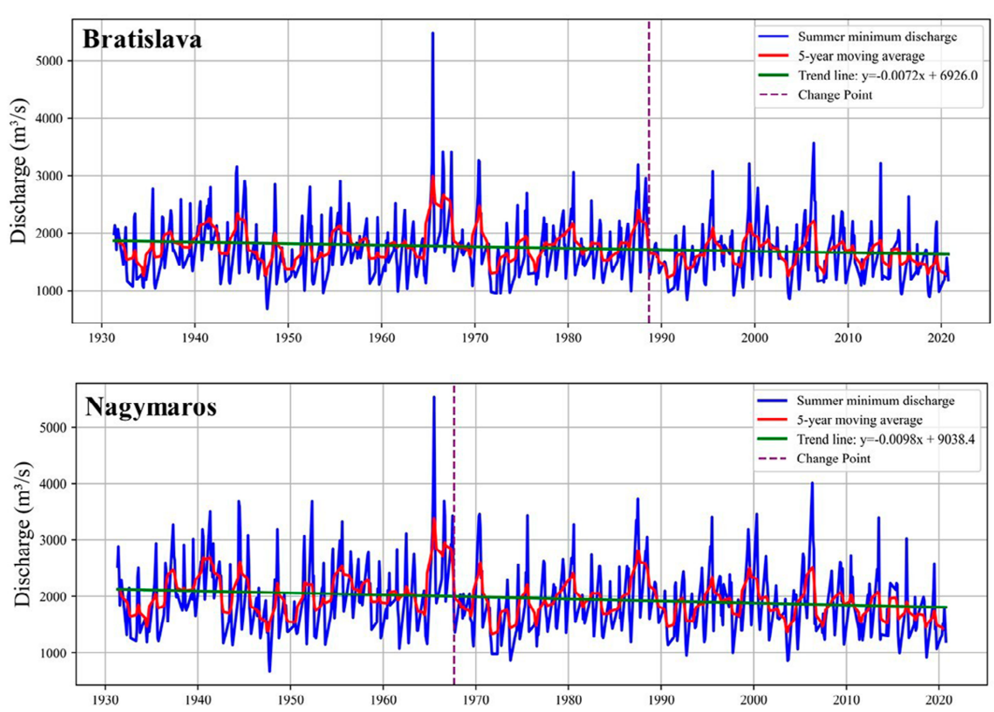

Figure 2. Spatiotemporal Variability of Summer Minimum Discharges

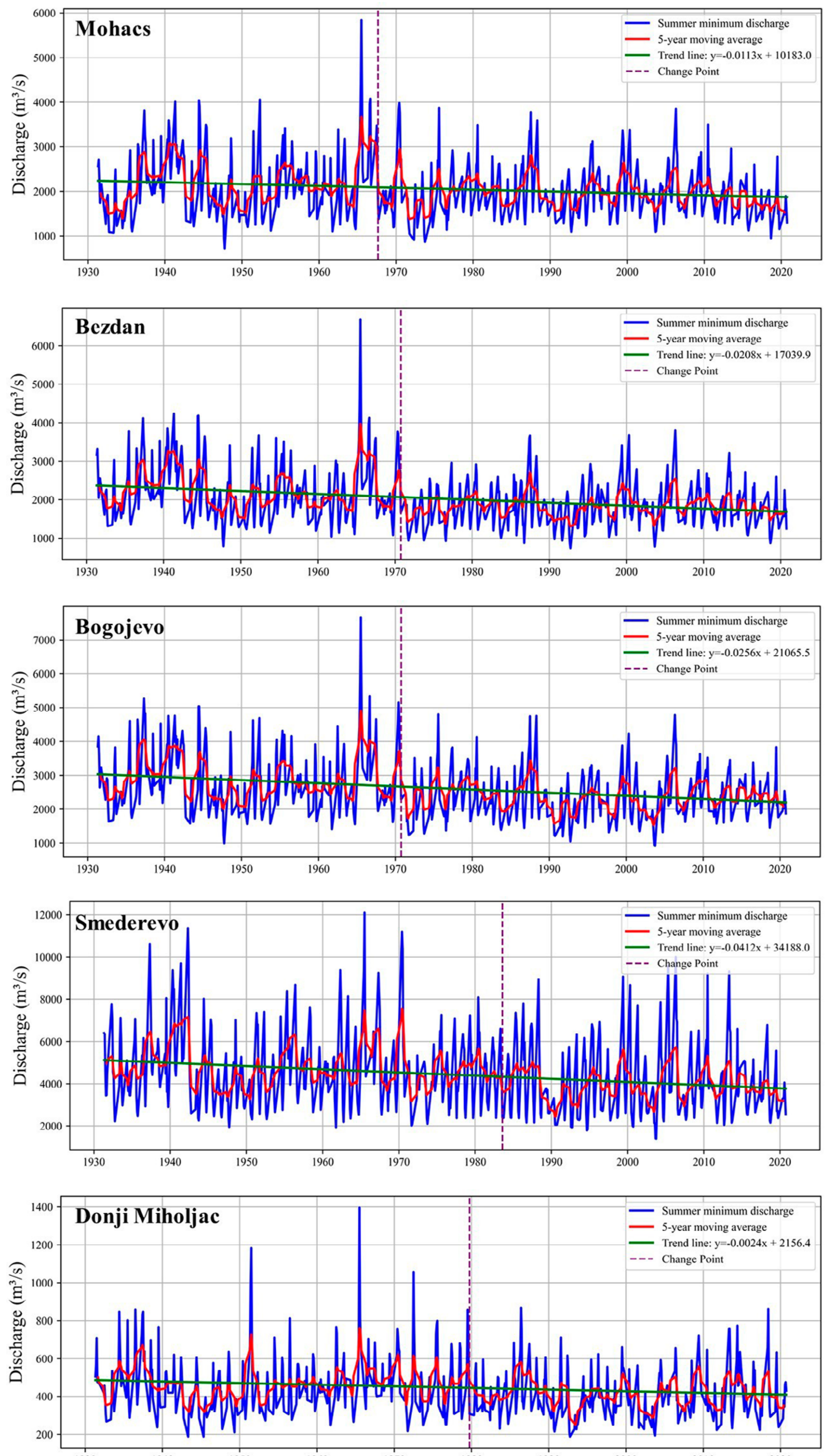

Figure 2. Spatiotemporal Variability of Summer Minimum Discharges (continued)

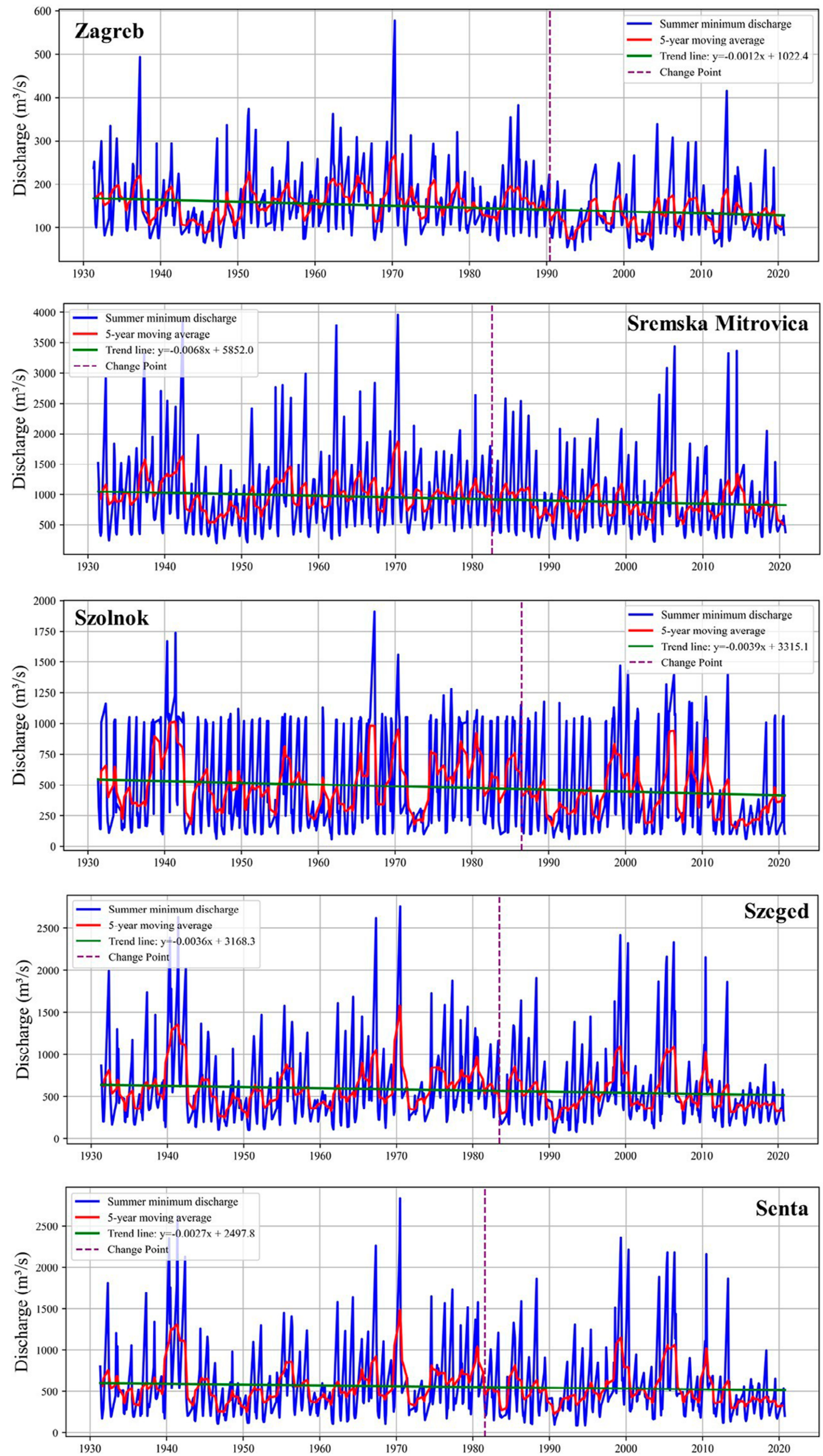

Figure 2. Spatiotemporal Variability of Summer Minimum Discharges (continued)

and Drava rivers. The stations on the Danube, which are arranged from upstream (Bratislava) to downstream (Smederevo), show a general trend towards decreasing summer low flows discharge, particularly noticeable in downstream sections. This indicates increasing hydrological stress due to cumulative water withdrawals, regulation and possible climatic influences. The variability of minimum flows is more pronounced in upstream sections such as Bratislava and Nagymaros, while downstream stations (e.g. Bezdan and Smederevo) show relatively weak fluctuations, probably due to flow regulation and groundwater interactions. This downstream dampening effect is attributable to the integration of flows within a larger catchment area, natural storage in extensive floodplains and alluvial aquifers, and the overarching influence of flow regulation structures (Poff et al., 1997; Tockner et al., 2009). A similar trend can be observed in the Tisza, where minimum flows in Szolnok are higher and more variable than in Seged and Senta, indicating a progressive decrease in groundwater supply downstream and increasing anthropogenic influences (Gocić & Trajković, 2013). A similar pattern can be observed on the Sava between Zagreb and Sremska Mitrovica, with extreme low water events being attenuated downstream. These results are consistent with established hydrological principles that flow regulation, inflows and groundwater exchange influence the downstream propagation of low flows. The Drava station (Donji Miholjac) shows pronounced interannual variability, indicating strong climatic control of minimum flows. The observed patterns indicate an increasing vulnerability of downstream river sections to prolonged periods of low flow. This phenomenon is of particular concern in the context of climate change and increasing water demand, as it can have significant environmental and socio-economic impacts The decrease in downstream variability underlines the impact of reservoirs and hydropower plants. While these anthropogenic activities can mitigate extreme low flow conditions, they also disrupt natural flow regimes. These results underline the need for integrated water management strategies that take into account both climatic and anthropogenic influences on low flow hydrology.

The results presented in Table 2 show a clear and statistically significant downward trend in summer minimum flows at most stations on the Danube, Tisza, Sava, and Drava rivers, as demonstrated by the Mann-Kendall test.

Table 2. Trend Analysis of Summer Minimum Discharges in the Danube, Tisza, Sava, and Drava Rivers Using the Mann-Kendall and Pettitt Tests

	Bratisalva (Danube)	Nagymaros (Danube)	Mohacs (Danube)	Bezdan (Danube)	Bogojevo (Danube)	Smederevo (Danube)
Mann-Kendall Test						
Slope	0.449	-0.588	-0.581	-1.052	-1.321	-2.302
p-value	0.000	0.000	0.000	0.000	0.000	0.000
5-year moving average Mann-Kendall Test						
Slope	-0.380	-0.547	-0.603	-1.003	-1.314	-2.271
p-value	0.000	0.000	0.000	0.000	0.000	0.000
Pettitt Test Results:						
Change Point Year	1988	1967	1967	1970	1970	1983
Test Statistic (U)	14251.0	13875.0	14214.0	23704.0	23932.0	21403.0
p-value	0.000	0.000	0.000	0.000	0.000	0.000
	Donji Miholac (Drava)	**Szolnok (Tisza)**	**Szeged (Tisza)**	**Senta (Tisza)**	**Zagreb (Sava)**	**Sremska Mitrovica (Sava)**
Mann-Kendall Test						
Slope	-0.130	-0.065	-0.128	-0.096	-0.066	-0.302
p-value	0.000	0.017	0.084	0.164	0.000	0.011
5-year moving average Mann-Kendall Test						
Slope	-0.127	-0.268	-0.197	-0.155	-0.074	-0.417
p-value	0.000	0.000	0.000	0.001	0.000	0.000
Pettitt Test Results:						
Change Point Year	1979	1986	1983	1981	1990	1982
Test Statistic (U)	16434.0	11866.0	10657.0	8410.0	21446.0	11818.0
p-value	0.000	0.007	0.022	0.125	0.000	0.008

At the majority of locations, the associated p-values were below 0.001 (reported as $p < 0.001$), indicating strong evidence against the null hypothesis of no trend. The negative slopes of the trend lines, especially for the annual discharge and the double 5-year moving average discharge, indicate a long-term decline in summer low flows. This pattern is particularly evident on the Danube, where all stations from Bratislava to Smederevo show significantly decreasing trends. The results of the Pettitt test indicate that the turning points in the series of summer low flows are between the late 1960s and early 1980s, with most stations experiencing abrupt shifts around 1970–1980. Of particular interest is the observation that Bratislava, Nagymaros and Mohacs have similar years with change points (1967–1970), suggesting that the upstream sections of the Danube were affected by changes in the hydrological system earlier than the downstream sections, such as Smederevo (1983). This observation suggests the hypothesis that large-scale climatic drivers or anthropogenic interventions, such as dam construction and water management policies, have progressively altered discharge regimes over time.

A similar trend can be observed in the Tisza, where Szolnok and Seged show significant decreasing tendencies, while no clear trend can be seen in Senta. For both Szolnok and Seged, points of change were identified in the mid-1980s, indicating that the changes in hydrological conditions in the Tisza catchment occurred somewhat later than in the Danube.

A similar downward trend can be observed at the stations on the Sava (Zagreb and Sremska Mitrovica), where the changes occurred between 1982and 1990. This temporal consistency is consistent with broader hydrological shifts in the region that can be attributed to changing precipitation patterns, increased evapotranspiration due to rising temperatures or increased human-induced changes.

A similar trend can be observed at the Drava station (Donji Miholjac), where a change point occurred in 1979. This indicates that the hydrological shifts in the Western Balkans and Central Europe mainly occurred between the late 1960s and the late 1980s. The comprehensive results show that summer low flows have decreased over time due to a combination of climate change (reduced precipitation and increased temperature-induced evapotranspiration) and human activities (regulation of reservoirs, groundwater abstraction). These changes underline the increasing vulnerability of water resources in the region and highlight the need for adaptive water management strategies to mitigate the impacts of persistent low flow conditions on ecosystems and water availability.

The regionalization in this study is based on the monhly low-flow data for the warm season (April–September) in the Carpathian Basin. This period is crucial for the assessment of hydrological extremes such as droughts and low flows, which are increasingly influenced by climate change. The method of self-organising maps (SOMs) was applied to classify the hydrological stations based on important statistical parameters such as mean, median and standard deviation,

Figure 3. Regionalisation of Carpathian basin

variance, skewness, kurtosis, range, minimum, and maximum discharge values, along with trend indicators such as slope, p-values, and change point detection (Figure 3).

The stations were divided into clusters based on their hydrological behavior. Cluster 1 includes stations on the Danube (Bratislava, Nagymaros, Mohács, Bezdan, Bogojevo, Smederevo) and the Sava (Zagreb, Mitrovica), which are characterized by higher discharges, greater variability and significant hydrological changes. These results are supported by recent studies indicating that larger catchments lead to greater discharge variability and response to climatic events (Tadić et al., 2022). These stations are influenced by the larger catchment area of the Danube and its tributaries, leading to more pronounced responses to precipitation variability and snowmelt dynamics. In contrast, Cluster 2 consists of stations on the Tisza (Szolnok, Szeged, Senta) and the Drava (Miholjac), which have lower discharge, less variability and a pronounced low flow regime. Research has shown that such low flow regimes are increasingly vulnerable to the effects of climate change (Leščešen et al., 2022). The grouping was influenced by differences in trend slopes, statistical significance (p-values), and detected change points in flow behaviour.

Climate change is expected to exacerbate hydrological extremes in the region. Stations in Cluster 2 could experience a further decrease in low flows due to increased evaporation rates and longer dry periods, while stations in Cluster 1 could experience greater variability in flows due to changing precipitation patterns, more intense precipitation events and increasing temperatures. These changes are consistent with observed trends in other European river basins, where climate change is associated with altered hydrological regimes, including more frequent and severe droughts and floods (Blöschl et al., 2019; IPCC, 2021). Identifying these trends through statistical parameters ensures a data-driven understanding of regional hydrological responses and emphasizes the need for continuous monitoring and adaptive water management.

This classification provides a robust framework for assessing hydrological changes in the Carpathian Basin and highlights the evolving impacts of climate change on regional water resources. The findings are consistent with recent studies that have documented similar patterns of hydrological change in response to climate variability and anthropogenic influences (e.g., Hall et al., 2014; Lorenzo-Lacruz et al., 2010).

Conclusion

This study provides a comprehensive analysis of long-term trends in summer minimum flows across the Carpathian Basin, with a focus on the Danube, Tisza, Sava and Drava rivers. By using a 90-year data set and applying robust statistical methods, including the Mann-Kendall and Pettitt tests, we found a significant decrease in summer low flows at most stations. These trends are particularly pronounced in the Danube, where downstream stations show a greater reduction in minimum flow compared to upstream sections. Changes in the hydrological regime were observed between the late 1960s and the early 1990s, suggesting that climatic and anthropogenic factors have increasingly altered river discharge dynamics over the last fifty years.

Regionalization using self-organizing maps (SOMs) revealed different hydrological behavior, with Cluster 1 stations (Danube and Sava) characterized by higher discharge and greater variability, while Cluster 2 stations (Tisza and Drava) showed lower discharge and less variability. These results are consistent with broader European trends, where climate change increases low-flows variability in larger catchments and exacerbates low flow conditions in smaller catchments. The observed patterns highlight the dual influence of climate change — manifested in reduced precipitation and increased evapotranspiration — and human activities, such as reservoir regulation and water abstraction, on regional hydrology.

The study underlines the growing vulnerability of the Carpathian Basin to hydrological extremes, especially prolonged droughts and reduced water availability. These changes pose a major challenge for the management of water resources, the sustainability of ecosystems and socio-economic development. Our results emphasize the need for adaptive water management strategies that account for both climatic and anthropogenic drivers. Future research should focus on integrating climate projections with hydrological models to better predict and mitigate the impacts of climate change on regional water resources.

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