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Unraveling the impact of large-scale climate circulations on the maximum discharges in the middle and lower Danube basin

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Abstract: Understanding the relationships between large-scale climate circulation and precipitation and river discharge at the local level is of central importance for deciphering hydroclimatological processes. Annual maximum river discharges in Europe are more sensitive to the variability of atmospheric circulation than mean discharges. However, there is a knowledge gap regarding the specific influence of atmospheric patterns on maximum discharge dynamics in the Middle and Lower sections of the Danube basin, especially in Serbia and Romania. In this study, historical climate data and the influence of atmospheric patterns (Greenland-Balkan Oscillation index, Mediterranean Oscillation index and North Atlantic Oscillation index) were analysed to understand their impact on hydrological extremes. The results showed significant correlations between discharge and atmospheric oscillations, in particular a statistically significant decreasing trend of maximum monthly discharge at Orsova station (trend: –0.0548, p-value: 0.0305) in the period 1961–2018. Correlation analyses showed significant positive correlations between runoff and atmospheric indices in different time periods and stations, underlining the complexity of these relationships. In addition, GEV analysis underlined the stability of maximum discharges at Bezdan and Bogojevo stations over time, with notable instability observed at Orsova and Ceatal Izmail stations. These results emphasize the importance of considering both temporal and spatial variations in river discharge dynamics when assessing the impact of climate change on hydrological extremes.

Keywords: Danube; Maximum discharges; Climate change impacts; Atmospheric oscillations; Extreme value analysis.

1 INTRODUCTION

Understanding the interconnections between large-scale climatic circulations and local-scale precipitation and river discharge is pivotal for unravelling the hydro climatological processes (Kingston et al., 2009). It was stated that annual maximum river discharges in Europe are more sensitive to atmospheric circulation variability than mean discharges (Bouwer et al., 2008). By identifying statistically significant correlations, it becomes feasible to forecast precipitation and river flow anomalies on seasonal timescales, especially when combined with accurate predictions of the driving large-scale climatic circulations. These long-term hydrological predictions are indispensable for enhancing the planning of water resources and bolstering human readiness for hydrological extremes, encompassing both floods and droughts (Wedgbrow et al., 2002).

Climate change projections from authoritative sources like the Copernicus Climate Change Service paint a concerning picture for the Danube Basin. Rising temperatures are expected to significantly disrupt the hydrological cycle. Increased evapotranspiration rates can worsen the severity and duration of droughts, threatening water availability for agriculture, industry, and human consumption (Copernicus Climate Change Service, 2022). Simultaneously, as warmer air holds more moisture, the potential for intensified precipitation events and a heightened risk of devastating floods increases. The February of 2024 was the warmest on record, while the temperature anomaly was extraordinarily high over the entire Danube River Basin, especially the middle and the lower part (Copernicus Climate Change Service, 2024). Extreme value analysis techniques play a crucial role in understanding these risks, aiding the modelling of return periods and the assessment of potential consequences (Mares et al., 2009). However, despite the recognised importance of extreme-value methods, applications of non-stationary GEV models that explicitly condition monthly and daily maxima on large-scale circulation indices in the middle and lower Danube remain relatively scarce, leaving an important methodological and regional research gap (Coles, 2001; Katz, et al., 2002; Steirou et al., 2019; 2022; Gardini, 2023). The novelty of this study lies in integrating large-scale atmospheric teleconnection indices (GBOI, MOI, and NAOI) into both correlation and non-stationary extreme value analyses to reveal their direct statistical imprint on Danube discharge extremes. By combining long-term hydrological records with climate-driven covariates, this research provides the first basin-wide quantitative assessment of how atmospheric circulation regimes modulate the frequency and magnitude of flood-generating discharges along the middle and lower Danube. By introducing GBOI, MOI and NAOI as covariates into the GEV location parameter, this study therefore directly addresses that gap, evaluating whether conditioning extremes on these teleconnection indices improves statistical characterisation of maximum discharges and helps attribute changes in the seasonality and magnitude of flood peaks to large-scale atmospheric drivers. The Danube Climate Adaptation Study (ICPDR, 2018) further emphasizes that these climate-driven changes are compounded by human activities within the basin, including demographic shifts, land-use transformations, and infrastructure developments. These modifications alter the landscape's ability to absorb and regulate water flows, potentially altering the frequency and magnitude of both maximum discharges and minimum discharges (Tonkin et al., 2018).

The flow of European rivers is influenced by a range of atmospheric oscillations. The North Atlantic Oscillation (NAO) has been found to significantly influences annual and winter precipitation as well as river flow regimes in the lower Danube Valley (Armaș, 2015; Steirou et al., 2017; Kukushkin, 2020). Further studies found that NAO impacts winter rainfall and river discharge in Mediterranean regions (Brandimarte et al., 2011). Over the Northern Europe, meridional delayed oscillation, with rivers lagging behind southern ones by approximately 5 years (Zanchettin et al., 2019). This is linked to the large-scale atmospheric circulation over the North Atlantic In other study, it was reported that the North Atlantic Oscillation (NAO) and the West Europe Pressure Anomaly (WEPA) are key factors in winter river flow and precipitation in western Europe (Jalón-Rojas and Castelle, 2021). Previously, results presented by Rimbu et al. (2004) highlighted an important decadal variation of the NAO and its impact on the Danube River Basin (DRB) discharge variability. Similar conclusion was reached by Knippertz et al. (2003) with their study that linked NAO and spring-time European rainfall. Pandžić et al., (2022) reported significant positive correlation between the NAO and a several hydrological stations in the central part of the DRB for winter discharge as a result of the mostly positive correlation between the NAO and winter precipitation in the upper part of the basin. Dolinaj et al., (2019) focused on the Danube River, showing that its discharge is correlated with precipitation and the Mediterranean Oscillation Index (MOI). Research conducted in Turkey found that MOI has a significant relationship with temperature and precipitation characteristics, and that the most significant correlations was found between the MOI and temperature during the winter season (Cenk et al., 2020). Mares et al., (2016, 2020) have established the influence of large-scale atmospheric circulation patterns, such as the Greenland-Balkan Oscillation (GBO), the North Atlantic Oscillation (NAO), and blocking-type atmospheric circulation, on precipitation patterns and consequently, on the discharge of the lower Danube, highlighting the Greenland-Balkan Oscillation (GBO), and its significant impacts to the middle and lower Danube River Basin (DRB), exceeding the influence of the North Atlantic Oscillation (NAO). Further analysis showcases the role of blocking-type atmospheric circulation that stalls typical weather patterns, leading to prolonged periods of excessive precipitation or drought (Mikhailova et al., 2012). Over the north-eastern region of Romania, a strong negative correlation between the winter NAO, rainfall amounts and river flows was found (Mihăilă, 2015). Cherenkova and Sidorova (2021) highlighted the impact of insufficient atmospheric moistening on the low annual discharge of large rivers in European Russia, with a close correlation between discharge and annual atmospheric moistening. Historical analyses highlight statistically significant trends in both strong and extreme maximum discharges on the Danube River, underscoring the urgency of understanding and preparing for future flood risks (Leščešen et al., 2022).

Stretching across 19 countries and serving as a vital artery for Central and South-eastern Europe, the DRB is a complex and dynamic system of immense ecological, economic, and cultural significance. However, the DRB's legacy is intertwined with the destructive forces of hydrological extremes – droughts and floods (Leščešen and Dolinaj, 2019; Leščešen et al., 2024). These events have historically led to significant challenges, including disrupted livelihoods, damaged infrastructure, and impacts on community well-being throughout the basin. In the era of climate change, the frequency and intensity of these hazardous events are projected to increase, posing an escalating threat to the region's sustainability and resilience (Mares et al., 2009; Mares et al., 2016).

The aim of this research is to assess the variability of discharges in the middle (Serbia) and lower (Romania) Danube Basin. It will analyse historical climate data and the influence of atmospheric patterns (GBOI, MOI and NAOI) to understand how these patterns influenced hydrological extremes. This will help create targeted strategies for reducing the impact of droughts and floods in the region. These three indices were specifically selected because previous studies have shown their strong and regionally relevant influence on precipitation and river discharge variability within the Danube Basin, making them particularly suited to understanding hydrological extremes in this area. Furthermore, the study does not employ modeled or projected data; it focuses solely on historical discharge and climate records to ensure robust and observation-based analysis. Results of this analysis will identify possible links between atmospheric patterns and Danube flow extreme in central and lower DRB as well as to improve predictions of the Danube River extremes in the region.

2 STUDY AREA

At 2,850 km, the Danube is the second longest river in Europe, flowing through 11 countries and covering a catchment area of 807,000 km^2. The river rises in the Black Forest in Germany and flows in an easterly direction to the Black Sea (Basarin et al., 2016; Schiller et al., 2010). The study area covers the middle section of the Danube catchment, in Serbia a part that includes the Bezdan and Bogojevo gauging stations. In addition, it extends to the lower part of the Danube catchment in Romania and includes the Orsova and Ceatal Izmail gauging stations (Fig. 1). The choice of these stations is crucial for capturing the hydrological dynamics of the Danube in this particular region.

Fig. 1. Study area showing gauging stations.

3 DATA AND METHODS

Daily discharge data for the period 1961–2020 were obtained from the Hydrometeorological Service of the Republic of Serbia (RHMSs) for the Serbian stations and from the National Institute of Hydrology and Water Management, Romania (INHGA) for the period 1961–2018 for Romania.

The hydrological stations in the study area are characterized by key parameters, including station name, elevation (H), distance from the mouth (L), period of available data and mean annual discharge within the available period (Q) (Table 1).

Base on the obtained daily data, monthly maximum discharges were calculated, as these values are an important measure for assessing water availability and managing flood risks (Higashiano and Stefan, 2019). While not every high discharge leads to flooding, it is well established that every flood event is preceded by an increased discharge (Shiklomanov et al., 2007). The use of monthly maximum discharges enhances flood analysis by making better use of available data, allowing for a more nuanced understanding of flood events (Davíðsson 2014). Therefore, we focused our analysis on monthly discharge maximums, as they are a reliable indicator of potential flood events (Scorzini et al., 2024).

It is important to comment on the influence that Djerdap reservoir and the Iron Gate dam. The Iron Gate I reservoir (completed 1972) spans ~135 km and holds about 5 billion m³ of Danube water (Teodoru et al., 2006). Such a huge reservoir strongly reduces maximum discharges and shifts seasonal runoff (Li and Xu, 2023). In practice, spring maximum discharges would be stored and released gradually over following months, smoothing and delaying peaks at Orșova. Indeed, Stratimirović et al. (2021) found that Danube damming introduced artificial flow oscillations and even a "complete or partial loss of annual cycles" in discharge up to ~220 km upstream. Although the Orșova gauging station is located immediately upstream of the Iron Gates I and II reservoirs, its discharge data are considered suitable for long-term hydrological (Pekárová et al., 2016; Mares et al., 2020) and teleconnection analyses because the station represents the cumulative natural and regulated flow from the upper Danube Basin. The Iron Gates cascade primarily affects short-term flow regulation, while monthly maximum discharges, used in this study, reflect broader hydroclimatic and basin-scale controls rather than direct reservoir operations. This ensures that the data remain representative of large-scale climatic variability and are not dominated by local anthropogenic effects.

The Mann-Kendall test (MK), a non-parametric method often used in hydrological and climatological analyzes to detect trends in time series data. Using a significance level of 0.05, the test evaluated the monthly maximum discharges for three time periods (1961-2020; 1961-2000 and 2001-2020). The dataset was separated into these periods to account for potential shifts in hydrological patterns before and after 2000, reflecting possible changes in climate variability and anthropogenic influences, while still allowing for an overall trend assessment across the entire 1961–2020 period. The MK test tests the null hypothesis that there is no trend against the alternative hypothesis that there is a trend in the analyzed series, either positive or negative. This approach has been used extensively in previous studies, including Bezak et al. (2016), Leščešen et al. (2022), Gnjato et al. (2023), which have demonstrated its effectiveness in identifying trends in river discharge dynamics in different environmental contexts.

The Greenland–Balkan Oscillation index (GBOI), introduced by Mares et al. (Mares et al., 2013) to reflect the baric contrast between the Balkan and the Greenland zones, was calculated as the difference in the normalized sea level pressure (SLP) at Nuuk and Novi Sad. Monthly SLP values were provided by Met Office Hadley Centre[1] and NCAR-Research Data Archive[2]. North Atlantic Oscillation Index (NAOI) is obtained from Hurrell Station-Based Monthly NAO Index[3].

Table 1. Basic characteristics of investigated stations.

Station name	Country	Elevation H (m a. s. l.)	Distance from the mouth L (km)	Area (km^2)	Period of available data	Mean annual discharge Q (m^3/s)
Bezdan	Serbia	80.64	1425.6	210250	1961–2020	2269
Bogojevo	Serbia	77.46	1367	251593	1961–2020	2792
Orsova	Romania	44.4	957	576232	1961–2018	5468
Ceatal Izmail	Romania	0.6	80	807000	1961–2018	6574

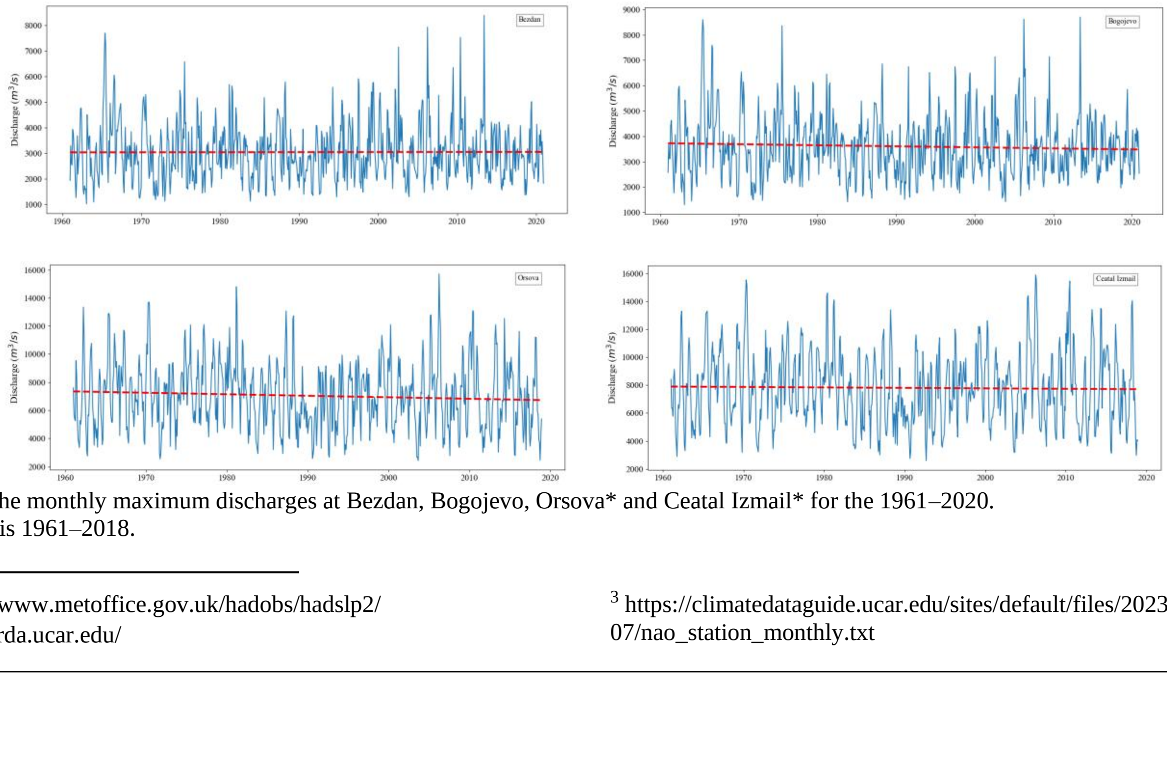

Fig. 2. The monthly maximum discharges at Bezdan, Bogojevo, Orsova* and Ceatal Izmail* for the 1961–2020.
* period is 1961–2018.

[1] https://www.metoffice.gov.uk/hadobs/hadslp2/
[2] https://rda.ucar.edu/
[3] https://climatedataguide.ucar.edu/sites/default/files/2023-07/nao_station_monthly.txt

The monthly average values of the Mediterranean Oscillation Indices (MOI), they were calculated from the daily values [4] .Correlation analysis was conducted to examine the relationships between teleconnection indices (GBOI, MOI, NAO) and the maximum daily monthly river discharge. Two types of correlation coefficients were applied: Pearson correlation coefficient and Spearman's rank correlation coefficient. Pearson correlation coefficient was used to assess the linear relationship between variables when assumptions of normality and linearity were met. Spearman's rank correlation coefficient was used to evaluate the association between variables when the assumptions of normality and linearity were not met or when dealing with ordinal data.

All correlation analyses were performed as two-tailed tests to assess the significance of the relationships between teleconnection indices and river discharge variables. Significance levels were set at $\alpha = 0.05$. Statistical analyses were conducted using IBM SPSS Statistics version 20. The significance of correlation coefficients was determined using appropriate statistical tests implemented within the software.

In this study, an analysis of the maximum daily monthly discharge was also carried out by applying the extreme value theory (EVT), according to the upgraded version of Gilleland and Katz (2016).

Similar approaches were achieved by fitting with the generalized extreme value (GEV) distribution in R software [5] (Mares et al., 2009). Towler et al. (2020) develops EVT in order to take non-stationarity into account, i.e., to include predictors that can vary the predictability of extremes. The statistical approaches from the present study can be complementary to these dynamical models, as they computationally inexpensive, and they can be of valuable help for dynamical methods (Towler et al., 2020).The GEV distribution has been highlighted as the most suitable for flood studies both in European context (Salinas et al., 2014), as well as in the region (Leščešen et al., 2022). The estimate of the shape parameter of the GEV distribution is extremely sensitive to record length (Lilienthal et al., 2022; Su and Smith, 2021), with strong bias and uncertainty for short records (Bertola et al., 2019).

In this work, the nonlinear flood frequency estimation was applied not as an engineering design tool but as a diagnostic approach to investigate the influence of large-scale atmospheric variability on the statistical behavior of discharge extremes. The GEV distribution was extended into a non-stationary framework in which its location and scale parameters were modeled as functions of teleconnection indices (GBOI, MOI, and NAO). This formulation, following Gilleland and Katz (2016), enabled the testing of whether fluctuations in these indices cause systematic shifts in the probability distribution of discharge maxima. Model parameters were estimated using maximum likelihood, and model performance was compared to the stationary GEV using the Akaike Information Criterion (AIC) and likelihood ratio tests. By embedding teleconnection indices as covariates, the non-stationary GEV approach identifies gradual changes in flood probability structures that would remain undetected in stationary analyses. This method, therefore, provides a physically grounded and computationally efficient framework for quantifying the climatic sensitivity of flood distributions, directly supporting the study's overarching objective of linking atmospheric circulation variability to changes in the magnitude and occurrence of hydrological extremes in the Danube Basin.

3 RESULTS AND DISCUSSION
3.1 Trends and correlations

First, we have examined the maximum monthly discharge data from two different periods: firstly, from 1961 to 2000 and secondly, from 2001 to 2020 for the Bezdan and Bogojevo stations in Serbia and from 2001 to 2018 for the Orsova and Ceatal Izmail stations in Romania. The first period comprised 480 values, while the subsequent period comprised 240 values for the Serbian stations and 216 values for the Romanian stations. By extending our analysis to this second period, we aimed to capture any temporal shifts or trends in river discharge dynamics over the first two decades of 21st century. These findings match large-scale analyses reporting no significant long-term trend for Danube (Shi et al., 2019), implying that our observation of largely stable maximum flows at Bezdan and Bogojevo is consistent with a broader picture of Danube hydrology. This is in line with findings that long-term climate variability and low-frequency oscillations (e.g., NAO and AMO) significantly influence hydrological responses, often on decadal scales (Massei et al., 2020). Table 2 shows results of the Mann-Kendall trend test of the maximum monthly discharges at Bezdan, Bogojevo, Orsova, and Ceatal Izmail stations along the Danube River across different time periods (Table 2).

At the Bezdan station, no statistically significant trend was observed for all three periods, which indicates relatively stable pattern of maximum monthly discharge over the entire data set. These stable trends are in line with global-scale studies that show the Danube's annual flows are not exhibiting strong long-term changes (Shi et al., 2019). No significant trend was observed at the Bogojevo station either, indicating a consistent discharge pattern over the analysed time periods in Serbian part of Danube River. However, a statistically significant decreasing trend was observed at the Orsova station for the period 1961-2018 (trend: -0.055, p-value: 0.031), indicating a decreasing trend in maximum monthly discharge in 21st century. While the observed decreasing trend at Orsova coincides with the operational period of the Iron Gates reservoirs, the temporal consistency of the trend with regional-scale hydrological changes across Central and Eastern Europe (Pekárová et al., 2016; Shi et al., 2019, Leščešen 2025) suggests that it cannot be solely attributed to reservoir management. For instance, a continental-scale analysis by Hannaford et al. (2013) identified a coherent pattern of decreasing maximum discharges magnitudes across Eastern Europe, a finding that aligns perfectly with the negative trend observed at Orsova. Discharges of major global rivers predominantly showed downward trends, with climate being the main influencing factor (Shi et al., 2019). In contrast, no significant trends were observed for the periods 1961-2000 and 2001-2018. Finally, at the Ceatal Izmail station, no statistically significant trends were observed across all three time periods, suggesting relatively stable discharge patterns without significant long-term changes. These results highlight the importance of considering station-specific trends and temporal variations to understand the dynamics of river discharge, especially in the context of hydrological management and climate change assessment.

[4] https://crudata.uea.ac.uk/cru/data/moi/

[5] https://staff.ral.ucar.edu/ericg/extRemes/

Table 2. Mann-Kendall trend analysis.

Station	1961-2020		1961-2000		2001-2020	
	trend	p-value	trend	p-value	trend	p-value
Bezdan	0.007	0.762	–0.000	0.942	–0.062	0.153
Bogojevo	–0.028	0.256	–0.042	0.172	0.021	0.627
Orsova	–0.055	**0.030**	–0.045	0.138	–0.055	0.224
C. Izmail	–0.021	0.406	–0.043	0.156	–0.048	0.291

Table 3. Mann–Kendall Trend Test Results for Seasonal Teleconnection Indices (1961–2020).

Index	Spring Slope	Summer Slope	Autumn Slope	Winter Slope	Significance (p<0.05)
GBOI	+0.012	+0.009	+0.004	–0.006	None
NAO	–0.003	–0.001	–0.002	–0.015	None
MOI	+0.006	+0.002	–0.007	+0.005	None

The long-term seasonal values of the GBOI, NAO and the MOI for the period 1961–2000 were analysed to assess possible trends and stability. Mann-Kendall trend tests and Sen's slope estimates revealed no statistically significant monotonic trends for most seasons, suggesting that these teleconnections are relatively stable on multi-decadal time scales. The GBOI shows small positive but non-significant slopes in spring and summer, which is consistent with its episodic amplification during periods of increased blocking over eastern Europe. The NAO shows small negative slopes in winter, indicating a slight but statistically insignificant weakening of winter westerlies, which is consistent with recent studies over the North Atlantic (Liu et al., 2025). The MOI shows greater interannual variability than the other indices, especially in autumn, but without a consistent change in direction. This stability argues in favour of using historical relationships between teleconnection and discharge for flood hazard assessment, as teleconnection regimes have not undergone systematic long-term shifts that would invalidate previous correlations. However, fluctuations in certain decades (e.g., strong negative NAO winters in the early 1990s) highlight the need for flexible modelling approaches that account for non-stationary teleconnection effects (Zanchettin et al., 2021; Mokhov et al., 2000).

3.2 Correlation analysis

The Pearson correlation analyses carried out for different time periods, namely 1961–2000 and 2001–2020, provide interesting insights into the relationship between the Danube discharge and atmospheric oscillations (GBOI, MOI and NAOI) at different stations. In the period 1961-2000 (Table 3), significant positive correlations between discharge and MOI were observed at the Bezdan and Bogojevo stations, indicating the significant influence of MOI on discharge behaviour (correlation coefficients of 0.271 and 0.270, respectively, with p-values of 0.000). These findings agree with Dolinaj et al. (2019), who showed that precipitation and the Mediterranean Oscillation Index (MOI) exert dominant control on both average and maximum Danube discharge at Bezdan (Dolinaj et al., 2019). This result is further corroborated by studies on major tributaries like the Sava River, where Milenković et al. (2017) also found that Mediterranean circulation patterns often have a more direct and significant impact on regional hydrology than the more distant NAO.

Previously it was reported that precipitation, MOI, and Western Mediterranean Oscillation Index (WeMOI) have constant and dominant influences average discharge, while maximum discharge is mainly influenced by precipitation and MOI on Danube River in middle part of Danube River in Serbia (Dolinaj et al., 2019). Similarly, significant positive correlations between discharge and GBOI were found at the Orsova and Ceatal Izmail stations (correlation coefficients of 0.205 and 0.113, respectively, both with p-values below 0.05), underlining the influence of GBOI on discharge. This supports Mares et al. (2016), who found that the Greenland–Balkan Oscillation Index (GBOI) strongly modulates precipitation in the middle and lower Danube basin and serves as a superior predictor (compared to NAO) for spring/summer discharge. Indeed, Mares et al. highlighted that winter/spring precipitation (PC1) combined with GBOI provides the best predictors for Danube spring/summer flows (Mares et al., 2016). The most significant influence on the discharge of the Lower Danube Basin is given by the Greenland-Balkan Oscillation index (GBOI) and blocking-type atmospheric circulation over Europe (Mares et al., 2020). However, no statistically significant correlations between discharge and NAO were found at any station during this period. This absence of NAO influence is consistent with prior analyses showing that NAO is a relatively weak predictor of Danube flow anomalies unless paired with other indices (Mares et al., 2025). This is a critical regional distinction, as studies in Western and Northern Europe frequently report strong, positive correlations between the NAO and winter river discharge (Lorenzo-Lacruz et al., 2022; Steirou et al., 2019), highlighting the Danube basin's unique response to large-scale atmospheric drivers. In contrast, the analysis for the period 2001–2020 (Table 4) showed a different dynamic.

While positive correlations between discharge and GBOI and MOI were observed at the Bezdan and Orsova stations, only the correlations with GBOI were statistically significant at Orsova (correlation coefficient of 0.184, p-value of 0.007). In particular, a significant negative correlation between discharge and MOI was observed at Orsova station (correlation coefficient of -0.238, p-value of 0.000), indicating a potential inverse relationship in this period. Such temporal instabilities have been noted by Steirou et al. (2017), who emphasized the complex interplay of NAO, EA/WR, and Siberian-Central Asian patterns in modulating Central European hydrology. Interestingly, such a reversal of the MOI–discharge link is not commonly reported in earlier Danube studies and may indicate temporal changes in climate-discharge coupling. Such a temporal instability in teleconnections is a key finding, echoing observations by Steirou et al. (2017) who noted that the relationship between climate indices and European river flows can be non-stationary, shifting in strength or even sign across different decades due to underlying changes in atmospheric circulation. Although positive correlations were found at the Bogojevo and Ceatal Izmail stations, none of them were statistically significant (Table 4).

Table 4. Pearson correlation results for the 1961–2000 period.

Station	GBOI		MOI		NAO		GBOI lag 1		MOI lag 1		NAO lag 1	
	r	p	r	p	r	p	r	p	r	p	r	p
Bezdan	0.045	0.322	0.271	**0.000**	0.039	0.396	–0.087	0.056	0.237	**0.000**	0.015	0.739
Bogojevo	0.047	0.308	0.270	**0.000**	0.032	0.486	–0.090	**0.049**	0.261	**0.000**	0.002	0.963
Orsova	0.205	**0.000**	–0.070	0.126	–0.014	0.761	–0.049	0.280	0.152	**0.000**	–0.012	0.788
C. Izmail	0.113	**0.014**	0.018	0.692	–0.018	0.699	–0.051	0.268	0.242	**0.000**	–0.015	0.736

***Bold** – statistically significant at the level 0.05.

Table 5. Pearson correlation results for the post 2001 period.

Station	GBOI		MOI		NAO		GBOI lag 1		MOI lag 1		NAO lag 1	
	r	p	r	p	r	p	r	p	r	p	r	p
Bezdan	0.178	**0.006**	0.172	**0.008**	–0.072	0.269	–0.089	0.170	0.159	**0.014**	–0.047	0.465
Bogojevo	0.112	0.083	0.152	**0.019**	–0.028	0.664	–0.088	0.175	0.166	**0.010**	0.178	0.006
Orsova	0.184	**0.007**	–0.238	**0.000**	–0.093	0.175	–0.032	0.645	–0.028	0.685	–0.054	0.428
C. Izmail	0.089	0.190	–0.147	**0.031**	–0.094	0.168	–0.044	0.517	0.059	**0.039**	–0.032	0.642

***Bold** – statistically significant at the level 0.05.

This insight is supported by studies showing that even modest teleconnection signals can improve predictive models: for example, Donegan et al. (2021) report that conditioning ensemble streamflow forecasts on indices like the NAO yields modest but meaningful skill improvements (e.g., median CRPSS increases of ~0.04 at a 1-month lead), especially at longer lead times. These considerations suggest that our findings of modest MOI and GBOI correlations, though explaining only a small fraction of discharge variance, could still provide useful predictive information when combined with other data. Indeed, operational forecasters caution that potentially useful climatic signals may be overlooked if their influence is assumed insignificant (Pagano and Garen, 2023). Understanding these relationships allows attribution of hydrological changes to specific climate modes, improving predictive capability for maximum discharges forecasting (Massei et al., 2020). In addition, when analyzing the influence of delayed atmospheric oscillations and runoff (where atmospheric oscillations are delayed by one month), negative correlations between runoff and GBOI-1 were observed at Bezdan and Bogojevo stations in the period 2001–2018, indicating a potentially negative influence of delayed GBOI-1 on runoff dynamics (correlation coefficients of –0.089 and –0.088 with p-values of 0.17 and 0.175), but the level of statistical significance is low. These results underline the complexity of the relationship between the Danube discharge and atmospheric oscillations and emphasize the need for site- and time-specific analyzes to fully understand the discharge dynamics (Table 5).

A comparison of the Spearman correlation analyses for the periods 1961–2000 (Table 6) and post 2001 (Table 7) shows remarkable differences in the relationship between the discharge of the Danube and the atmospheric oscillations at the Bezdan, Bogojevo, Orsova and Ceatal Izmail stations. In the earlier period, positive correlations between discharge and MOI were observed at the Bezdan and Bogojevo stations, indicating a significant influence (480 values) of MOI on discharge dynamics. In addition, significant correlations between discharge and GBOI were observed at the Ceatal Izmail station. However, no statistically significant correlations between discharge and NAO were found at any station. In contrast, the analysis for the period 2001–2020 revealed significant positive correlations between discharge and GBOI and MOI at the Bezdan and Bogojevo stations and at the Ceatal Izmail station, indicating a consistent influence of these oscillations on discharge dynamics over the years. Interestingly, a significant negative, correlation between discharge and MOI was found at the Orsova station for the latter period, indicating a possible change in the relationship between these variables over time. In addition, no significant correlations between discharge and NAO were found at any station in either period, emphasizing the variability of the influence of different atmospheric oscillations on the Danube discharge over time.

A comparison of the analyses for the period 2001–2018, taking into account delayed atmospheric oscillations (GBOI, MOI and NAO), with the results of the previous period provides further insights into the temporal dynamics of the relationship between discharge and atmospheric oscillations. At the Bezdan and Bogojevo stations, statistically significant positive correlations between discharge and MOI were observed for both periods, indicating a consistently positive influence of the MOI one month earlier on the discharge dynamics. At the Orsova and Ceatal Izmail stations, however, no significant correlations between discharge and delayed atmospheric oscillations were observed for either period, highlighting the variability of the effects of delayed oscillations at the different stations and over time. These findings underscore the complex nature of the relationship between Danube River discharge and atmospheric oscillations, emphasizing the need for further research to understand the temporal variability and implications of these relationships for water resource management and climate adaptation strategies.

These results underline the complexity of the relationship between Danube River discharge and atmospheric oscillations. They are consistent with other Danube basin studies that emphasize oscillation impacts differing by location: for instance, multiple analyses have shown that NAO-related signals are often strongest in winter precipitation over Serbia and Slovenia whereas indices like GBOI play a more dominant role in controlling Southeast European hydrology (Mares et al., 2025). In other words, while NAO strongly modulates climate in Western Europe (enhancing winter rainfall and river flows there) (Mares et al., 2025), our findings confirm that in the Danube's lower basin the Greenland–Balkan and Mediterranean indices are relatively more important drivers. It should be noted, however, that even statistically significant correlations with low magnitudes can still hold practical value. For instance, Xu et al. (2024) emphasize that weak correlations do not mean that there are no interactions between large-scale ocean signals and the local hydrological cycle, since teleconnections often impact river discharge indirectly via precipitation and other intermediate factors.

A comparative perspective also reinforces the robustness of our findings. In contrast to Steirou et al. (2017), who identified the North Atlantic Oscillation as the dominant control of winter streamflow variability across Central Europe, our results show that this influence weakens considerably in the middle and lower Danube Basin. By extending the spatial focus eastward, our study demonstrates a clear transition from Atlantic to Mediterranean and continental climatic control, with the Mediterranean Oscillation Index (MOI) and the Greenland–Balkan Oscillation Index (GBOI) emerging as the primary drivers of discharge variability. Moreover, unlike Steirou et al., who examined primarily the mid- to late-twentieth-century period, we compared pre-2000 and post-2000 conditions and found evidence of temporal non-stationarity, including a reversal of the MOI–discharge relationship at Orşova after 2000. This suggests a shift in dominant circulation regimes, possibly linked to changes in Mediterranean blocking patterns and regional atmospheric pathways. By combining correlation and trend analyses across multiple teleconnections, our approach therefore provides a broader and more dynamic understanding of the climatic controls governing maximum discharges of the Danube River.

It can be concluded that the station-specific nature of these correlations – strong MOI effects upstream, stronger GBOI effects downstream, and minimal NAOI effects everywhere – highlights the need for detailed, seasonally- and site-specific analyses. Indeed, previous seasonally focused studies have found that NAO's imprint on the Danube is usually confined to winter precipitation (Mares et al., 2025), whereas Mediterranean teleconnections (MOI/WeMOI) tend to influence the basin in other seasons. Our monthly-maximum analysis captures the integrated outcome of these factors, but seasonal breakdown might further clarify the timing of each oscillation's impact. These comparisons with the literature show that our results are broadly in line with earlier research on the Danube: we find that MOI and GBOI are key positive influencers of discharge (as reported by Dolinaj et al. 2019 and Mares et al. 2016), that NAO correlations are weak or absent (as other authors have noted), and that any detected trends (or lack thereof) do not contradict larger-scale findings.

Table 6. Spearman's correlation results for the 1961–2000 period.

Station	GBOI		MOI		NAO		GBOI lag 1		MOI lag 1		NAO lag 1	
	ρ	p	ρ	p	ρ	p	ρ	p	ρ	p	ρ	p
Bezdan	0.052	0.252	0.265	**0.000**	0.041	0.371	–0.076	0.096	0.247	**0.000**	0.021	0.642
Bogojevo	0.061	0.179	0.271	**0.000**	0.033	0.466	–0.081	0.076	0.275	**0.000**	0.002	0.957
Orsova	0.244	**0.000**	–0.082	0.071	–0.004	0.939	–0.031	0.493	0.139	**0.002**	–0.034	0.460
C. Izmail	0.127	**0.005**	0.003	0.950	–0.017	0.705	–0.027	0.556	0.230	**0.000**	–0.030	0.506

***Bold** – statistically significant at the level 0.05.

Table 7. Spearman's correlation results for the post 2001 period.

Station	GBOI		MOI		NAO		GBOI lag 1		MOI lag 1		NAO lag 1	
	ρ	p	ρ	p	ρ	p	ρ	p	ρ	p	ρ	p
Bezdan	0.187	**0.004**	0.193	**0.003**	–0.094	0.147	–0.077	0.235	0.170	**0.008**	–0.037	0.564
Bogojevo	0.148	**0.022**	0.178	**0.006**	–0.050	0.441	–0.057	0.382	0.196	**0.002**	–0.005	0.943
Orsova	0.160	**0.018**	–0.221	**0.001**	–0.071	0.286	–0.043	0.527	–0.049	0.474	–0.047	0.495
C. Izmail	0.070	0.308	–0.152	**0.025**	–0.091	0.184	–0.053	0.440	0.049	0.475	–0.042	0.540

***Bold** – statistically significant at the level 0.05.

3.3 Analysis of maximum discharges by GEV

In order to see whether the statistical distributions of maximum discharges with respect to two consecutive intervals are stable from the point of view of statistical parameters, two periods were considered, namely 1961–2000 for all four stations and the period 2001–2020 for the stations in Serbia, and 2001–2018 for the stations in Romania.

Fig. 3 show the scatter plots (by month) and the Fig. 4 shows GEV adjustments for the 4 stations considered in this study for the two analysed periods 1961–2000 and the corresponding period until 2020.

The analysis of the scatter plots (Fig. 3) shows that the Bezdan and Bogojevo stations exhibit stability with respect to the month in which the highest maxima occur, i.e., June has the highest maxima both in the period 1961-2000 and in the second analysed period 2001–2020. Regarding the Orsova and Ceatal Izmail stations it is notable that a certain instability related to the generation of maximum daily discharges at the monthly level. In Orsova the maximum occurs in the spring months (March and April), in Ceatal Izmail in the spring months (April and May) and at the beginning of summer (June). Such seasonality is influenced by winter NAO patterns, which strongly correlate with Central European streamflow variability and flood risk (Steirou et al., 2017). With regard to the GEV adjustment shown in the lower panels of Fig. 4c and they differ in most cases in the period after 2001 compared to the period in the 20th century.

The GEV distribution analysis was not used here for flood design purposes (e.g., 100–year return levels), but rather as a diagnostic tool to evaluate how atmospheric variability alters the statistical structure of monzhly maximum discharges. By examining changes in the fitted parameters between periods, we assess whether climate-induced non-stationarity manifests as shifts in the frequency or intensity of discharge extremes. This analytical perspective aligns with recent advances in hydroclimatology emphasizing the role of circulation indices as covariates in extreme value models (Gilleland and Katz, 2016; Towler et al., 2020).

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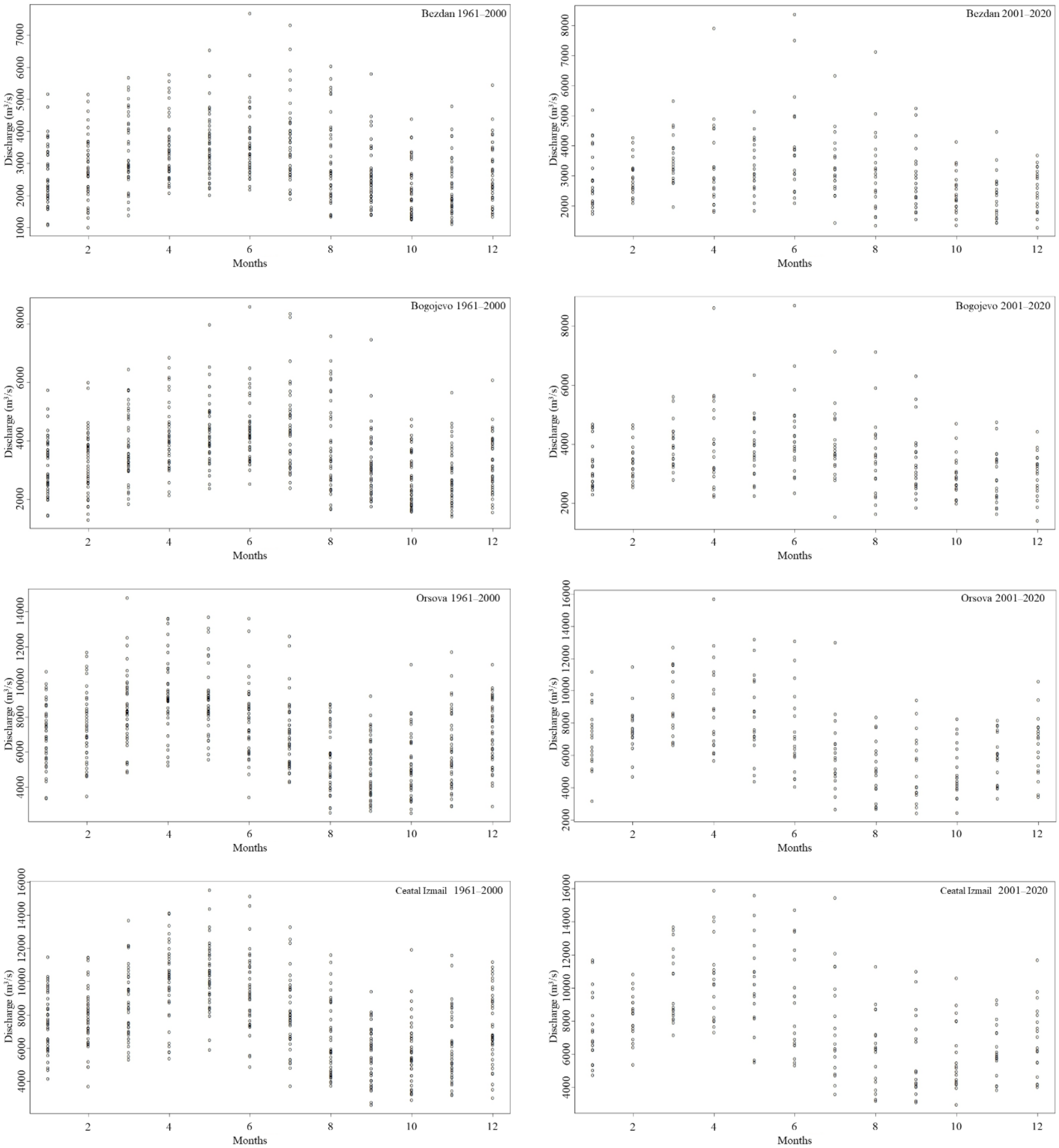

Fig. 3. Scatter plot (by month) of the maximum monthly discharge at investigated stations for two considered period.

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The analysis of the GEV distribution in Fig. 4c and 4d shows for each selected hydrological station the quantile in the model, the simulated empirical quantile, the probability density of the GEV and the return period. Some observations are made on the characteristics of this runoff. The proposed model captures the events well with respect to the small and medium values of the extremes, but with somewhat stronger deviations in the range of the large values, as shown in the upper panels of Fig. 4c and 4d for the selected time intervals.

These deviations are physically meaningful, as they often coincide with years of anomalous atmospheric circulation, such as negative NAO or strong GBOI winters, when flood peaks deviate from the expected climatological envelope. Hence, parameter shifts in the GEV fits provide indirect evidence that changes in large-scale atmospheric forcing influence flood behavior across the basin.

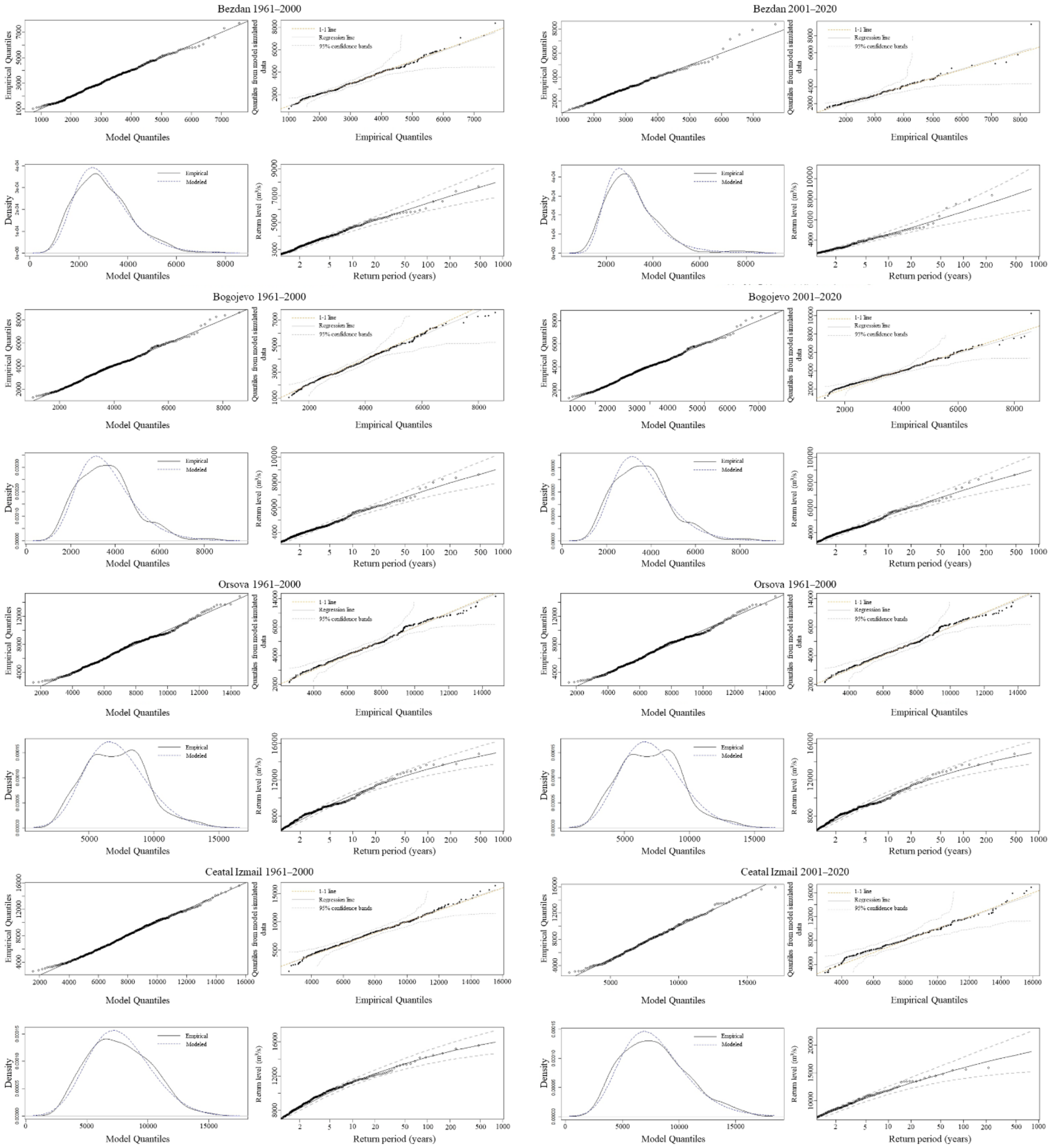

Fig. 4. GEV fit diagnostics for monthly daily maximum discharge dataset for the 1961–2000 and post 2001 period.

Table 8. GEV parameters for all four stations (1961–2000).

	Bezdan		Bogojevo		Orsova		Ceatal Izmail	
	Value	**St. error**	**Value**	**St. error**	**Value**	**St. error**	**Value**	**St. error**
μ	2513.39	48.59	3074.13	54.90	6178.34	109.69	6738.73	121.32
σ	939.74	35.85	1067.95	39.61	2176.91	80.28	2398.01	92.08
ξ	–0.04	0.04	–0.06	0.03	–0.17	0.03	–0.18	0.03

Table 9. GEV parameters for all four stations (post 2001 period).

	Bezdan		Bogojevo		Orsova		Ceatal Izmail	
	Value	**St. error**	**Value**	**St. error**	**Value**	**St. error**	**Value**	**St. error**
μ	2578.24	59.81	3058.42	63.04	5851.67	167.08	6671.05	193.83
σ	824.88	44.49	878.73	44.61	2207.28	124.55	2532.93	152.42
ξ	0.04	0.05	–0.01	0.04	–0.10	0.05	–0.11	0.06

The following two panels from Fig. 4c and 4d show a unimodal probability density that is relatively well captured by the model. The model (dotted curve) exaggerates the maximum compared to the actual situation of the probability density (continuous curve). The GEV distribution parameters (location, scale and shape) with standard errors in brackets are presented in Tables 8 and 9. Parameter estimation is realized by maximum likelihood estimation (MLE).

The comparison between the two analyzed periods shows that the downstream stations (especially Orșova and Ceatal Izmail) exhibit a slight contraction in the scale parameter and a more negative shape parameter, indicating a modest reduction in the upper-tail heaviness of the distribution. This suggests that extreme floods have become statistically less probable in the 21st century, a pattern coherent with the observed decrease in maximum discharge at Orșova and consistent with broader European findings (Hannaford et al., 2013; Shi et al., 2019).

The development of extreme events in the discharge of the Danube from 1961–2000 (Tab.7) was realized according to a GEV distribution of the Weibull type with the shape parameter ξ negative. In the following period, the extreme hydrological regime was maintained, except for the Bezdan event, which changed from Weibull to Frechet, which is represented by the positive shape parameter.

Unimodal statistical distribution, can be found at all stations with the exception of Orsova in the period 1961–2000 (Fig. 4c). Here the empirical distribution (continuous curve) is bimodal (with two peaks). This can be attributed either to an instability of the distribution due to an erroneous selection of the maximum events (the independence of the events in the formation of a maximum block is not guaranteed) or to a real structure with two basins of attraction, which requires further investigation to clarify the true cause.

The return period in correspondence with the return level, whose fits are highlighted by a straight line, is within the confidence interval as it obviously starts from the origin of the axis system and forms an angle close to 45 degrees, except for the situation at Orsova. At the Orsova, the relationship between the return level and the return period is curiously represented by a curve with concavity downwards and with more significant deviations that lie outside the confidence interval (the two dotted curves flanking the return level – return period curve, in the area of small and medium extreme events). This section demonstrates that the nonlinear (non-stationary) GEV analysis contributes to a better understanding of atmospheric influences on discharge extremes, not by providing engineering design values but by revealing the sensitivity of flood probability distributions to climate indices. This diagnostic application of EVT complements the correlation and trend analyses and provides a mechanistic bridge between statistical evidence of non-stationarity and large-scale circulation dynamics. Consequently, it directly supports the paper's central aim, to quantify and interpret how atmospheric teleconnections (GBOI, MOI, and NAOI) modulate hydrological extremes along the Danube.

3.3 GEV analysis by fitting with covariates

In order to detect the influence of atmospheric oscillations at planetary and regional scales considered by the climate indices (GBOI, MOI and NAOI) on the maximum discharge, in this study first we analyzed the response of the maximum discharge in June at Bezdan station for the period 1961-2020 and the daily maxima at Orsova station for the month of April for the period 1961-2018. This analysis was performed by introducing into the location parameter of the GEV distribution one of the three climate indices with lags of 1 to 3 months. The likelihood ratio test was then used to determine the statistically significant cases, i.e., in these cases the climate predictor contributes to the generation of the maximum. In this way, the potential large-scale predictors for the generation of the maximum discharge in the respective area were determined.

For the maximum discharges in June at the Bezdan station from the period 1961-2020, statistically significant results were only obtained among the predictors considered when the GBOI from March was introduced as a covariate. This outcome is consistent with recent climate-informed flood analyses: for instance, Steirou et al. (2019) found that including indices like the NAO as covariates significantly improved GEV-based flood estimates across Europe.

In the case of the maximum daily discharge in April at the Orsova station in the period 1961-2018, the likelihood ratio test indicated the climate indices GBOI and NAOI from the months of February and March as significant predictors, with the GBOI from March showing the highest statistical significance. This finding aligns with Mareș et al. (2009), who reported that incorporating winter NAO as a covariate significantly improves GEV fits for spring flood maxima in the lower Danube basin.

Subsequently, for the period 1961–2000 only, we analyzed the response of the monthly maximum daily discharges of the Bezdan and Orsova stations to the introduction of the monthly averages of GBOI, MOI and NAOI from the same month corresponding to the discharges (simultaneous analysis).

Table 10. Testing the introduction of covariates in the location parameter of GEV, for the Bezdan station for the 1961–2000 period.

Statistical measures	GBOI	MOI	NAOI
AIC	8065.67	8032.86	8065.42
BIC	8082.38	8049.57	8082.12
p-value	0.320	0.000	0.265

Table 11. Testing the introduction of covariates in the location parameter of GEV, for the Orsova station for the 1961–2000 period.

Statistical measures	GBOI	MOI	NAOI
AIC	8775.29	8795.85	8796.58
BIC	8791.99	8812.54	8813.27
p-value	0.000	0.380	0.842

The results of GEV estimation of outflows by introducing the three climate indices as covariates are analyzed using the Akaike information criterion (AIC), the Bayesian information criterion (BIC) and the p-value 0.05 (Tables 10 and 11). These results reveal regional distinctions similar to those found in other studies: for example, Steirou et al. (2022) note that large-scale modes (NAO, EA/WR, SCA, etc.) modulate flood probabilities across Europe (Steirou et al., 2022), which is consistent with our finding that MOI dominates at Bezdan while GBOI dominates at Orsova.

Taking into account the values of AIC, BIC and especially the value of p, we deduce that in the case of the simultaneous analysis of the introduction of one of the three climatic indices in the location parameter (μ) of the GEV distribution, it emerged as the best predictor for the daily extremes of a month for the Bezdan station is the monthly average of the MOI of the respective month. The same distribution was showed to be the best fit for the Slovakian and Austrian part of Danube River (Salinas et al., 2014). For the discharge from the Orsova station from the analyzed period 1961–2000, the most significant predictor is GBOI. This regional differentiation is consistent with the physical mechanisms described by Ionita et al. (2012), who linked low-flow periods in the lower Danube to atmospheric blocking patterns over Scandinavia and Eastern Europe, a circulation type closely related to the GBOI pattern. Our emphasis on GBOI and MOI is supported by analyses of the Danube climate: Mares et al. (2016) found GBOI to be a stronger predictor than NAOI for Danube-basin precipitation, and Mares et al. (2025) similarly show GBOI dominating NAOI in Southeastern European hydroclimate.

These climate indices GBOI and MOI can be considered as good predictors to be considered in a multiple regression with suitable weights for both stations regarding the monthly daily maxima. The results in Tables 9 and 10 agree with the results obtained in Table 3, regarding the statistical significance of the simultaneous correlations (in the same month) between maximum discharge and large-scale climatic indices. Overall, our findings corroborate the consensus from climate-informed EVT studies: conditioning GEV models on atmospheric indices can significantly improve flood risk estimates (Steirou et al., 2019; Mares et al., 2009). Our approach is methodologically similar to that of Salinas et al. (2014), who successfully used NAO as a covariate for GEV models in the Upper Danube, though our results demonstrate that the most relevant climate predictor shifts from NAO upstream to MOI and GBOI in the middle and lower basins.

If for the atmospheric predictors with a certain lag compared to the occurrence of maximum discharges, indices can be calculated directly from the observational data, for the significant predictors considered simultaneously in the same month, their values can be easily obtained from the SLP data provided by the long-range weather forecasting centers or from climate prediction models through appropriate downscaling methods of SLP values. In this way, the results obtained in this study can be used to estimate with a certain anticipation the maximum discharges.

4 CONCLUSION

Presented study investigated the intricate relationships between large-scale climatic circulations and hydrological dynamics at the local scale in the Danube River Basin (DRB), focusing on the middle and lower sections in Serbia and Romania, respectively. Our results show the importance of understanding these interactions for effective water resource management and climate adaptation strategies in the face of escalating extreme hydrological events, especially floods and droughts.

Results has shown that relatively stable patterns of maximum monthly discharges at most stations, with the exception of a statistically significant downward trend observed at Orsova station for the period 1961–2018. This underlines the need for continuous monitoring and adaptive management strategies to address potential shifts in the hydrological regime.

Correlation analyses revealed significant relationships between runoff and atmospheric oscillations such as the Greenland-Balkan Oscillation Index (GBOI) and the Mediterranean Oscillation Index (MOI), which illustrates the influence of large-scale climatic patterns on local hydrological processes. However, the temporal and spatial variability of these relationships underlines the complexity of their interactions.

The application of extreme value theory (EVT) provided insights into the differences in the statistical distributions of maximum discharges between different time periods, indicating possible shifts in hydrological regimes. Furthermore, the influence of atmospheric variability on maximum discharge varied between stations and time intervals, emphasizing the need for site-specific analyses. Our results have implications for climate adaptation efforts in the DRB and provide valuable insights for the development of targeted strategies to mitigate the effects of hydrological extremes.

In addition to the comprehensive findings elucidated in our study, an analysis of the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and the parameter significance (p-value) reveals intriguing insights regarding the predictive capacity of different climatic indices on extreme hydrological events. Notably, in the case of simultaneous analysis introducing one of three climatic indices into the location parameter (μ) of the Generalized Extreme Value (GEV) distribution, the monthly average of the Mediterranean Oscillation Index (MOI) emerged as the most robust predictor for daily extremes at the Bezdan station. Conversely, for discharge at the Orsova station during the period 1961–2000, the Greenland-Balkan Oscillation Index (GBOI) demonstrated the highest predictive power. These indices, GBOI and MOI, exhibit promise as significant predictors in multiple regressions, with their respective weights tailored to each station's monthly daily maxima.

Overall, our research contributes to the expanding body of knowledge on the complex interactions between climate variability, atmospheric circulations, and hydrological processes in the DRB. By elucidating these relationships, we aim to inform evidence-based decision-making and enhance the region's capacity to adapt to the challenges posed by climate change. Further research is warranted to explore the temporal and spatial variability of these interactions and their implications for water resource management in the DRB.

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