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A Combined Seasonal Mann–Kendall and Innovative Approach for the Trend Analysis of Streamflow Rate in Two Croatian Rivers

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Abstract: Climate change profoundly impacts hydrological systems, particularly in regions such as Croatia, which is renowned for its diverse geography and climatic variability. This study examined the effect of climate change on streamflow rates in two Croatian rivers: Bednja and Gornja Dobra. Using seasonal Mann–Kendall (MK) tests, overall streamflow trends were evaluated. Additionally, innovative polygon trend analysis (IPTA), innovative visualization for innovative trend analysis (IV-ITA), and Bayesian changepoint detection and time series decomposition (BEAST) algorithms were used to assess the trends' magnitudes and transitions. The seasonal MK analysis identified significant decreasing trends, primarily during summer. The results of IPTA and IV-ITA revealed consistent decreasing trends throughout most months, with a notable increase in September, especially at high flow values. The rivers' behavior differed between the first and second halves of the month. BEAST analysis detected abrupt changes, including earlier shifts (1951–1968) in the Bednja and more recent ones (2013–2015) in both the Bednja and, to a lesser extent, the Gornja Dobra rivers. This comprehensive approach enhances our understanding of long-term streamflow trends and short-term fluctuations induced by climate change.

Keywords: streamflow rate; trend analysis; IPTA method; IV-ITA; BEAST; Croatia

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1. Introduction

Climate change has significant impacts on global temperatures and hydrological cycles [1,2]. These effects can be significant, leading to the alterations in the water-holding capacity of the atmosphere and an increase in the frequency and intensity of extreme precipitation events. Rising temperatures alter the water cycle, changing precipitation patterns and thereby directly impacting river flows. It is widely acknowledged that temperature will hasten the global hydrological cycle, resulting in shifts in global and regional hydrological regimes, and spatial and temporal water variability [3,4].

Surveys have indicated a direct link between climate change's impact on water resources and shifts in the water cycle [5–7]. Increasing temperatures notably affect river flows through changes in rainfall patterns [8]. For example, Labat et al. [9] demonstrated that each 1 °C increase boosted streamflows by 4%. Furthermore, many researchers have noted that water resources have already been disturbed by recent climate forcings, manifesting as an intensification of the impact on the hydrological cycle [10–12].

Therefore, understanding and mapping the water cycle's changes in detail is crucial for combating climate change and sustainably managing water resources. Additionally, monitoring and analyzing the variability in hydrological variables (precipitation, evapotranspiration, and streamflow) are essential for assessing the impacts of climate change and to ensure the sustainable use of water resources [6,13]. Analysis of the trends of river flow is essential for effective water resource management and sustainability [14,15]. These analyses provide critical insights into how environmental factors, such as climate change, influence hydrological patterns, informing policies on water conservation, supply, and irrigation [7]. Techniques of analyzing trends, including the Mann–Kendall and Sen's slope tests, are commonly used to detect and quantify fluctuations in flow data.

Moreover, climate change may induce a process of oversimplification, affecting the natural pattern of watercourses, with bars tending to become barer and more stable, and vegetation colonizing exposed sandbars more readily. From this perspective, Nones et al. [16] combined the MK test with an analysis of satellite data to examine the hydrological trends, sandbar exposure, and riparian vegetation coverage, showing a less dynamic active channel in European piedmont rivers.

In recent years, graphical methods have gained prominence for analyses of trends, offering advantages in interpreting temporal changes in the flow's values and monthly transitions [17,18]. Innovative approaches, such as innovative trend analysis (ITA) and innovative polygon trend analysis (IPTA), enable detailed examinations of monthly and seasonal trends, enhancing our understanding of hydrological variability [19,20]. Additionally, methods such as improved visualization for innovative trend analysis (IV-ITA) provide enhanced visualization and quantitative assessment of trends' slopes, contributing to a comprehensive analysis of the dynamics of river flow [18].

Several studies utilizing statistical and graphical methods have investigated global changes in hydrological regimes, confirming behavioral shifts [4,21–28]. Li et al. [4] observed declining trends in annual discharge in the Songhua River Basin post-1990. Akçay et al. [22] found notable decreasing trends in monthly stream flows in Turkey's Eastern Black Sea Basin, particularly in summer. Gupta and Chavan [23] observed various trends in monthly streamflow values across four major river basins in southern India. Malani and Yadav [25] identified a significant decrease in daily runoff in the Upper Tapi Basin, India. Ali et al. [27] noted decreasing annual average flow at the Cuntan and Zhutuo stations on the Yangtze River, with varying monthly trends.

An alternative method for detecting changepoints in hydrological time series is the Bayesian changepoint detection and time series decomposition (BEAST), which is capable of identifying abrupt changes, seasonal fluctuations, and trends simultaneously [29]. BEAST has been effectively applied in various domains, including analyses of streamflow rates [30].

In this study, a combined approach to analyzing trends has been proposed, using the seasonal MK test, IPTA with the star concept, IV-ITA, and BEAST for analyzing streamflow rates in two Croatian rivers: Bednja and Gornja Dobra. While some studies have examined the overall streamflow rate trends of the Bednja and Gornja Dobra [31–33], none have analyzed interannual behavior or provided the magnitude and slope of the trends' transitions between monthly segments.

It should be noted that the river Bednja flows through alluvium media, while the Gornja Dobra flows through karst [34]. The analysis, conducted at seven flow stations along the selected rivers, revealed spatial and temporal flow trends and quantified monthly-scale change effects. This is important, because both rivers have alternating dynamic regimes, which often result in flooding and dry periods, which can be seen in Figure 1.

Understanding and managing these variations is crucial for applications such as agriculture, irrigation, and hydropower generation, as well as for assessing the availability of water and managing local water stress induced by climate change and human activities. This comprehensive study offers novel insights into annual and monthly trends of river flow, utilizing innovative techniques of trend detection.

Figure 1. Dry periods and flooding of the rivers Bednja (**a**,**b**) and Gornja Dobra (**c**,**d**) [35].

2. Materials and Methods

2.1. Study Area and Dataset

The daily flow recorded from 1 January 1947 to 31 December 2022, was considered, with variations observed at each monitoring station. The shortest time series corresponds to the stations 5140-Lepoglava and 5143-Ključ, spanning from 1987 to 2022. On the other hand, the longest time series was found at the stations 4038-Luke and 5089-Ludbreg, spanning from 1947 to 2022. Detailed statistics regarding the catchment area and flow rate of each river are presented in Table 1. Figure 2 provides a representation of the stations' locations, a digital elevation model of the country, and the hydrographic network.

Table 1. Essential characteristics of the measured streamflow rates for the stations investigated.

Station	Gornja Dobra River			Bednja River			
	4088 Turkovići	**4038 Luke**	**5089 Ludbreg**	**5065 Tuhovec**	**5143 Ključ**	**5075 Zeljeznica**	**5140 Lepoglava**
Discharge (m^3/s)							
Mean	10.65	6.94	6.89	5.95	4.99	3.77	1.34
Median	8.87	5.93	4.87	4.06	3.30	2.66	0.78
Max	41.58	30.06	34.16	29.01	28.14	19.24	8.16
Min	0.40	0.63	0.25	0.45	0.40	0.26	0.04
Std deviation	7.61	4.95	5.90	5.15	4.59	3.26	1.37
CV	0.71	0.71	0.86	0.87	0.92	0.86	1.03

Table 1. *Cont.*

Station	Gornja Dobra River		Bednja River				
	4088 Turkovići	**4038 Luke**	**5089 Ludbreg**	**5065 Tuhovec**	**5143 Ključ**	**5075 Zeljeznica**	**5140 Lepoglava**
First quartile	4.58	2.96	2.68	2.31	1.86	1.38	0.41
Third quartile	14.98	9.56	9.29	7.79	6.40	4.94	1.79
Skewness	0.97	1.19	1.61	1.71	1.89	1.61	1.91
Catchment area (km^2)	298.00	162.00	546.98	469.54	415.67	307.95	89.80
Start of the ts	1 January 1963	1 January 1947	1 January 1947	1 January 1959	1 January 1987	1 January 1959	1 January 1987
End of the ts	31 December 2022	31 December 2022	31 December 2022	31 December 2022	31 December 2022	31 December 2022	31 December 2022

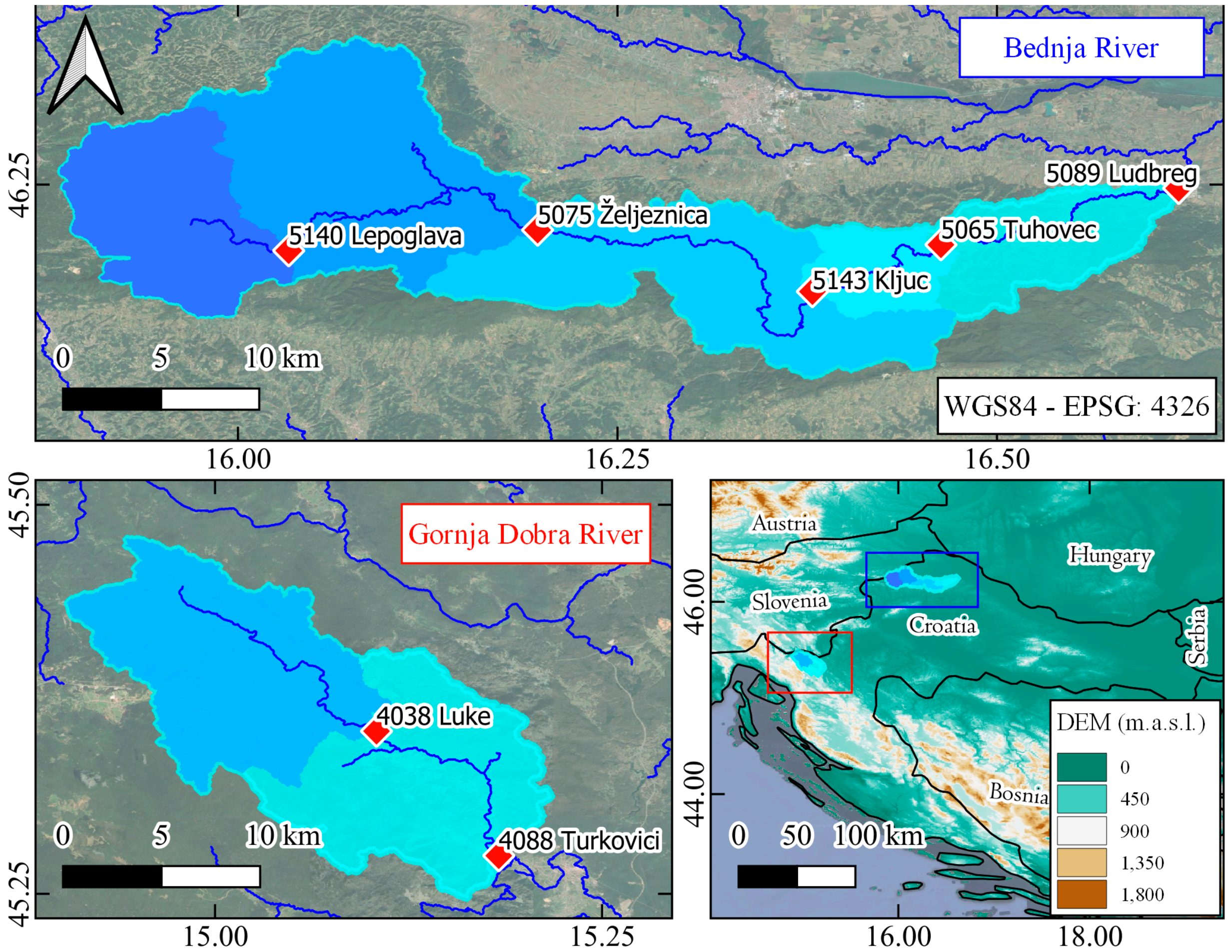


Figure 2. Location of the seven stations with a representation of the hydrographic networks and river basins.

Generally, streamflow rates peaked during the winter and spring months, reaching their minimum values in the summer. The stations with the lowest and highest monthly mean flow rates were 5140-Lepoglava (1.34 m^3/s) and 4088-Turkovići (288.34 m^3/s), respectively.

Figure 3 displays box plots representing the monthly mean streamflow rates, while the lowest and highest interquartile ranges, equal to the difference between the third quartile (Q3) and the first quartile (Q1), were computed for 5140-Lepoglava (1.37 m^3/s) and 4088-Turkovići (10.4 m^3/s).

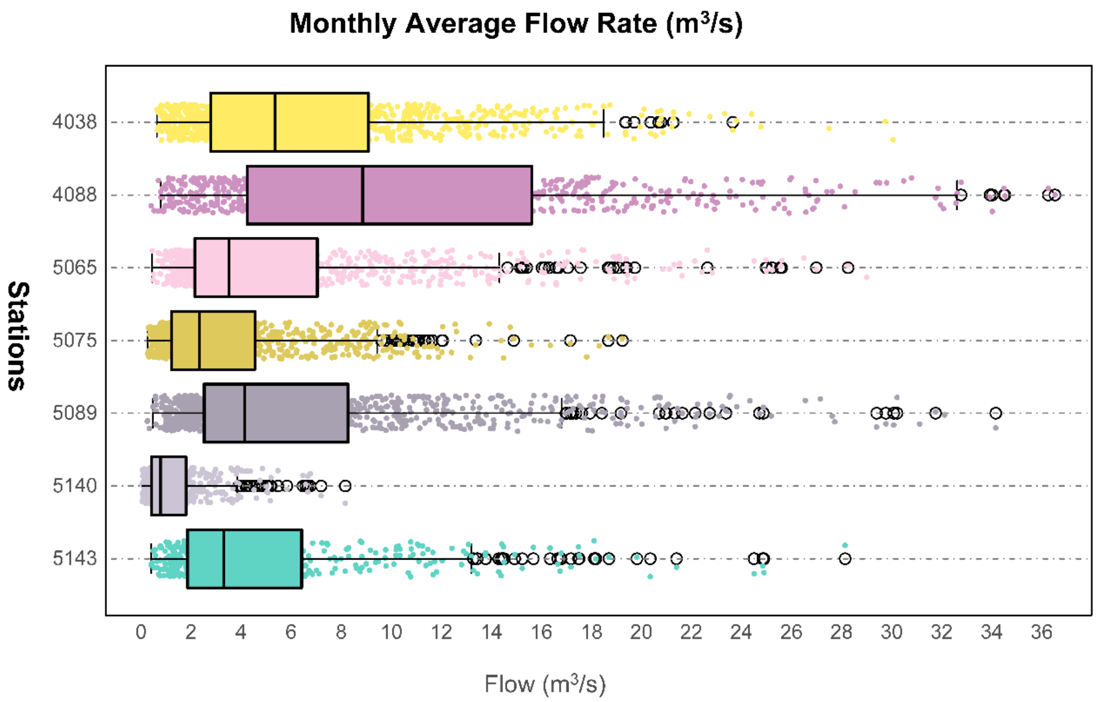


Figure 3. Box plots of the monthly streamflow rate.

2.2. Models

2.2.1. Seasonal MK

MK is a non-parametric test [36,37] that is widely used in hydrology to identify statistically significant trends in time series. Time series of streamflow rates may exhibit distinct seasonal patterns. Therefore, the seasonal MK test can be utilized to calculate the S statistic for each specific season under consideration [38]. Given that this study concentrated on the monthly trends of streamflow rate, the S statistic was computed for each of the months m (S_m), with the overall statistic S_S defined as:

$$S_S = \sum_{m=1}^{p=12} S_m \tag{1}$$

The longer the time series, the more accurately the distribution of S_S approximates a normal distribution. Consequently, it can be standardized according to

$$Z = \begin{cases} \frac{S_S - 1}{\sigma_S}; \ S_S > 0 \\ 0; \ S_S = 0 \\ \frac{S_S + 1}{\sigma_S}; \ S_S < 0 \end{cases} \tag{2}$$

where σ_S is the standard deviation of S_S. The Z value serves as a metric for detecting statistically significant trends. A significance level of 0.05 was considered, consistent with prior literature [39]. Additionally, Sen's slope was applied to assess the slope of the linear trend. Specifically, the slope is the median of β_m computed for each month m:

$$\beta_m = \text{median}\left(\frac{Y_{jm} - Y_{km}}{j - k}\right) \text{ for } \forall k < j \text{ and for } m = 1, \ldots, 12 \tag{3}$$

In general, positive values of β may suggest the possible existence of increasing trends, while negative values may indicate decreasing trends. In this context, Sen's slope represents the average monthly increase or decrease in the streamflow rate.

Therefore, in this study, the trends of the streamflow rate for both rivers were investigated using the seasonal MK test. This statistical method allowed us to assess the presence and direction of trends in the streamflow data. The outcomes of the test were analyzed considering each month, from January to December, and overall, based on Equations (1) and (2). This allowed for a comprehensive analysis of both the monthly variations and overall trends in streamflow. Indeed, by examining the monthly variations, researchers can identify seasonal patterns, such as increased streamflow during certain months due to rainfall or snowmelt. On the other hand, assessing overall trends provides an insight into any systematic changes in streamflow rates over time, which could be indicative of broader environmental changes or human impacts on the rivers.

2.2.2. Innovative Polygon Trend Analysis (IPTA) with the Star Concept

IPTA is one of the most recent innovative graphical methods of analyzing trends proposed in the literature [19]. IPTA is a non-parametric method and can be applied to time series for calculating the size and slope of trends' transitions between consecutive periods (e.g., months, weeks). The polygon generated by the method illustrates the one-year variation in the data. The straight lines connecting consecutive periods (months, weeks, etc.) provide information about the changes between consecutive periods. When the transitions between months are parallel to the horizontal (vertical) axis, it indicates a change in the transition between months in the first (second) half. In contrast, this change disappears in the second (first) half. Detailed calculation steps and methodology can be obtained from Şen et al. [19]. The graphs related to the IPTA method are reported in Section 3.2. A straight line divides the diagram into two parts in a 1:1 (45°) Cartesian coordinate system. If the distribution points marked on the Cartesian coordinate system are above (below) the 1:1 line, there is an increasing (decreasing) trend [17]. In the IPTA method, the significance measure can be obtained by the percentage of relative error (α) between the two half-series, where $\alpha < \pm 5\%$ assumes that no significant trend exists in the given time series.

In addition, IPTA with the star concept was proposed by Şen [20]. The method allows the transitions in the IPTA to be evaluated separately. The graph provides the following helpful information:

- Each arrow's length indicates the quantity of the related monthly data. Longer arrow lengths signify greater transitions between the two months;
- The horizontal (vertical) axis shows the change in the variable during the first (second) half of the period;
- The difference between the horizontal and vertical amounts indicates the change in the monthly streamflow rate.
- Quadrant I (Quadrant III) show positive (negative) changes in both halves;
- Quadrant II (Quadrant IV) indicates an increase (decrease) in the first half and a decrease (increase) in the second half.

2.2.3. Improved Visualization for Innovative Trend Analyses (IV-ITA)

The ITA method provides a new perspective on trend analyses by revealing monotonic or non-monotonic trends and considering the values at different levels of the data. However, the ITA method does not show the magnitude of the data and trends in the subcategories. IV-ITA, proposed by Güçlü [18], shows the amount of data in the subcategories (low and high) and the amount of change. The IV-ITA method can detect whether there is a change point in the trend of the data and can determine the presence and level of the trend separately for low and high data values. A sample IV-ITA graph is reported in Figure 4, related to the Tuhovec station for the month of September, to facilitate the understanding of the method. Specifically, the absence of a trend is indicated when all difference values in the IV-ITA method exhibit minor random deviations aligned with the horizontal axis (y = 0 line) or lie directly on the horizontal axis itself. Conversely, the presence of an increasing trend is denoted by points lying above the horizontal axis, while a decreasing trend is indicated by points below it. The methodology uses the Pettitt test to pinpoint the transition point within the time series data, thereby identifying the subcategories "high" and "low". For a comprehensive understanding of the detailed steps of calculation and the methodology, readers are referred to Güçlü [18]. However, it should be noted that due to the need to analyze a significant number of stations, in Section 3.3, the IV-ITA results are presented in the form of maps depicting the average trends for the high and low subcategories for each station and month.

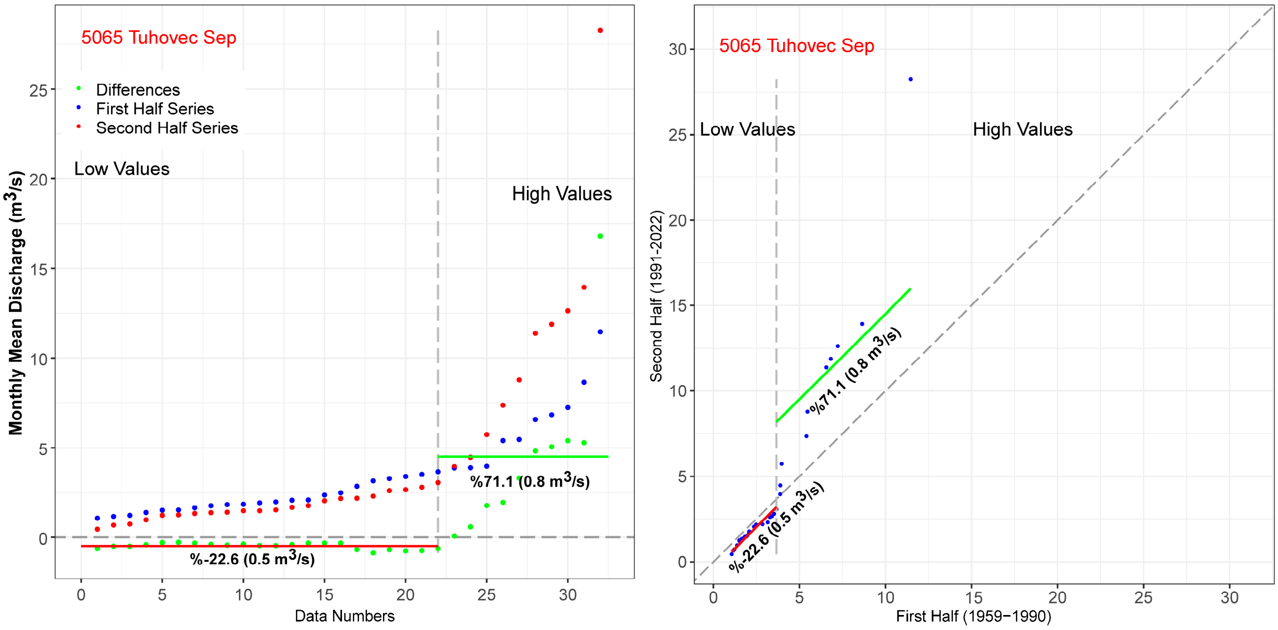


Figure 4. Examples of IV-ITA (**left**) and ITA (**right**) graphs.

2.2.4. BEAST Algorithm

The BEAST algorithm was used to identify changepoints in the trend within the time series of the streamflow rate. The BEAST algorithm dissects a time series denoted as Y(t) into distinct components: a trend (T), seasonal variations (S), abrupt changes in the trend (θt) and seasonality (θs) at time t, and random noise (ε). These components are combined additively to model the complete time series

$$Y(t) = T(\theta_t) + S(\theta_s) + \varepsilon \tag{4}$$

where ε represents the Gaussian random error term N(0, δ^2) with an unknown variance δ^2. To ascertain the unknown parameters M = {θt, θs, δ^2}, the Bayesian theorem was applied, and a posterior probability distribution was computed using Markov chain Monte Carlo (MCMC) sampling. The process can be described as follows:

$$f(Y) \propto f(M) * f(M) \tag{5}$$

The posterior probability, represented as f(M|Y), contains extensive details regarding the decomposition of the time series, including factors such as the occurrences and locations of changepoints within the trend and seasonal elements. However, deriving an analytical solution for f(M|Y) is not feasible due to its complexity, thus requiring simulation via the MCMC sampling method. Additional insights into BEAST's computational procedure were provided by Zhao et al. [29].

3. Results

3.1. Seasonal MK Test

Table 2 presents the results of the MK test and the IPTA method for the monthly average flow data. The analysis revealed that there was no significant trend in the months when the calculated absolute Z value was less than −1.96 or greater than 1.96, representing the limits of the 95% confidence interval.

Table 2. Seasonal MK and IPTA results.

	Seasonal MK Test												**Innovative Polygon Trend Analysis**												**Seasonal MK Parameters**		
Station	**Months**																										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Z**	**β (%)**	***p***
Ludbreg																									−3.65	−0.15	$p \leq 0.05$
Tuhovec																									−5.32	−0.23	$p \leq 0.05$
Ključ																									−0.48	−0.04	0.63
Željeznica																									−5.24	−0.15	$p \leq 0.05$
Lepoglava																									−2.15	−0.05	$p \leq 0.05$
Turkovići																									0.89	0.08	0.37
Luke																									−2.35	−0.08	$p \leq 0.05$

Increasing trend | No trend | Decreasing trend

Only the Turkovići station on the Gornja Dobra River showed a significant increasing trend in February. In contrast, the Ludbreg, Tuhovec, and Željeznica stations on the Bednja River exhibited significant decreasing trends in April, May, June, and July. Additionally, the Tuhovec and Željeznica stations showed significant decreasing trends in January and August. At the other stations on the Bednja River, namely Ključ and Lepoglava, no significant trends were detected, except in October. The variability in the results among these monitoring stations, despite being situated on the same river, can be attributed to differences in the length of the data. The Ludbreg, Tuhovec, and Željeznica stations utilized longer historical flow data. Furthermore, significant downward trends were observed at the Turkovići station on the Gornja Dobra River in August and at the Luke station in July and August, coinciding with the months with the lowest flow values.

In addition, the seasonal MK parameters, Z, β, and p, are also reported in Table 2. In particular, the stations located on the Bedjna River exhibited overall decreasing and statistically significant ($p \leq 0.05$) trends, with Z values ranging between -5.32 (Tuhovec) and -2.15 (Lepoglava). An exception was represented by Ključ, which, as observed in the monthly analysis, exhibited no statistically significant trend ($p > 0.05$), although the overall trend was slightly negative ($Z = -0.48$). Moving to the Gornja Dobra River, only the upstream Luke station exhibited an overall statistically significant decreasing trend, with $Z = -2.35$. The downstream Turkovići station showed an overall increasing trend instead ($Z = 0.89$), which, however, was not statistically significant. These findings underscore the spatial variability in the trends of river flow within the study region.

3.2. IPTA with the Star Concept

The results of applying IPTA with the star concept to analyze flow patterns on the Bednja and Gornja Dobra rivers are presented in Figures 5 and 6, respectively. The IPTA results for the Ludbreg, Tuhovec, and Željeznica stations with similar periods of historical records showed comparable patterns of behavior. However, upon closer examination of these stations, distinct streamflow patterns emerged across various months of the year. The highest monthly mean flows were recorded at the Ludbreg station, while the lowest were recorded at the Željeznica station. IPTA with the star concept revealed a consistent increase in streamflow rates from August to March, with the most significant increase occurring during the October–November transition. Conversely, there was a decrease from March to August, which was particularly pronounced during the April–May and March–April transitions.

At Ludbreg, minimal changes were observed in the transitions from August to September and from November to December during the first half (1947–1984), while an increase of about 2 m^3/s was noted in the second half (1985–2022). This pattern was reflected in the star plot, where the corresponding arrows aligned closely with the vertical axis. Additionally, in the September to October transition, there was an increase of about 1.75 m^3/s in the first half, whereas the second half witnessed a more modest increase of only 0.4 m^3/s. Conversely, during the transition from July to August, no significant change in the flow values was observed in the second half, while a decrease of about 2.5 m^3/s was noted in the first half. This is illustrated in the star graph, with the corresponding arrow falling above the horizontal axis. In the June–July transition, a decrease of 0.75 m^3/s was observed in the first half, and a decrease of 1.75 m^3/s was noted in the second half. Moreover, in the March–April and December–January transitions, the average flow values decreased by 1 m^3/s in the first half, while this decrease was 2.5 m^3/s in the second half. An examination of the monthly trends reveals that September and October exhibited upward trends, while the other months displayed downward trends. The decreasing trend in December was not significant.

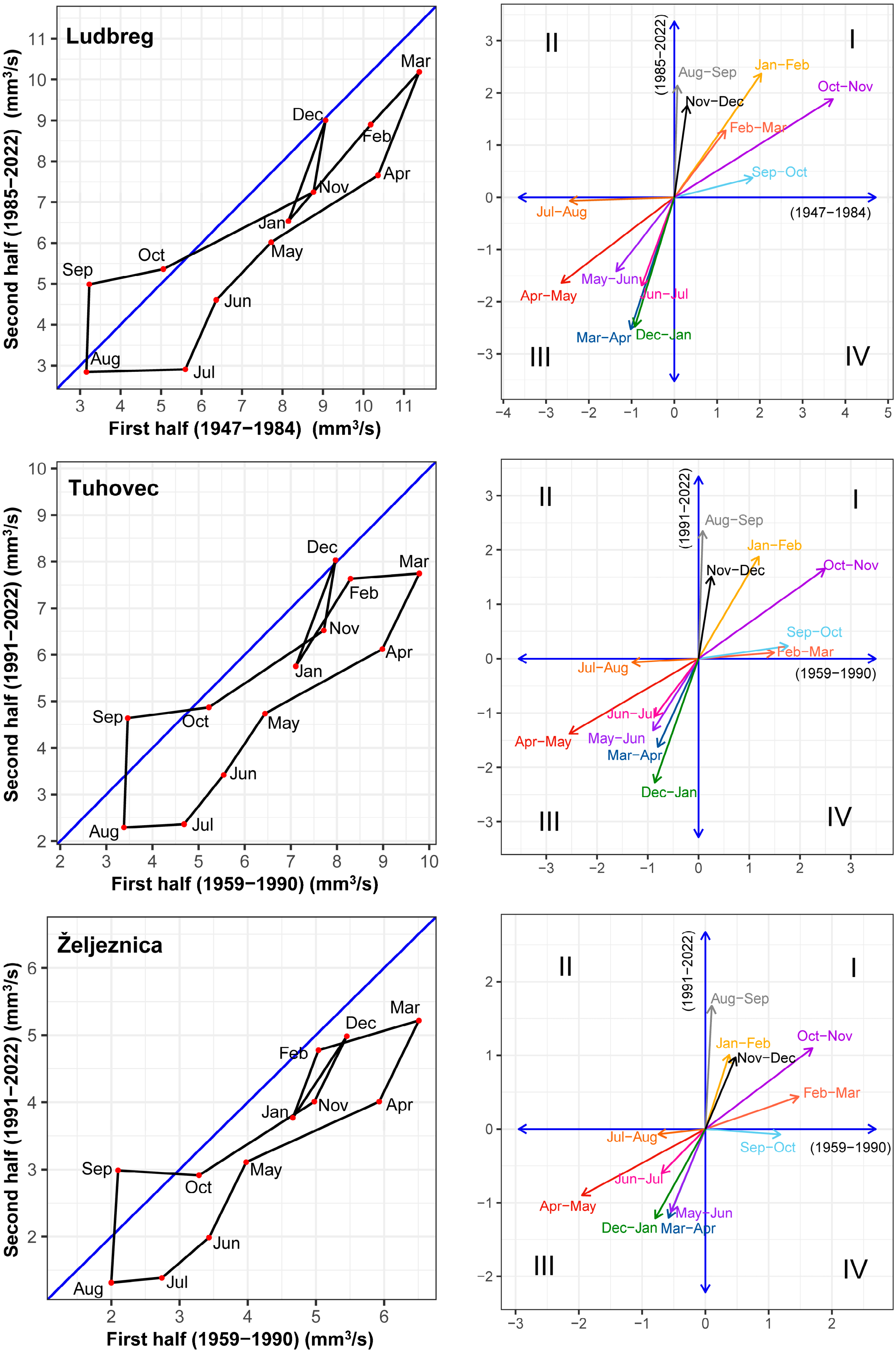


Figure 5. *Cont.*

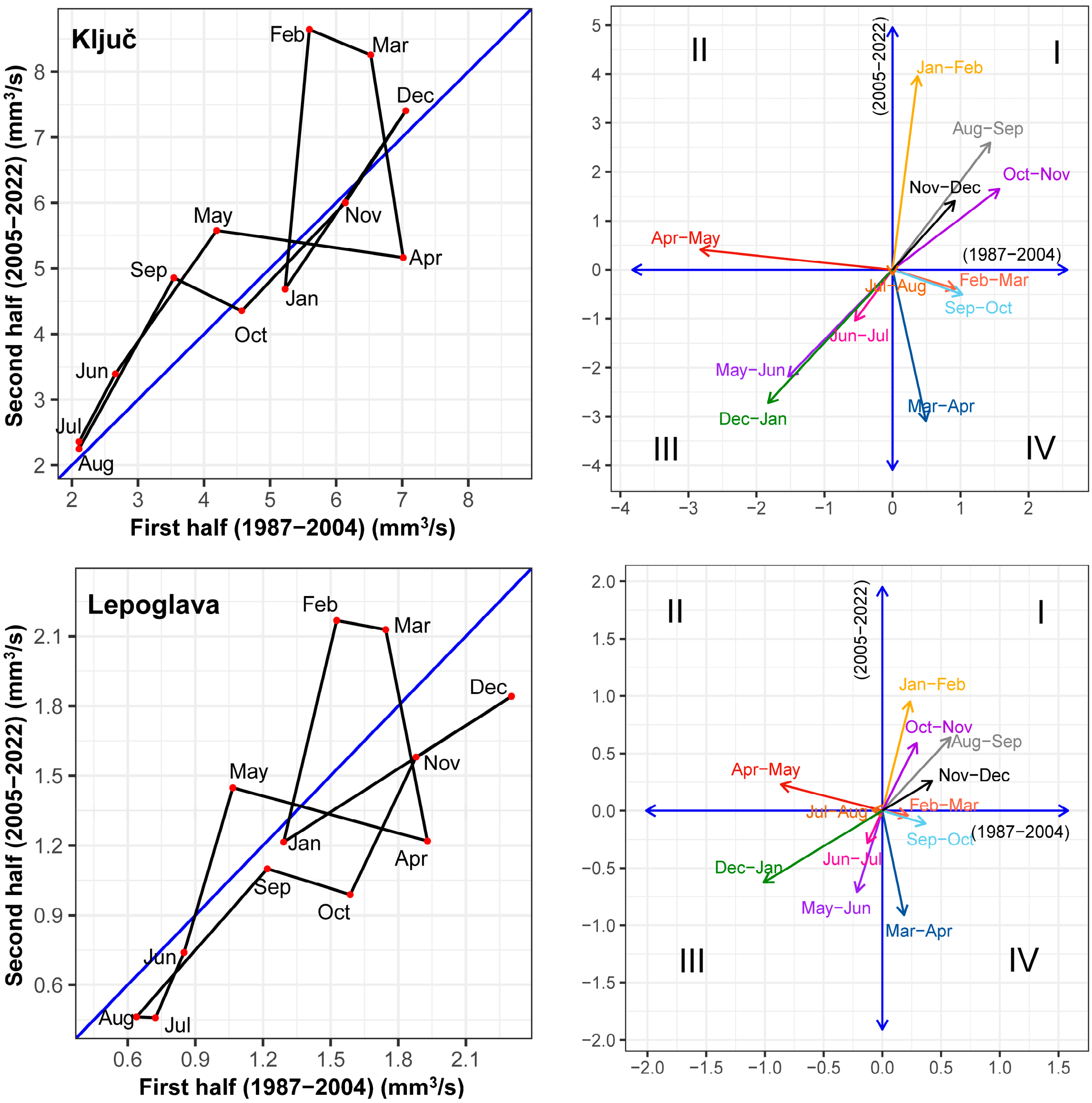


Figure 5. IPTA with star graphs for the Bednja River. An explanation of the quadrants is provided in Section 2.2.2.

The IPTA and star graphs of the Tuhovec and Željeznica stations exhibited highly similar patterns. At the Tuhovec station, minimal changes were observed in the transitions from August to September and from November to December during the first half (1959–1990), while an increase of about 2 m^3/s was noted in the second half (1991–2022). Similarly, in the transition from September to October, there was an increase of about 1.75 m^3/s in the first half, with relatively low changes in the second half. Conversely, during the transition from July to August, no significant change in the flow values was observed in the second half, while a decrease of about 1.4 m^3/s was observed in the first half. In the April–May transition, a decrease of 2.5 m^3/s was observed in the first half, while this decrease was 1.5 m^3/s in the second half. However, in the second half, this decrease was observed during the March–April, May–June, and December–January transitions, with average flow values decreasing by less than 1 m^3/s in the first half but varying between 1.4–2.25 m^3/s in the second half. Regarding the monthly trends, September and October exhibited an increasing trend, while the other months displayed a decreasing trend. However, December did not exhibit any discernible significant trend. Notably, September stood out as the sole month demonstrating an increasing trend in the average flow values, whereas nearly all other months displayed a decreasing trend. The results for the Željeznica station mirrored those of the Tuhovec station; however, the values observed at the Željeznica station were comparatively lower.

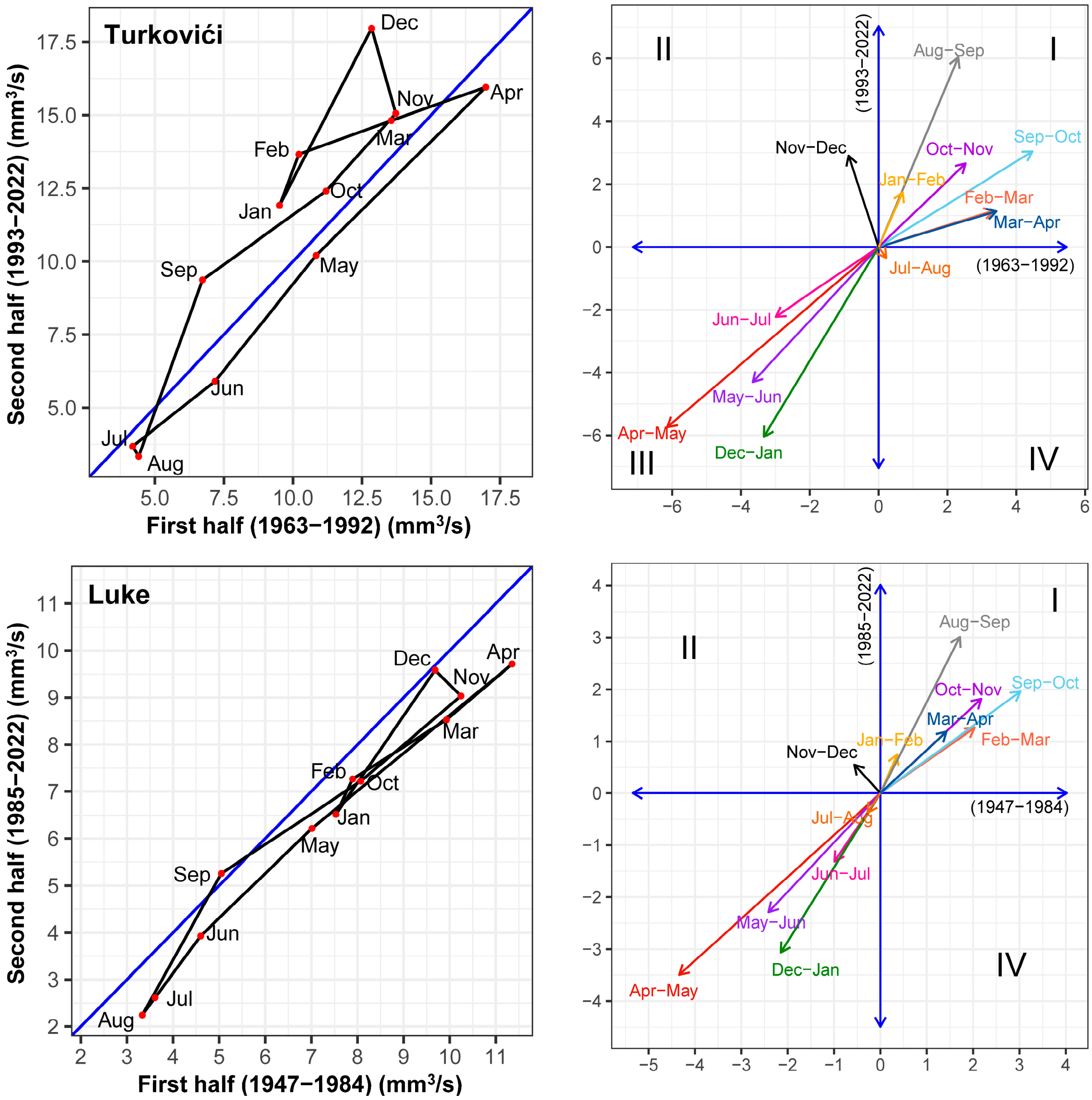


Figure 6. IPTA with star graphs for the Gornja Dobra River. An explanation of the quadrants is provided in Section 2.2.2.

The Ključ and Lepoglava stations, also situated on the Bednja River, had shorter time series compared with the Ludbreg, Tuhovec, and Željeznica stations, spanning from 1987 to 2004 in the first half and from 2005 to 2022 in the second half. Thus, a direct comparison with the aforementioned stations is challenging. Nevertheless, a comparison of the Ključ and Lepoglava stations still revealed interesting insights. Both stations exhibited July and August as the months with the lowest average flow values, while February, March, and December showed the highest averages. Additionally, the Ključ station's monthly average flow values surpassed those of the Lepoglava station. A consistent decrease was observed from February to August for both stations, with the most significant decline during the transitions from March to April and May to June. From August to December and January to March, the average flow values increased, although a sudden decrease occurred during the December to January transition, amounting to approximately 2.8 m^3/s at Ključ and 0.6 m^3/s at Lepoglava. At the Ključ station, a decrease of 2.8 m^3/s during the first half of the April to May transition was observed, while an increase of 0.5 m^3/s occurred during the second half, as evident in the star plot. Conversely, the opposite scenario occurred during the transition from March to April. Transitions from September to October and from February to March exhibited an increase of approximately 1 m^3/s during the first half, with only a 0.5 m^3/s decrease during the second half. Additionally, a minimal increase was observed during the first half of the January to February transition, contrasting with a notable 4 m^3/s increase during the second half.

The results from the Lepoglava station closely resembled those from Ključ station, albeit with lower average flow values and smaller transition values. These differences can be attributed to the local geographic and hydrological conditions, which may influence the flow rates recorded at the monitoring stations. These conditions could be related to the depressions, which would be filled with water in the case of spilling. In other words, a certain amount of the water will be stored in such retentions. Despite similar trends, variations between the stations underscore the significance of considering the hydrological conditions and local topography.

In the monthly trends, the Ključ station exhibited a decreasing trend only in January and April, with no significant trend detected in October, November, and December, while an increasing trend was observed in all other months. Conversely, at the Lepoglava station, an increasing trend occurred in February, March, and May, with a prevailing decreasing trend in all other months.

On the Gornja Dobra River, the Turkovići and Luke stations, along with the other five stations on the Bednja River, showed the lowest monthly average flows in June and August, while the highest average flows were recorded in December and April. Notably, the Turkovići station generally exhibited greater monthly average flow values compared with the Luke station. These stations experienced an increase from August to December, followed by a sharp decrease during the December–January transition, and then another increase until April. Subsequently, the flow values decreased from April to August, with the most significant decline occurring during the transition from April to May.

At the Turkovići station, during the November–December transition, a decrease of 1 m^3/s was observed in the first half of the period, while there was an increase of 3 m^3/s in the second half of the period. Similarly, during the February–March and March-April transitions, there was an increase of 3.5 m^3/s in the first half of the period, compared with only 1 m^3/s in the second half of the period. During the December–January transition, the decrease in both periods amounted to 3.5 m^3/s in the first half, escalating to 6 m^3/s in the second half of the period. Notably, the increase in the average flow values during the August–September transition was 2 m^3/s in the first half of the period, whereas it rose to 6 m^3/s in the second half of the period. The monthly average flow values showed an increasing trend in January, February, March, September, October, November, and December, while they decreased in all other months.

At the Luke station, different behaviors were observed between the first and second halves of the period during consecutive months. The most significant differences occurred during the November–December transition, with a decrease of 0.5 m^3/s in the first half of the period, contrasting with an increase of 0.5 m^3/s in the second half of the period. Similarly, during the August–September transition, the increase of 1.5 m^3/s in the first half of the period nearly doubled to 3 m^3/s in the second half of the period. The Luke station exhibited a decreasing trend in the monthly average flows, except in September and December, when no significant trend was observed.

3.3. IV-ITA Analysis

Figures 7 and 8 illustrate the monthly and yearly results of average streamflow for groups in the low and high categories using the IV-ITA method. Figure 7 presents the streamflow measurement stations on the Gornja Dobra River, while Figure 8 displays the stations on the Bednja River. Furthermore, Table 3 offers a comparison of the IV-ITA values of the high and low categories on a monthly scale.

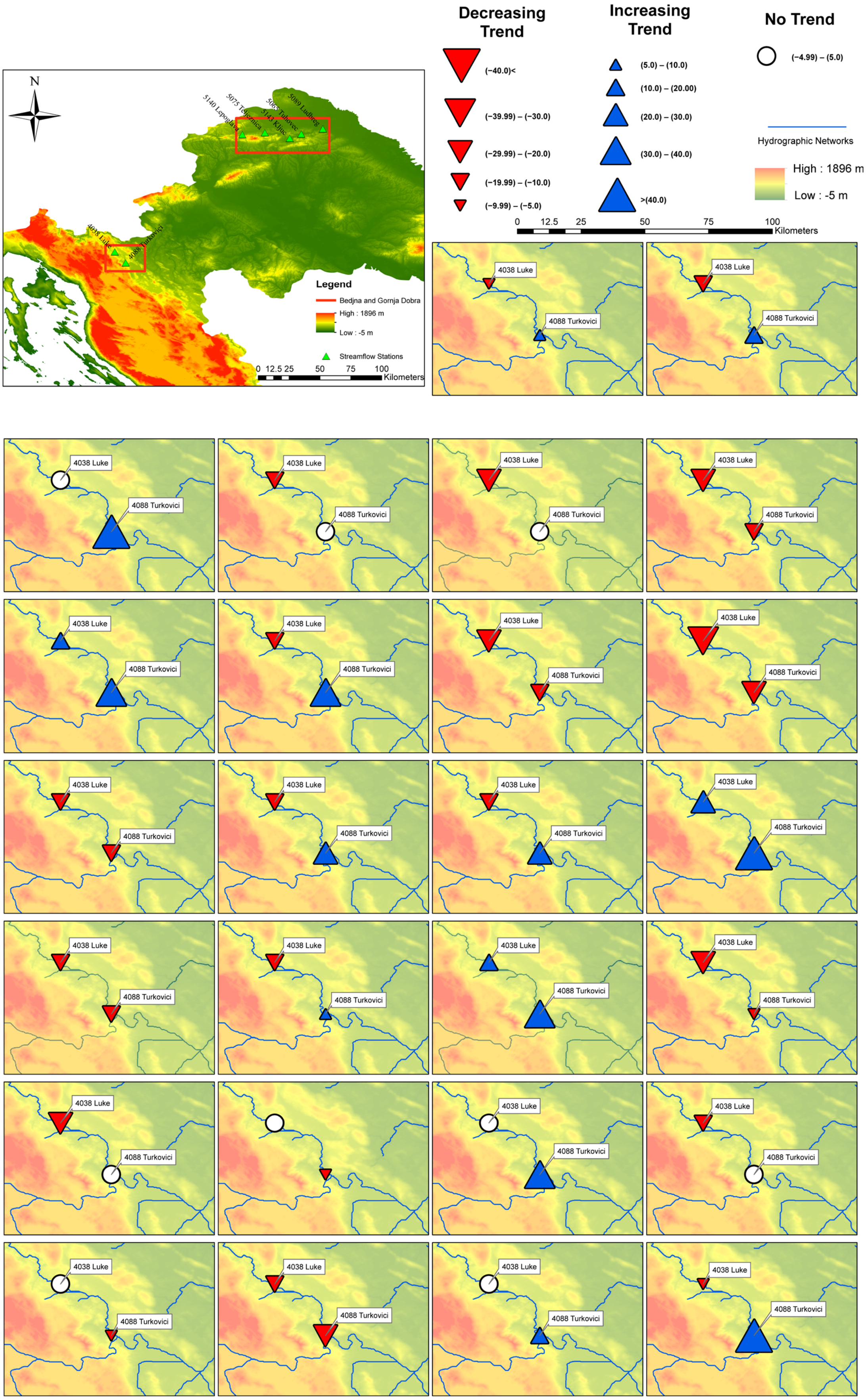


Figure 7. IV-ITA graphs for the Gornja Dobra River.

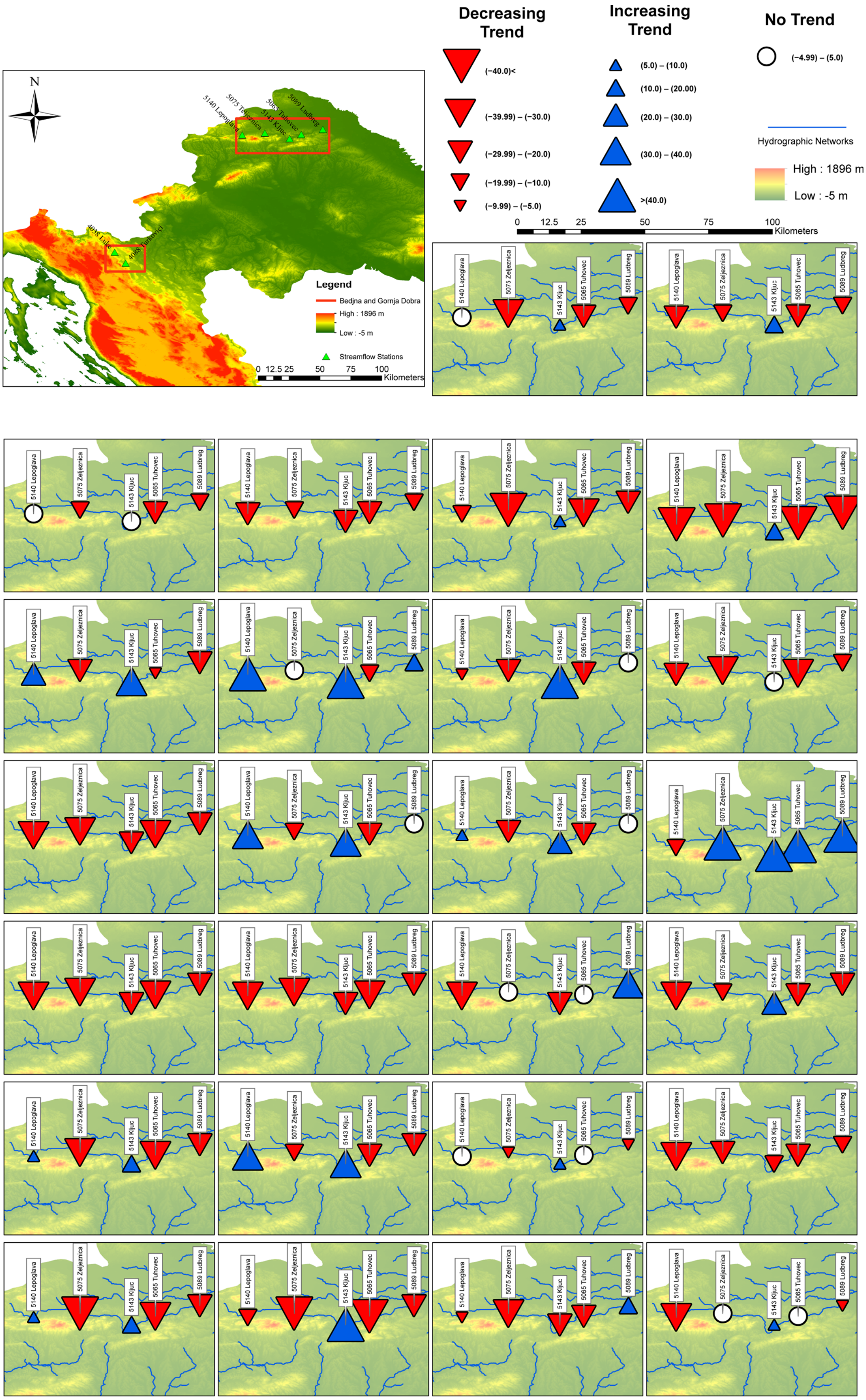
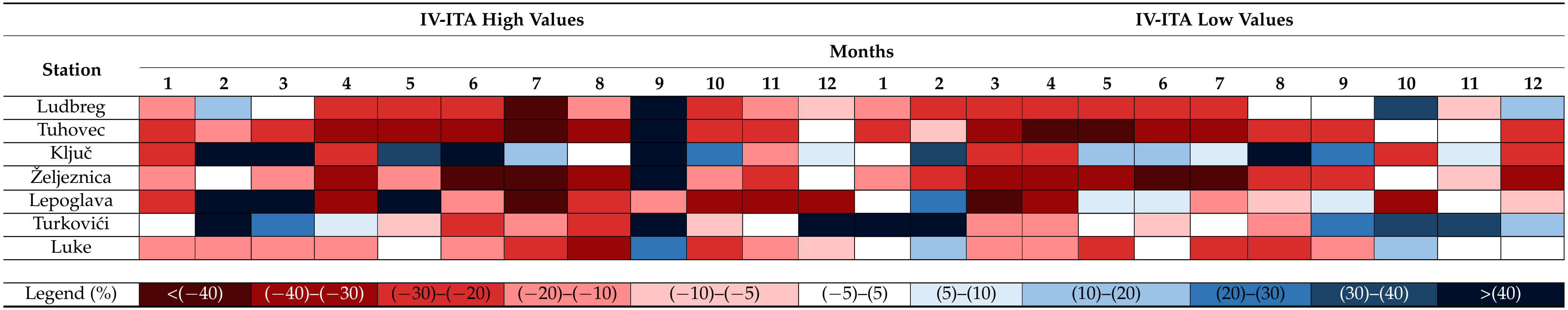


Figure 8. IV-ITA graphs for the Bedjna River.

Table 3. Comparison of the IV-ITA's high and low categories' values.



Notes: The low category's values showed increasing trends at the Ludbreg station in February; the Tuhovec, Željeznica, and Luke stations in September; the Ključ station in October; the Lepoglava station in March and September; and the Turkovići station in March and April. In these stations and months, high category's values exhibited decreasing trends. Conversely, at the Ludbreg station in October and December, the Ključ station in March, the Lepoglava station in June, the Turkovići station in October, and the Luke station in February and October, the low category's values decreased, while the high category's values increased. In August at the Ludbreg station, October and November at the Tuhovec station, January at the Ključ station; October at the Željeznica station; January and November at the Lepoglava station; May and July at Turkovići station; and January, June, November, and December at the Luke station, the low category's values decreased without significant trends in the high category's values. Conversely, at the Ludbreg station in March, the Tuhovec station in December, and the Željeznica station in February and December, no significant trend was observed in the low-category months, while the high category's values tended to decrease.

According to the results depicted in Figures 7 and 8, a decreasing trend was observed in the average streamflow data for the low category during January, April, and November, with the exception of the Turkovići station. Conversely, in June, July, August, and October, decreasing trends were noted, excluding the Ključ station. The pronounced decreases in July and August were particularly notable, as these months are characterized by generally lower flows, with reductions exceeding 20% observed at nearly all stations during these months. In May, although a decreasing trend prevailed at most stations except for Ključ and Lepoglava, the Ključ and Lepoglava stations showed an increasing trend of over 30%. Additionally, in September, a month with relatively low flow values, an increasing trend of almost 40% was evident at all stations except for Lepoglava.

Regarding high category's average streamflow data, a decreasing trend was observed in all stations during March and April, months characterized by high values. This trend ranged from 10% to 20% in the Gornja Dobra River and exceeded 20% in the Bednja River. Additionally, in July, when average flows are low, a decreasing trend dominated in all stations except for Ključ and Turkovići, with reductions exceeding 20%.

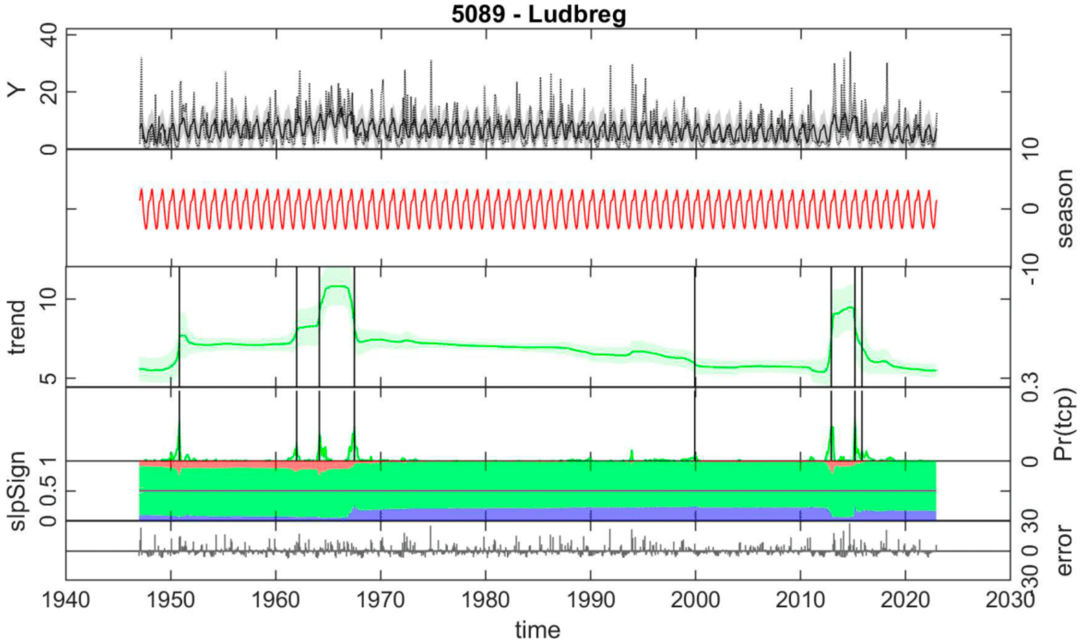
At the Tuhovec and Željeznica stations, a decreasing trend was observed in almost all months for both the high and low categories' values, except for September through December for the low category's values and excluding October for the high category's values. Similarly, at the Ludbreg station, which has data with a similar to the Tuhovec and Željeznica stations, a decreasing trend was predominant. However, an increasing trend was detected for the low category's values in February through September and for high category's values in October and December.

3.4. BEAST Analysis

The BEAST analysis revealed a complex scenario for both rivers, Bednja and Gornja Dobra. For the Ludbreg station (Figure 9), located on the Bednja River, during the period between 1951 and 1968, various abrupt changes in the trend (θt) were observed, both increasing and decreasing. In this period, the most positive abrupt change occurred in 1951 (θt = 0.772 m^3/s), while the most negative one occurred in 1968 (θt = −0.681 m^3/s). Moreover, during the past few decades, marked abrupt changes were also observed, with a positive one in 2013 (θt = 0.695 m^3/s) and the most negative one along the entire time series in 2015 (θt = −0.950 m^3/s). In the context of the time series of streamflow, a marked positive abrupt change and a marked negative abrupt change refer to significant and sudden shifts in the trend of the streamflow's data. A positive abrupt change indicates a sudden and substantial increase in the streamflow's values, which can be caused by events such as heavy rainfall. These events lead to an abrupt rise in water levels and increased discharge in rivers. On the other hand, negative abrupt changes indicate that drought conditions, reduced precipitation, or changes in land use affecting the availability of water can contribute to a marked negative abrupt change, leading to a sudden drop in water levels and decreased discharge in rivers.

The other stations located upstream along the Bednja River exhibited different outcomes. In particular, Tuhovec, Ključ, and Željeznica showed lower abrupt changes with lower probabilities. However, all three stations displayed positive and negative abrupt changes in 2013 and 2015, respectively, although the magnitudes were lower compared with Ludbreg. The station of Lepoglava, the most upstream station, exhibited peculiar features with marked positive and negative abrupt changes in 2010 (θt = 0.508 m^3/s) and 1968 (θt = −0.749 m^3/s), respectively. However, even for this station, in 2013, a positive abrupt change (θt = 0.142 m^3/s) was observed.

The Gornja Dobra River showed less marked abrupt changes in its trend. For the Turkovići station (Figure 10), the most positive abrupt change occurred in 2013, as observed for the Bednja River. However, θt was very low and equal to 0.020 m^3/s, with a low probability of a changepoint, suggesting lower confidence compared with what was observed for the Bednja River, in the presence of a significant shift in the trend. The Luke station, located upstream of the Turkovići station along the Gornja Dobra River, exhibited similar values of abrupt change, with an overall low probability of occurrence.

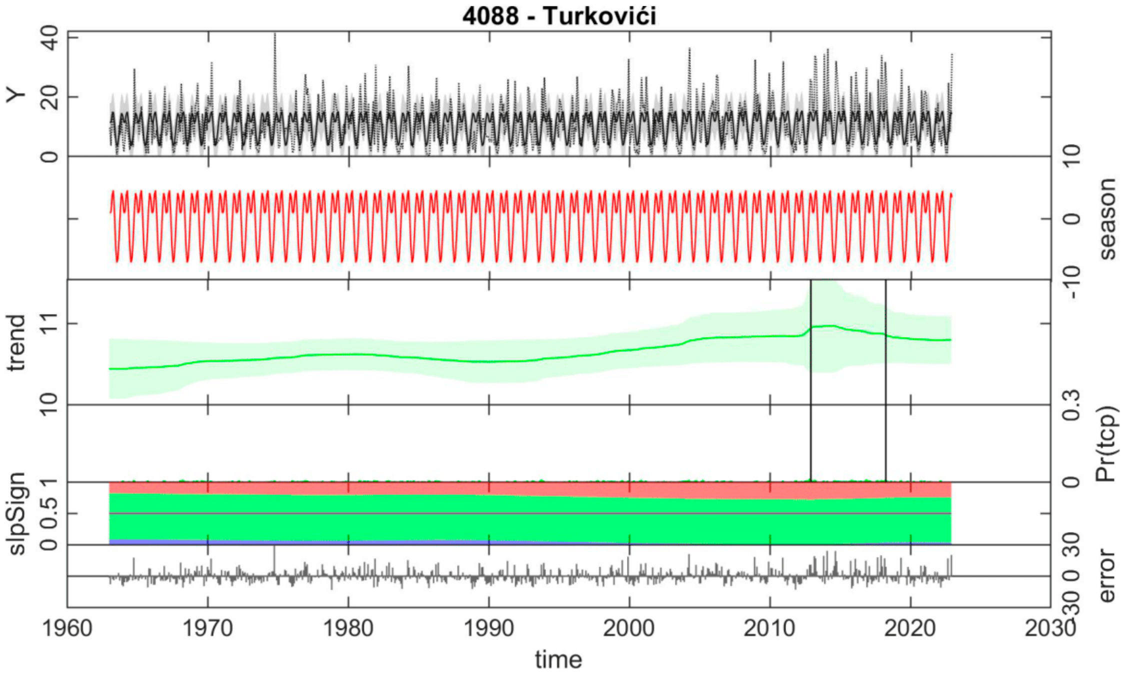


Legend

- Y = Time series of the sttreamflow rate;
- season = detection of abrupt seasonal changes;
- trend = detection of abrupt changes in the trend;
- Pr(tcp) = probability of a changepoint in the trend;
- slpSign = probability of the trend's slope being positive (red part), zero (green), or negative (blue);
- error = residual errors between the observed and BEAST-modeled values.

Bednja River														
5089-Ludbreg			**5065-Tuhovec**			**5143-Ključ**			**5075-Željeznica**			**5140-Lepoglava**		
Date	Pr	θ_t	Date	Pr	θ_t	Date	Pr	θ_t	Date	Pr	θ_t	Date	Pr	θ_t
1951	0.45	0.772	1962	0.08	0.032	1994	0.06	0.021	1967	0.06	−0.006	1988	0.29	−0.072
1952	0.12	−0.150	1971	0.07	−0.033	1995	0.05	−0.002	1984	0.07	0.014	1990	0.19	−0.029
1962	0.24	0.250	1973	0.11	−0.040	1999	0.05	−0.003	1985	0.09	0.025	1994	0.65	0.211
1964	0.39	0.509	1994	0.06	0.026	2004	0.05	0.010	1988	0.22	−0.094	1998	0.48	0.508
1968	0.53	−0.681	2000	0.06	−0.023	2006	0.06	0.000	1990	0.11	−0.028	1999	0.52	−0.749
1994	0.09	0.130	2004	0.06	0.025	2011	0.05	−0.006	1994	0.06	0.020	2004	0.25	0.062
2000	0.12	−0.064	2013	0.34	0.247	2013	0.12	0.054	2000	0.07	−0.014	2011	0.20	−0.047
2013	0.67	0.695	2015	0.12	−0.136	2014	0.05	0.001	2013	0.38	0.165	2013	0.58	0.142
2015	0.45	−0.950	2016	0.09	−0.052	2015	0.08	−0.054	2015	0.15	−0.083	2016	0.19	−0.027
2016	0.19	−0.199	2018	0.07	−0.030	2016	0.06	−0.006	2016	0.09	−0.028	2018	0.17	−0.025

Figure 9. BEAST analysis performed on the Bednja River.



Legend

- Y = time series of the streamflow rate;
- season = detection of abrupt seasonal changes;
- trend = detection of abrupt changes in the trend;
- Pr(tcp) = probability of a changepoint in the trend;
- slpSign = probability of the trend's slope being positive (red part), zero (green), or negative (blue);
- error = residual errors between the observed and BEAST-modeled values.

Gornja Dobra River					
4088-Turkovići			4038-Luke		
Date	Pr	θt	Date	Pr	θt
1968	0.03	0.006	1949	0.04	−0.001
1977	0.03	0.004	1950	0.03	0.002
1994	0.03	0.007	1981	0.03	−0.001
2001	0.03	0.005	1982	0.05	−0.006
2004	0.04	0.007	1983	0.04	−0.006
2013	0.05	0.020	1986	0.03	−0.004
2015	0.03	−0.001	2013	0.04	0.009
2016	0.04	−0.003	2015	0.03	−0.002
2017	0.04	−0.005	2016	0.05	−0.012
2018	0.04	−0.009	2017	0.03	−0.005

Figure 10. BEAST analysis performed on the Gornja Dobra River.

4. Discussion

Streamflow, as a crucial component of the hydrological cycle, plays a vital role in determining the availability of water across various sectors, including agriculture, ecosystems, industrial activities, drinking water supply, and groundwater recharge. Variations in streamflow can significantly impact these sectors, affecting agricultural productivity, disrupting the ecological balance, impeding industrial processes, compromising access to drinking water, and altering the groundwater's recharge rates. Therefore, comprehending and predicting variations in streamflow is essential for effective management of water resources and sustainable development.

The IPTA and IV-ITA methods offer advantages over the MK test and the existing ITA method. The IPTA method enables the detection of monthly and seasonal transitions and exhibits greater sensitivity in identifying monthly trends. By analyzing partial trend sequences instead of monotonic trend sequences, IPTA provides insights into both the quantitative and qualitative aspects of internal temporal variability [23,40]. Additionally, the IV-ITA method proves useful in examining potential positive and negative extremes by separately analyzing values in the low and high categories. For the two significant rivers in Croatia analyzed in this study, the geographical region has undergone changes due to climate change and human impacts, thereby affecting the current hydrology. Approaches akin to IPTA and IV-ITA can aid in the management of drinking water, and mitigation of flood and drought risk, while BEAST can assist in pinpointing possible years of change. Notably, the literature lacks studies examining river flows in Croatia using innovative methods. This study used the MK test, IPTA, IV-ITA, and BEAST approaches to identify trends in the flows of the Gornja Dobra and Bednja rivers in Croatia and pinpoint potential years of change. Monthly trends and the magnitudes of the trends were determined for both rivers, and the status of low and high flows was evaluated by calculating trends and their magnitudes for different categories of flow.

The trends of flow observed in the Bednja River stations (Ludbreg, Tuhovec, and Željeznica) in the Varaždin Region, and the Gornja Dobra River station (Turkovići) in the Karlovac Region are influenced by the distinct hydrological regimes prevalent in these regions of Croatia.

The Varaždin Region, situated north of Zagreb, typically experiences a continental climate with variable precipitation patterns throughout the year, as well as a sand and gravel structure in the underground layers. The seasonal MK test revealed decreasing trends in the Ludbreg, Tuhovec, and Željeznica stations during the dry months of April to July, reflecting the region's susceptibility to summer drought conditions, which impact river flow.

Conversely, the Karlovac Region, where the Gornja Dobra River is located, may exhibit different hydroclimatic characteristics. The significant increasing trend observed in February at the Turkovići station could be influenced by regional factors such as winter precipitation and snowmelt, which are common in continental climates. The properties of the karst relief (caverns, holes, underground structures, and the existence of underground watercourses) are in support of such an increasing trend.

However, the results of IPTA and IV-ITA for the mean flows in both rivers revealed a more complex behavior than the MK test's findings. Between the Bednja and Gornja Dobra rivers, significant changes were evident between the first and second periods of the analyzed data. Noticeable alterations in the flow rates and monthly trends could be observed between these two periods in both river systems.

In the Bednja River, a decreasing trend in the average flow values was observed, except for September. Similarly, the Dobra River showed a similar decreasing trend, especially during the summer months, at both stations along the river. However, at the Turkovici station, there was a predominant increasing trend, particularly during the autumn and winter months.

In the Bednja River, particularly at the Ludbreg, Tuhovec, and Željeznica stations, the second period generally exhibited more pronounced increases or decreases in the value of flow compared with the first half. For example, the transitions from August to September and November to December showed minimal changes in the first half, while significant increases were observed in the second half. Conversely, decreases in the flow during transitions such as July–August and December–January tended to be more pronounced in the first half. Similar contrasting patterns between the first and second periods were evident in the Gornja Dobra River.

According to the results of IV-ITA, there was a decreasing trend in the average value of the low category of flow for the Bednja River except for October and December, with a similar trend observed in the Dobra River, particularly during the summer months. In the mean value of the high of category flow, a dominant decreasing trend was observed for both rivers, with the trend being more severe, especially in spring and summer.

Increasing agricultural irrigation, industrial use, and water demand by cities, especially in summer, may have caused a decrease in river flows, potentially leading to drought conditions. Moreover, pollution from heavy metals, chemicals, and wastewater in rivers with decreasing flows may disrupt the river's ecosystem.

The high category's mean values of flow tended to increase for both rivers, especially in September, possibly due to the highest precipitation occurring in this month, which marks the onset of precipitation in Croatia. However, sudden increases after dry periods may lead to flash floods and material damage in riverine environments. Examining trends in precipitation in the region is crucial for understanding these patterns.

The BEAST analysis confirmed the complex patterns in the rate of streamflow for both rivers. In the Bednja River, abrupt changes were noted between 1951 and 1968, with recent decades also witnessing significant abrupt changes, such as positive shifts in 2013 and notably negative ones in 2015. Similarly, the Gornja Dobra River exhibited fewer pronounced abrupt changes, with confidence levels varying compared with the Bednja River.

The results of this study were compared with recent similar work, revealing no prior studies investigating streamflow trends in Croatia using ITA methods. However, Čanjevac and Orešić [31] analyzed the annual trends of Croatian rivers from 1989 to 2009, detecting significant decreasing trends in the Bednja River and an increasing trend at the Turkovići station on the Gornja Dobra River. On a seasonal basis, the Bednja River displayed decreasing trends in almost all seasons, while the Turkovići station exhibited an increasing trend in winter and a decreasing trend in summer. Despite similarities to our findings, the analysis was more complex when examined monthly.

Studies using the IPTA method have been conducted globally in regions with various climates. For instance, Gupta and Chavan [23] analyzed monthly stream flows from 1970 to 2018 using the IPTA method in basins with different climatic characteristics in South India. They observed an increase in the average monthly flow during low-flow months in some sub-basins of the Mahanadi River in a tropical monsoon climate. Conversely, decreasing trends were noted in almost all sub-basins of the Godavari Basin with dry sub-humid, wet sub-humid, and semi-arid climates during both high- and low-flow months. Similarly, in the Krishna and Cauvery river basins with a sub-arid tropical climate, decreasing trends were observed in some sub-basins over an extended period, except during post-monsoon periods. In the study conducted by Akçay et al. [22] in the Eastern Black Sea Basin of Turkey, characterized by an oceanic climate, significant decreasing trends in the summer months were attributed to reduced precipitation and increased evaporation.

The study encountered different challenges and limitations. The accuracy of the analysis relied heavily on the quality and length of the time series. Incomplete or short time series can affect the reliability of the identified trends and abrupt changes. Within the context of climate change, pairing methods of analyzing trends such as MK with innovative methods such as IPTA, IV-ITA, and BEAST can offer significant value in providing a more comprehensive characterization of the hydrological phenomena under investigation. This approach facilitates a deeper understanding of the trends and abrupt changes in hydrological variables, thereby enhancing our ability to assess the impacts of climate change on water systems.

As we look ahead, potential future applications could extend to the analysis of various hydrological variables, including groundwater levels. Groundwater levels are susceptible to abrupt and sudden fluctuations over seasons or years, influenced by a range of natural and human-induced factors.

Moreover, although the investigated rivers cover different areas of Croatia, the climatic and meteorological conditions did not exhibit significant diversity. From this perspective, in future studies, the proposed methodology could be tested to investigate rivers in other climates, e.g., semi-arid, where the seasonal patterns of the rate of streamflow could be quite different. This could enable us to ascertain if the devised approach holds validity for analyzing rates of streamflow in diverse regions worldwide, each facing unique challenges in the management of water resources.

Future research should further investigate the integration of additional climatic variables, land use data, and remote sensing information to achieve a more comprehensive understanding of the dynamics of the rate of streamflow. By incorporating these diverse datasets, researchers can gain insights into the complex interactions shaping patterns of streamflow. In particular, exploring trends in the climatic variables alongside trends in the rate of streamflow could offer valuable insights into the direct impacts of climate change on water systems. Finally, in the future, advanced methodologies utilizing hybrid machine learning/deep learning (ML/DL) algorithms could complement the newly developed approach to analyzing trends, enabling researchers to glean more nuanced insights and enhance the precision of assessments of the rate of streamflow. Hybrid ML/DL models are adept at discerning complex patterns and correlations between external inputs and target variables [41], thereby improving the detection of trends and abrupt changes. These algorithms offer superior predictive abilities, facilitating precise forecasting of the rate of streamflow [42,43].

5. Conclusions

The study presents a thorough examination of the trends of streamflow in two Croatian rivers, using a range of statistical methods. Notably, it revealed consistent decreasing trends, which were particularly pronounced during the summer months of July and August. These trends were identified through the seasonal Mann–Kendall test, indicating a significant shift in the flows' dynamics. Furthermore, the analysis using the IPTA, IV-ITA, and BEAST algorithms unveiled intriguing insights into the trends' transitions, showcasing a complex scenario with distinct variations between the rivers.

One of the key findings is the presence of distinct monthly transitions, demonstrating varying behaviors in different parts of the year. For instance, in the Bednja River, transitions such as August–September and November–December exhibited notable shifts, particularly in the latter half of the year. Similarly, the Gornja Dobra River displayed distinctive patterns, with changes observed in the values of flow across different months.

Additionally, the study highlighted a noteworthy increase in high-flow values, which was particularly evident in September, indicating a significant shift in the trend. Moreover, the analysis revealed abrupt changes in the trend during specific time periods, such as in 1951–1968 and 2013–2015, with varying magnitudes across the rivers.

These findings underscore the critical impact of river dynamics on various aspects of managing water resources. The proposed approach emerges as a valuable decision-making tool for monitoring rivers' water resources that is capable of capturing both long-term trends and short-term fluctuations, which are essential for effective strategies for managing water resources.

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and F.G.; supervision, F.G. and G.d.M. All authors have read and agreed to the published version of the manuscript.

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