Analysis of homogeneity and isotropy of the flow in the watercourses by applying the RAPS and IPTA methods

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Abstract:
Due to the frequent climatic changes occurring worldwide, which are related to extreme meteorological parameters as well as human activities, it is obvious that these influence the flow regimes of rivers. River flow is the most important factor determining the hydrological regime of any river. This has a substantial influence on the water resources and the environment surrounding the river. Hydrotechnical structures are also dimensioned on the basis of the flow as the primary input parameter. The flow conditions have different properties and correlations with the material of the river bed. In this paper, possible dependencies and phenomena are investigated using real case studies on two rivers in Croatia - examples of river courses in alluvium and karst areas - with regard to homogeneity and isotropy analyses. For this purpose, rescaled adjusted partial sums and innovative polygon trend analysis methods will be applied on the form of a combination of methods at the same watercourses. It has been shown that the analysed time series of the flows do not exhibit homogeneity and isotropy. In addition, fluctuations and irregularities were detected in the same time series. This is key information for determining the reliability of the flow forecast.

Keywords:
hydrology; IPTA; RAPS; river flow; irregularities

1 Introduction

Open-channel flow is a complex process that is influenced by various natural and anthropogenic factors with climate change playing a substantial role. This leads to heterogeneous, anisotropic, unsteady, and nonlinear flow characteristics, which typically cause fluctuations in the hydrological patterns of rivers. Due to the frequent phenomena of extreme values in precipitation, evaporation, and temperature [1, 2], increasingly frequent river regulatory interventions [3], and the building of dams [4], it is becoming progressively more challenging to anticipate future flow patterns. This leads to over- or under-dimensioned hydrotechnical objects, especially misjudgements regarding the phenomenon and intensity of water waves or floods.

The alluvium and karst medium analyses should be categorised based in the river flow. Globally, alluvium is composed of layers of gravel, sand particles, silt and clay. At the same time, the karst areas have a system of caverns, which implies that the karst areas, in general, are more complex than alluvium media. Thus, two rivers in Croatia were considered in this study. One is situated in alluvium media (Bednja River), as shown in Figure 1, whereas the other is found in the karst area (Gornja Dobra River), as shown in Figure 2 [5].

Figure 1. River Bednja at the Ludbreg measurement station

Figure 2. River Gornja Dobra at the Turkovići measurement station

It should be emphasised that the research presented in this paper is not oriented towards the hydrogeological and geological properties of the watercourse through which the flow occurs. Alluvial media are not as complicated as karst media when it comes to the occurrence of caverns, holes, sinkholes, and all other geological formations that are characteristics of karst. The main objective was to present and apply a novel methodology to explain the properties of water flow time series. Such purport homogeneity and isotropy, together with the continuation (i.e., irregularities) of the water flow time series, are essential for obtaining a complete picture of the water flow regime. For this purpose, the rescaled adjusted partial sums (RAPS) and innovative polygon trend analysis (IPTA) methods were used. Any factual assumption is unreliable if there is no homogeneity or isotropy in the flow time series, as was found by applying the IPTA method. In addition, irregularities were examined using the RAPS method. This is an important indicator of broader environmental changes and human influence on the rivers.

The first step in determining homogeneity and isotropy was to analyse the existing time series for possible fluctuations and irregularities in the time series of the average daily flows of the Bednja and Gornja Dobra rivers by applying the RAPS method. The second step is to determine the linear trends of the average monthly values of the arithmetic mean and standard deviation of the average daily flows. In the third step the IPTA method was applied to the arithmetic mean values and standard deviations of the average daily flow to analyse the homogeneity and isotropy.

The methodology described provides an understanding of the variability, homogeneity, and isotropy of the analysed time series of the flow. Specific information is obligatory for the dimensioning and building of hydrotechnical facilities, such as bulks, hydropower plants, dams, flooding protection objects, and regulation construction. In addition, efficient monitoring and maintenance of these buildings require updated water flow and depth values. Reliable predictions for the future are not possible without verified access to the nature/characteristics of the flow changes, i.e., the variability of the flow.

2 Literature review

Temporal fluctuations in river flows are of interest because they are directly linked to the frequency of floods and droughts [6]. Therefore, such analysis is subject of interest and research as it is challenging. Various methods and analyses have been used for this purpose. Considering this type of analysis, it can be concluded that it is impossible to make a uniform and general classification of methods.

According to [7], models for hydrological processes at different time scales, such as long- and short-term stages, exist in two general categories: physical (hydrological) based and data-driven models. Physically based models attempt to develop streamflow equations using the hydrological processes of a watershed, such as the geomorphology of the basin. Data-driven models are so-called “black-box” methods that extract the streamflow patterns from historical data for modelling and forecasting future flows. These models require analysis and preparation of the input data, model definition and calibration, and determination of the errors that lead to uncertainty in the predicted values. It has been reported [8] that the predicted (forecast) values have discrepancies because they were determined using unique hydrological models that have different definitions for each hydrological process.

The usual trend analysis of river flow time series includes the determination of decreasing and increasing trends in the analysed time series [9]. In addition, their magnitudes and significances were determined using non-parametric and parametric statistical methods [10]. The Mann–Kendall test is the most commonly used test, as defined in [11, 12]. This procedure does not require the data set to have a relatively standard Gaussian distribution.

The RAPS method is also widely used to determine the fluctuations and irregularities of the analysed time series, especially in hydrology [5, 13, 14]. It is a method in which the graphical interpretation provides insight into the subseries that may occur in connection with the natural or anthropogenic influences. This cannot be determined by a simple trend analysis, i.e., regression.

IPTA is currently one of the most commonly used methods for analysing the homogeneity and isotropy of the hydrological time series [15, 16]. IPTA provides insights into trend transitions between successive sections of two equal segments from the original hydrological time series, and results in a trend polygon that provides a productive basis for finer descriptive and numerical interpretations and inferences from a given time series [17]. This method has a strong connection with the Sen-slope (SS) method, a nonparametric method for estimating the median of all pairwise slopes (magnitudes) of the obtained trendline [18, 19].

The same author also invented the innovative-Şen trend (IST) detection method. The IPTA method further improves the SS and IST methods. An improvement was observed in the analysis of the shape and position of the obtained polygons of the analysed data, which were grouped into two divisions, providing insight into the homogeneity and isotropy of the original time series.

In light of the presented research on streamflow analysis and prediction, it is imperative to find the most effective and straightforward method for the hydraulic and hydrological analysis of river flow. Based in the arguments of the presented literature review, the RAPS and IPTA methods were applied. Based on the state-of-the-art insights and knowledge presented, such a combination has not been applied elsewhere in the time series analysis of the flows. Although the definition of the linear trend is the most common procedure in the analysis of hydrological time series, especially for the flows, flows, it is not justified in this case because the values of R^2 are negligible. Therefore, a new and efficient methodology is required.

3 Methodology

3.1 RAPS method

RAPS is a commonly used method for analysing time series, especially in hydrology [5, 13, 20]. The parameters used are the average value and the standard deviation of the analysed time series. This method visualises a new (obtained) subseries from the original continuous data series. A graphical representation of the sums of the calculated RAPS values provides insights into the new subseries in which data aberrations and similar incidents occur. The equation for defining RAPS is as follows.

$$RAPS_{\mathrm{k}} = \sum_{t=1}^{k} \frac{Y_{\mathrm{t}} - \bar{Y}}{S_{\mathrm{y}}} \tag{1}$$

Where Y_t is the individual value of the analysed member of the studied time series, $\bar{Y}$ is the average value of all members of the diagnosed time series, Sy is the standard deviation of all members of the analysed time series, k is the number of all members of the time series, and t = 1, 2, ..., k is a counter during the summation process [21]. It can be concluded that RAPS is a method in which the cumulative value of the standard deviation from the average value provides information about the existence of subseries within the original time series.

The final RAPS value must be zero, to determine whether the calculation was performed correctly. A negative RAPS slope does not indicate a negative slope in the original time series.

3.2 IPTA method

An Innovative Polygonal Trend Analysis (IPTA) can identify subperiods (parts) (of the analysed time series) (daily, weekly, monthly, etc.) and determine the trend transitions between successive sections of two equal segments of the original hydrometeorological time series, resulting in a polygonal trend [22]. This method can reflect the periodic properties of hydrometeorological variables and is often used on a monthly and seasonal scale to determine trend transitions between months and seasons [22, 23]. IPTA has been successfully used to analyse streamflow in Pakistan [24]. The final result was used to determine which months of the year showed increasing or decreasing trends. This result is significant for justifying

decisions and for policymakers. The research presented in [15, 25, 26] analysed the homogeneity and anisotropy of rainfall data in Vietnam. In addition, in this case, parts of the years (months) were identified to determine where increasing or decreasing rainfall trends were detected.
The IPTA method is suitable for such analyses both as a stand-alone application and in combination with other methods [27]. This paper combines the RAPS and IPTA methods.
Equation (2) shows the general matrix format of the IPTA method [27]:

$$\begin{bmatrix} x_{1,1}, & x_{1,2}, & \cdots & , x_{1,12} \\ x_{2,1}, & x_{2,2}, & \cdots & , x_{2,12} \\ \vdots & \vdots & \vdots & \vdots \\ x_{i,1}, & x_{i,2}, & \cdots & x_{i,12} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n,1}, & x_{n,2}, & \cdots & x_{n,12} \end{bmatrix} \begin{matrix} \left.\right\} \text{Upper Series (First Half) } n = 1,2,3,\ldots,\frac{n}{2} \\ \left.\right\} \text{Lower Series (Second Half) } n = \frac{n}{2}+1, \frac{n}{2}+2,\ldots,n \end{matrix} \tag{2}$$

The data series was divided into two equal parts. These are presented graphically in a Cartesian coordinate system in Figure 3. The values of the upper series are placed on the y-axis and the values of the lower series on the y-axis.
Time-series data are divided into two equal sets, and the two sub-series are arranged in ascending order. After the arrangement, the 1st half series is plotted on the x-axis (horizontal axis), and the 2nd half series on the y-axis (vertical axis) in the Cartesian coordinate system with a 1:1 (45°) line. The areas of the upper/lower triangles show increasing/decreasing patterns in the data series. When the data is collected in the Cartesian coordinate system (CCS) on a 45° (1:1) line or very close to this line, this indicates no substantial pattern in the series and a weaker trend slope [28, 29].

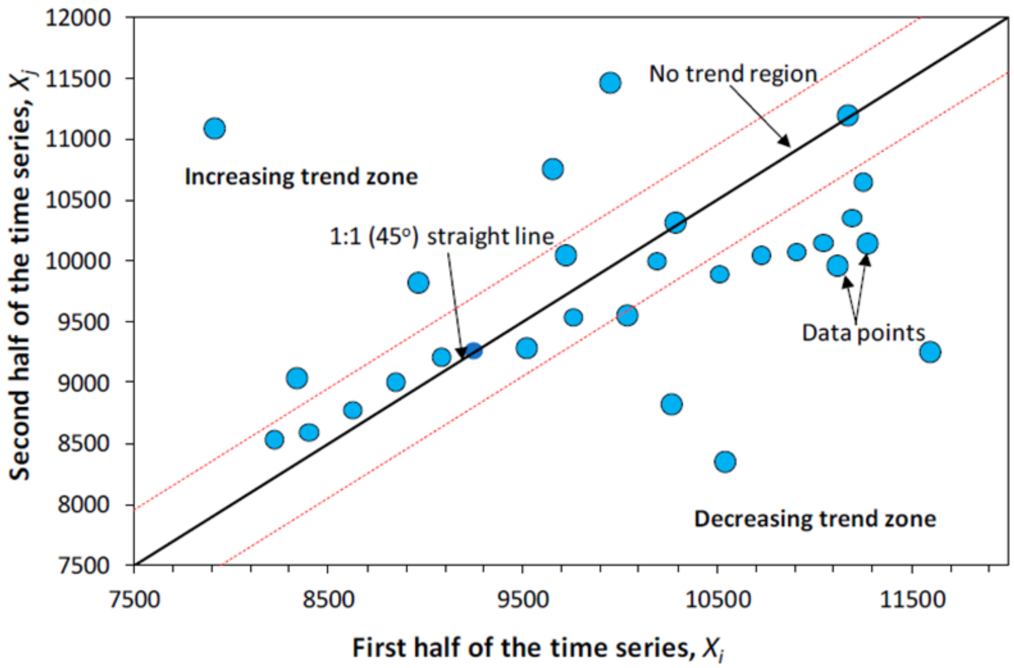

Figure 3. Graphical representation of the IPTA method [30]

The rules and guidelines for interpreting an IPTA diagram are as follows [17]:

- A straight line between two consecutive years indicates a change in the monthly values. The closed polygon represents the natural balance behaviour of the monthly values for one year.
- The length of each straight-line length represents the successive annual changes.

- If the slopes of each straight line in the IPTA template are sufficiently close to each other in both the vertical and horizontal directions, this means that the relative annual values contribute only insignificantly to the variation for each successive month. Likewise, all straight lines in the IPTA template first explain the 12-month variation in qualitative (descriptive) inference at each recording location.
- Each polygon side implies an assumption of linear change between successive years. A linearity assumption of less than one year implies more realistic results in trend analysis.
- If the slopes of all straight lines in an IPTA template do not differ from each other, all sides appear around a single global direction. Connecting the polygon vertices provided a broken line that closely matched the fit of the global regression line. When the polygon is very narrow, the internal change within the values is relatively homogeneous and isotropic, and exhibits uniform variation behaviour, whereas comparatively wider polygons indicate heterogeneous temporal variation.
- In general, any polygon with a rising form implies that the prevailing conditions are almost balanced. In contrast, two or more polygons (loops) may occur rather than a single polygon.

The probability of an intricate polygon occurring depends on the dynamics and complexity of the hydrometeorological event and can be directly proportional [17].

4 Study area and data

Figure 4 shows the locations of the investigated measuring stations on the river Bednja (MS Ludbreg) and the river Gornja Dobra (MS Turkovići). These two locations were selected as typical examples of Croatia's two characteristic reliefs. The river Bednja is located in an alluvial area consist mainly of sand and gravel. The river Gornja Dobra is surrounded by karst, where complex hydrological conditions prevail compared to the alluvial environment.

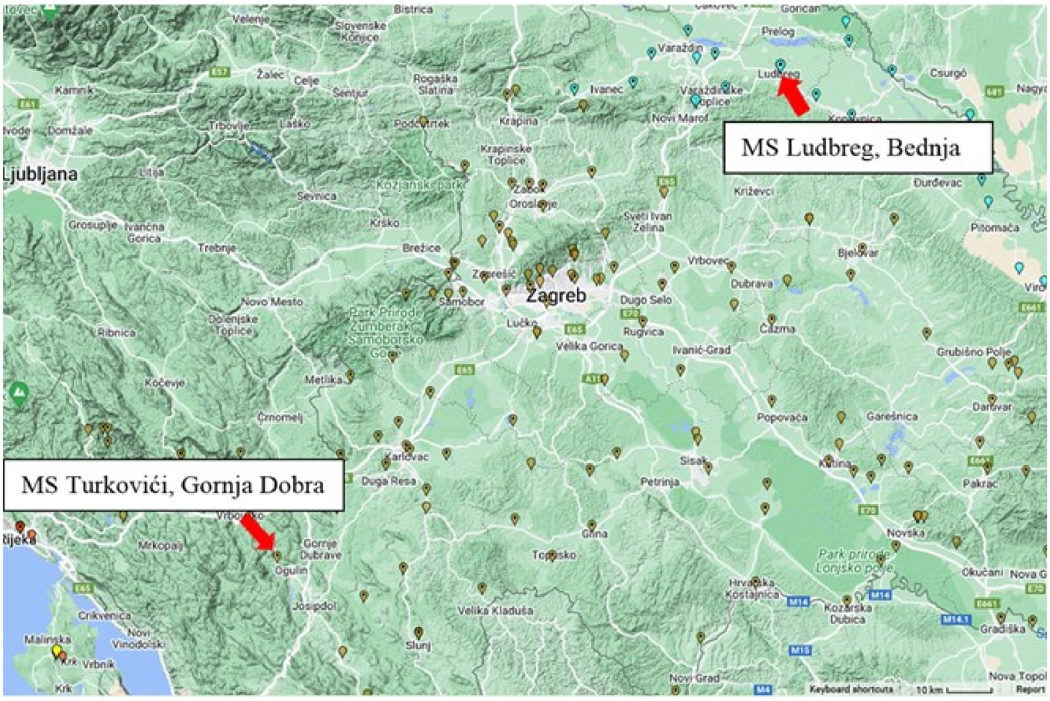

Figure 4. Location of the Ludbreg and Turkovići measurement stations in Croatia [31]

From Figure 5 [5], it can be seen that the river network consists of a large number of tributaries, located mainly in the upper part of the catchment (left part), which continues to the formation of the lowland part in the area of the Lepoglava measurement station and then proceeds to the

Željeznica, and then directly into into the completely different part of the catchment, which includes Ključ, Tuhovec and finally the downstream Ludbreg measurement station Based on the fieldwork and the knowledge and experience gained [5, 14], there are only surface watercourses in the catchment area.

Figure 5. Location of the Ludbreg measurement station on the Bednja River [32]

From Figure 6 and from fieldwork and literature [5, 31], it can be concluded that there are also underground flows with surface flows. These karst water formations and bodies include the abyss rivers, privileged underground flows, caverns, and cracks. In addition, the river network in relation to the river Bednja is complicated in terms of the number and dividing forms of the tributaries, and the main watercourses. There are also two large hydropower plants, HEPP Lešće and HEPP Gojak, which have a significant impact on the hydrological system of the river Gornja Dobra and even in the area of the river Donja Dobra, as is evident in Figure 6.

Figure 6. Location of the Turkovići measurement station on the Gornja Dobra River [33]

Figures 7 and 8 show cross sections of the Bednja (Figure 7) and Gornja Dobra watercourses (Figure 8) at the locations of the hydrological measuring stations.

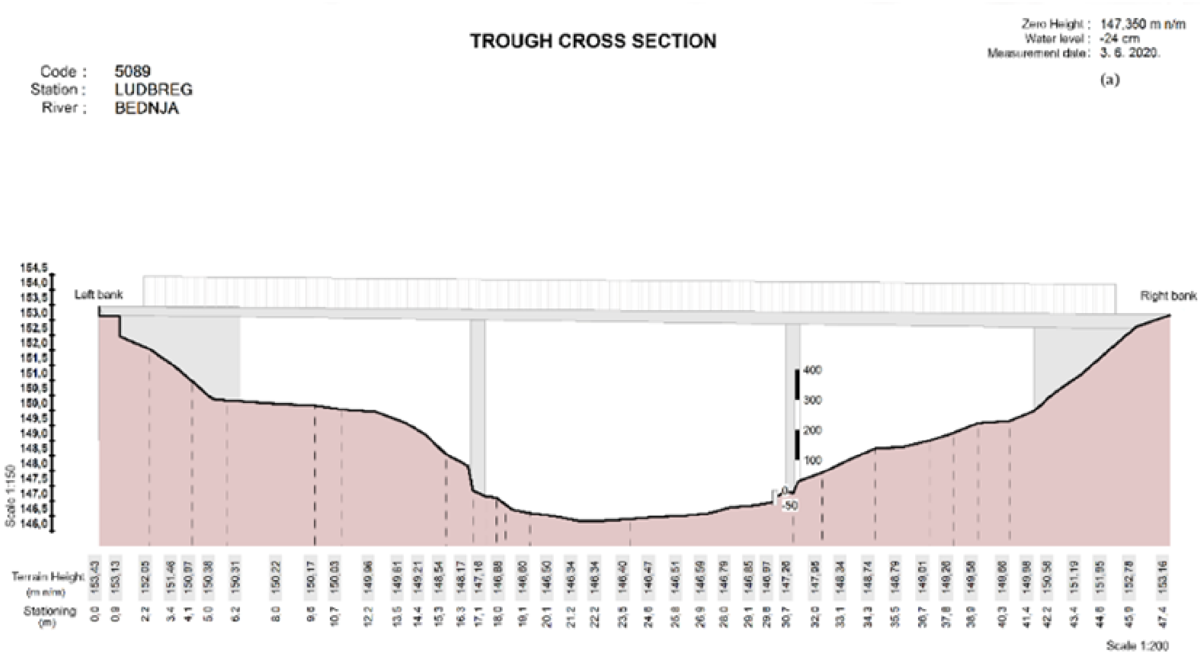

Figure 7. Cross-section profile of the Ludbreg measurement station on the Bednja River [34]

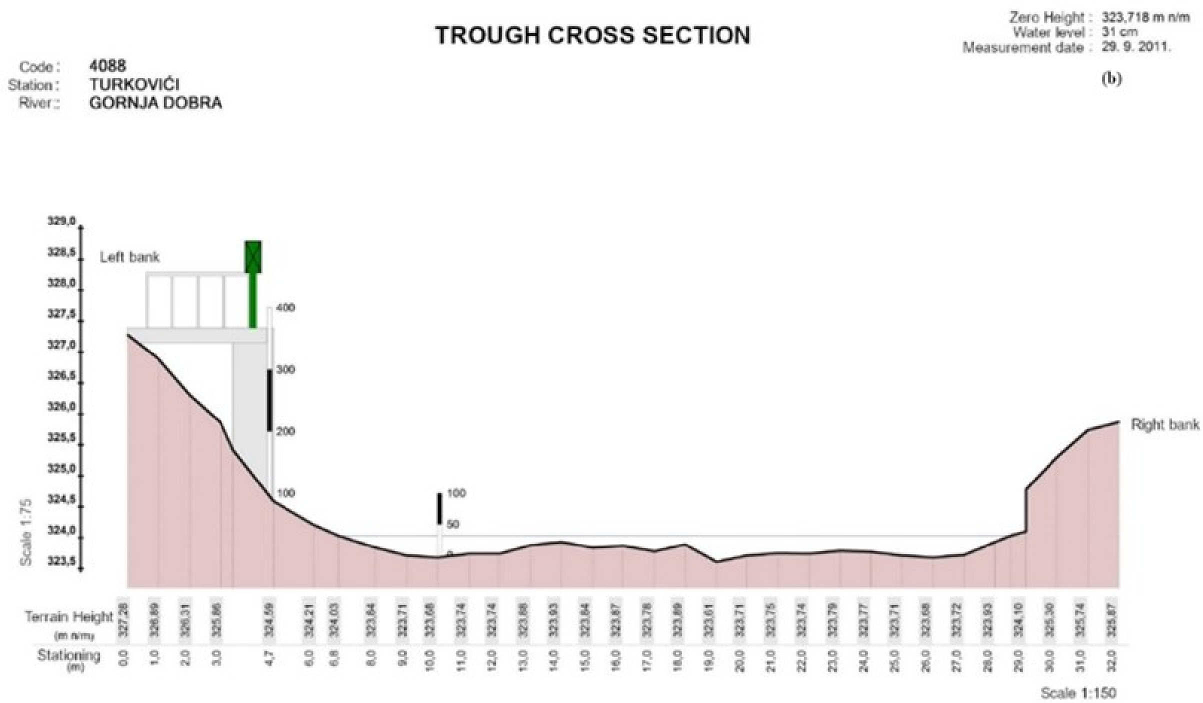

Figure 8. Cross-section profile of the Turkovići measurement station on the Gornja Dobra River [34]

The Bednja riverbed is more exposed to erosion and sediment deposition as it is an alluvial medium.

Figure 9 shows the hydrogram for the Ludbreg measurement station on the Bednja River from 1999 to 2019, and Figure 10 shows the hydrogram for the Turkovići measurement station on the Gornja Dobra River from 1999 to 2019.

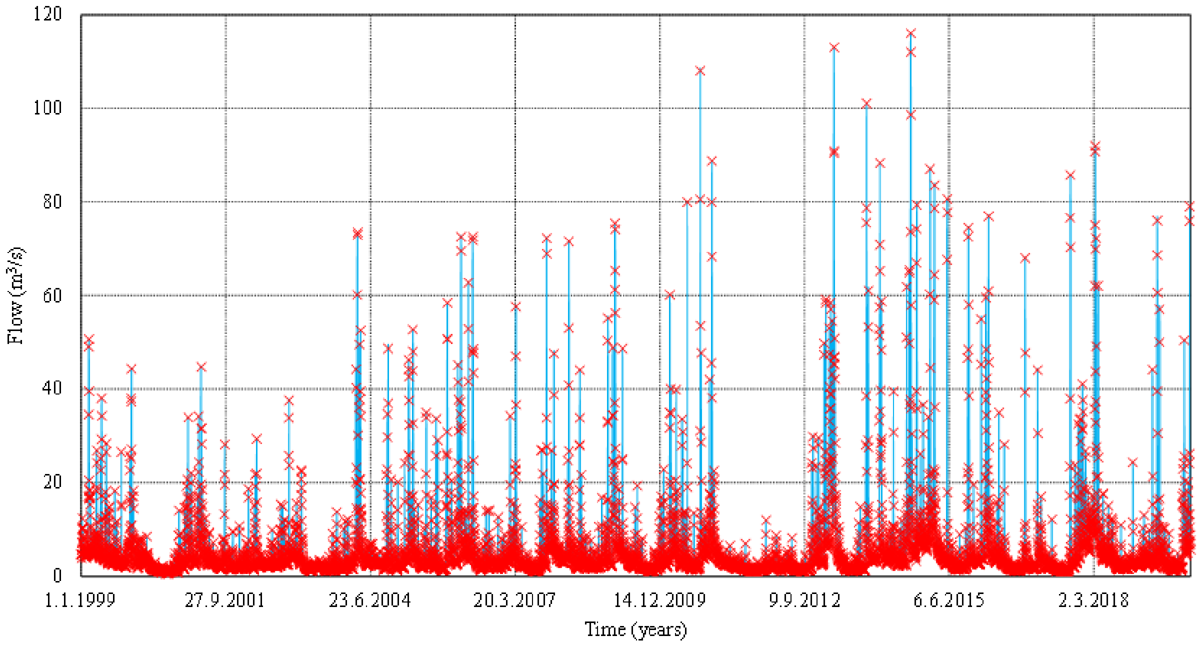

Figure 9. Hydrogram for the Ludbreg measurement station on the Bednja River from 1999 to 2019 [34]

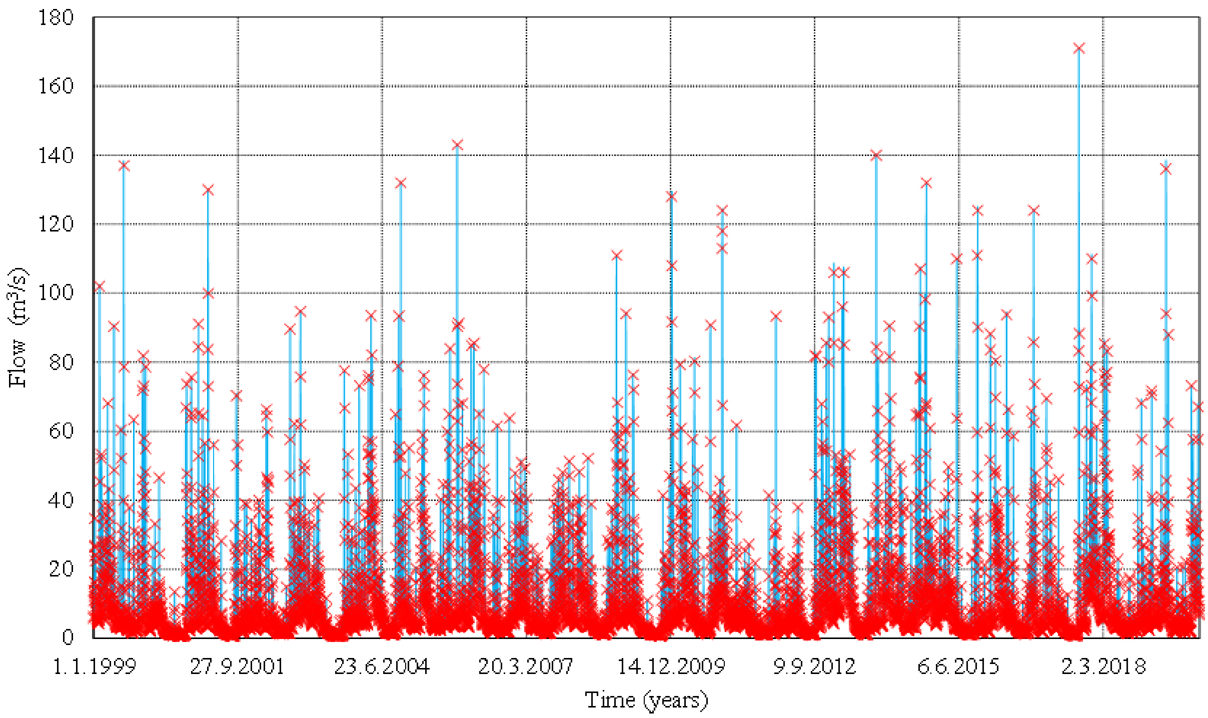

Figure 10. Hydrogram for the Turkovići measurement station on the Gornja Dobra River from 1999 to 2019 [34]

The years 2011 and 2012 were the driest during the observation period. This was particularly evident for the Bednja River. This is not so evident for the Gornja Dobra River.

5 Results and Discussion

5.1 RAPS values

Equation (1) was used to evaluate the time-series data shown in Figures 9 and 10. The RAPS values were determined as shown in Figures 11 and 12.

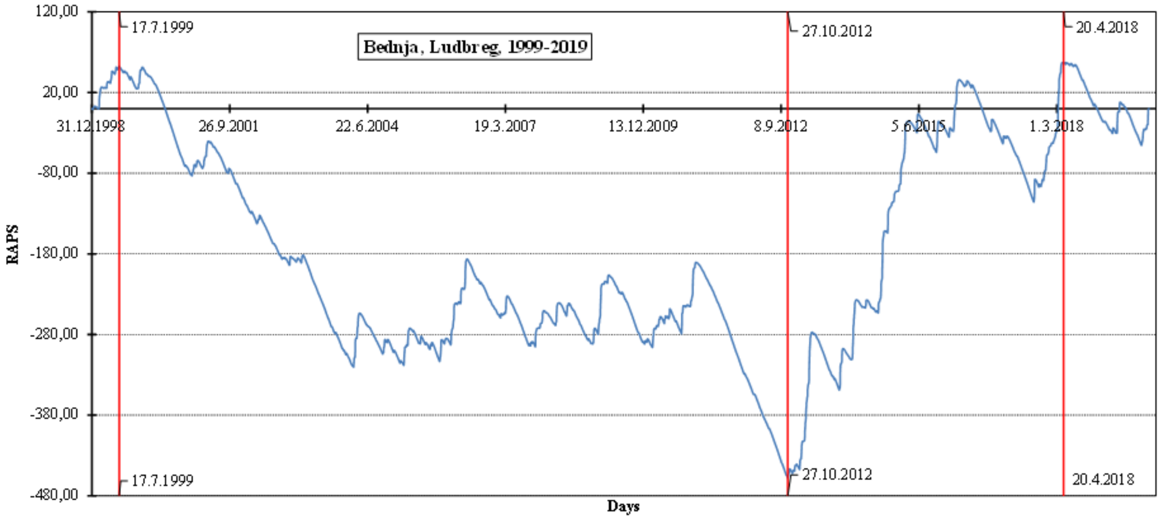

Figure 11. RAPS diagram for the Ludbreg water measurement station on the Bednja River from 1999 to 2019

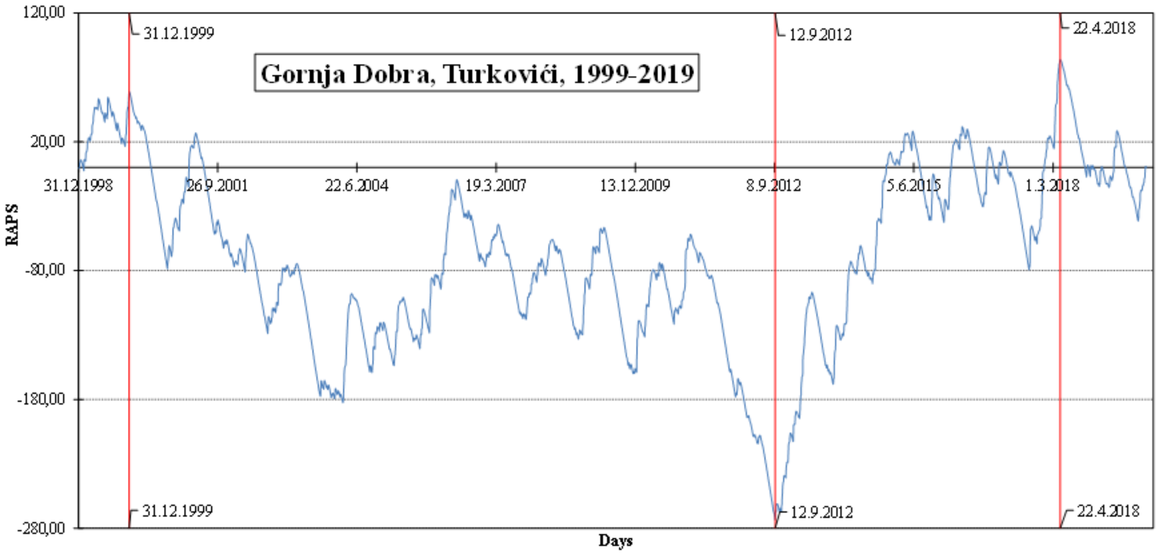

Figure 12. RAPS diagram for the Turkovići water measurement station on the Gornja Dobra River from 1999 to 2019

In both diagrams (Figures 11 and 12), it can be observed that the patterns of the RAPS values overlap. Due to the long length of the analysed time series (20 years, from 1999 to 2019), the question arises whether such overlapping will be observed in a short period, i.e., during the annual base, five, ten, or even a more extended period. The fact that three subperiods were observed, with the border in the middle/end of 1999, the last quartile of 2012, and April 2018. The subject and aim of this study was not to investigate the causes of the new subseries, which could be natural and/or anthropogenic. The subject is to analyse the homogeneity and isotropy of the analysed time series; therefore, the IPTA method is applied in the analysis.

5.2 IPTA values

The linear trends (Figures 13, 15, 17, and 19) determined show that the linear trends have negligible R^2 values. The average and standard deviation of the mean daily flows per month are marked with dots. From all IPTA diagrams (Figures 14, 16, 18, and 20), it could be concluded that most of the slopes between certain points are generally sharp and discontinuous, with no tendency to continue in a line. The lines between the points merge into one another. This indicates that the investigated flows are not homogeneous or isotropic. This was supported by the fact that none of the IPTA diagrams were closed. Both diagrams of the Bednja River show a smaller bulge than the case of the Gornja Dobra. This can be explained by the fact that Bednja lies in alluvial relief, while Gornja Dobra lies in karst relief (Figure 4-6). Sinkholes, depressions, holes, the effects of abyssal rivers, and all other karst formations and water bodies contribute significantly to the heterogeneity and anisotropy of the alluvial relief where such formations and/or water bodies do not exist.

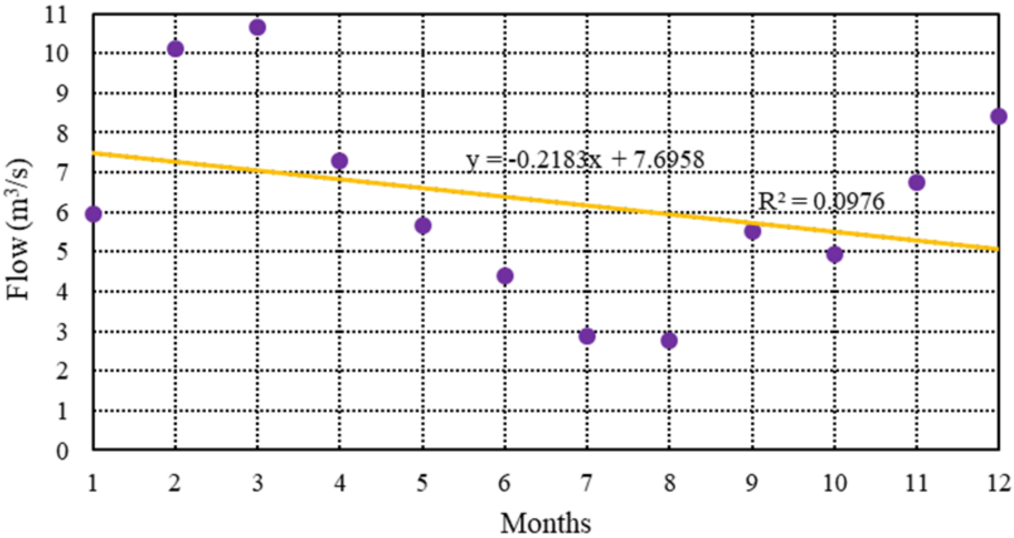

Figure 13. Average values of mean daily flows per month at the Ludbreg water measurement station on the Bednja River from 1999 to 2019

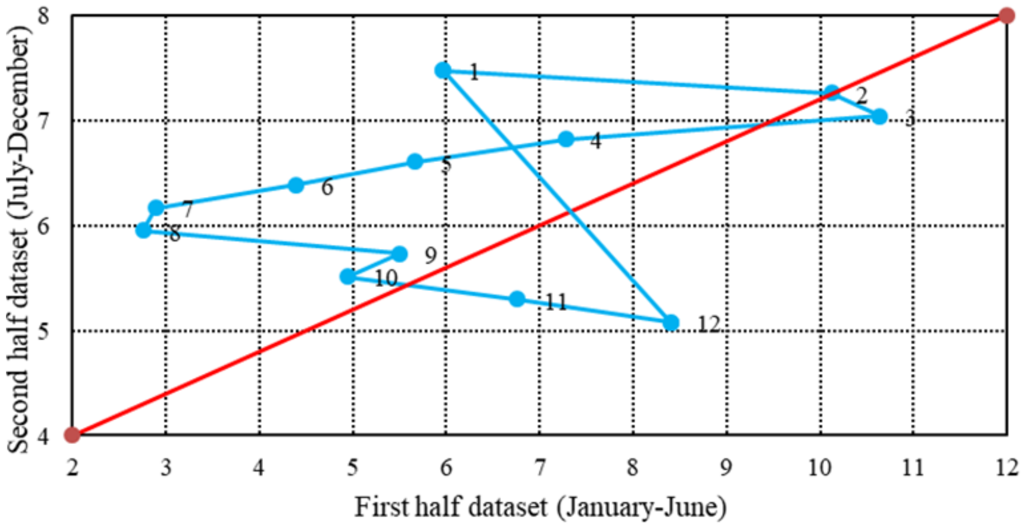

Figure 14. IPTA method for the linear trend of mean monthly values of mean flows at the Ludbreg water measurement station on the Bednja River from 1999 to 2019

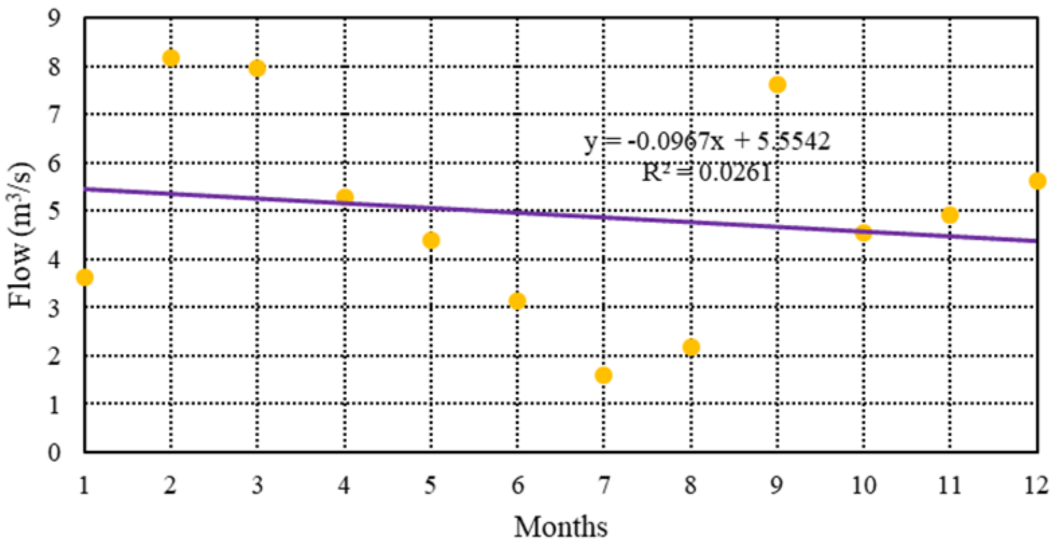

Figure 15. The standard deviation of mean daily flows per month at the Ludbreg water measurement station on the Bednja River from 1999 to 2019

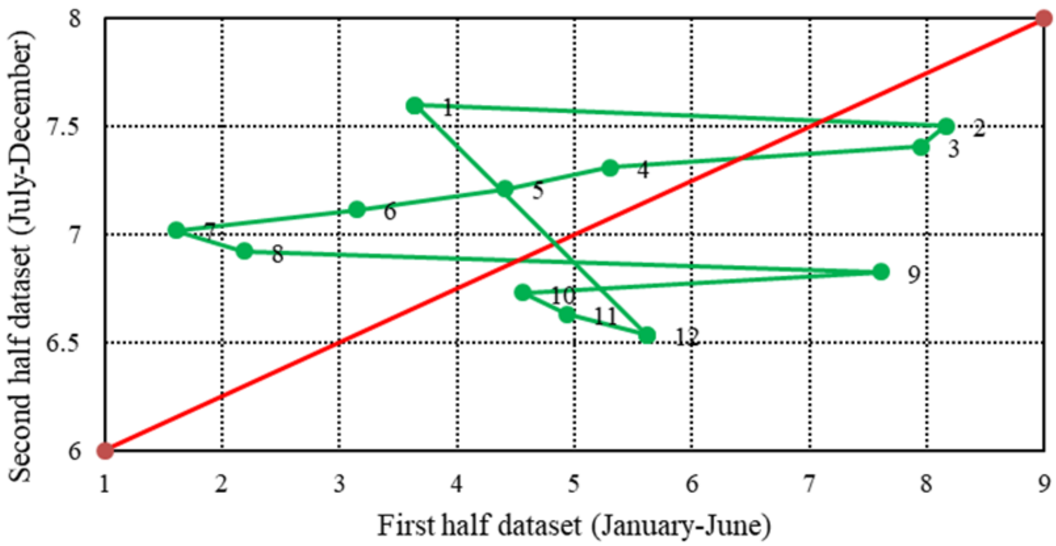

Figure 16. IPTA method for the linear trend of the monthly values of the standard deviation of the mean flows at the Ludbreg water measurement station on the Bednja River from 1999 to 2019

In the second step of the analysis, the increasing or decreasing trend between months was defined in the IPTA diagrams for the average and standard deviation values. Regarding the Ludbreg measurement station on the Bednja River, decreasing trends for the averaged values were found for months 3, 4, and 12 (Figure 14). Decreasing standard deviation values were observed for months 2, 3, 9, 10, 11, and 12.

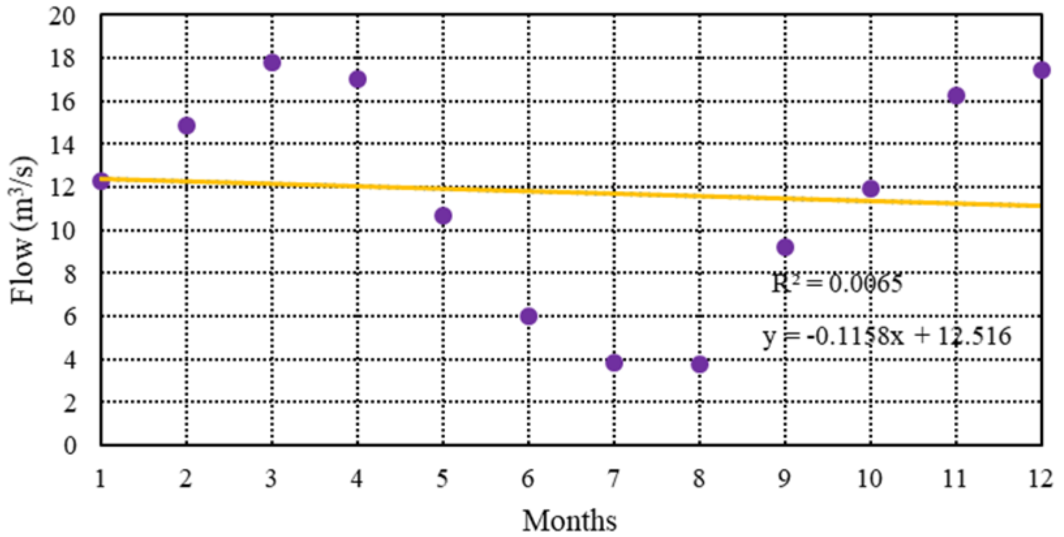

Figure 17. Mean monthly values of mean flows at the Turkovići water measurement station on the Gornja Dobra River from 1999 to 2019

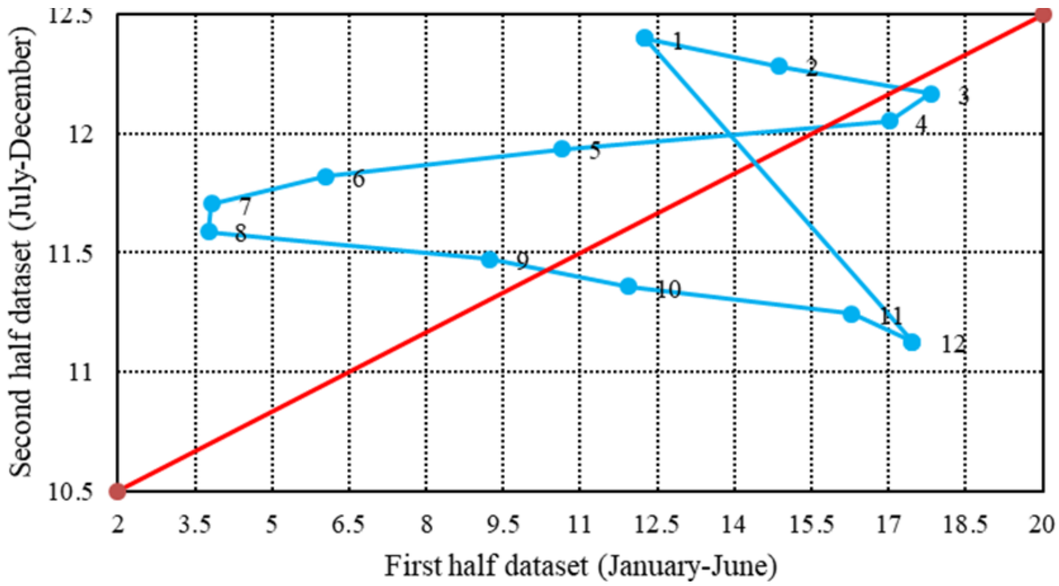

Figure 18. IPTA method for the linear trend of the mean monthly values of flows at the Turkovići water measurement station on the Gornja Dobra River from 1999 to 2019

For the Turkovići measurement station on the Gornja Dobra River, the average values for the 3rd, 4th, 10th, 11th, and 12th months are also on a downward trend, Figure 18. The IPTA diagram shows that the standard deviation values decreased in the 1st and 4th month, as illustrated in Figure 20. This can be explained by the complexity of the hydrological and hydrogeological systems, where the standard deviation values are indicators of homogeneity and isotropy. IPTA polygons are not narrow for either measurement station, which leads to the conclusion that the monthly averages are not homogeneous or isotropic. In other words, there is no uniformity, i.e., there is no balance in the flow values.

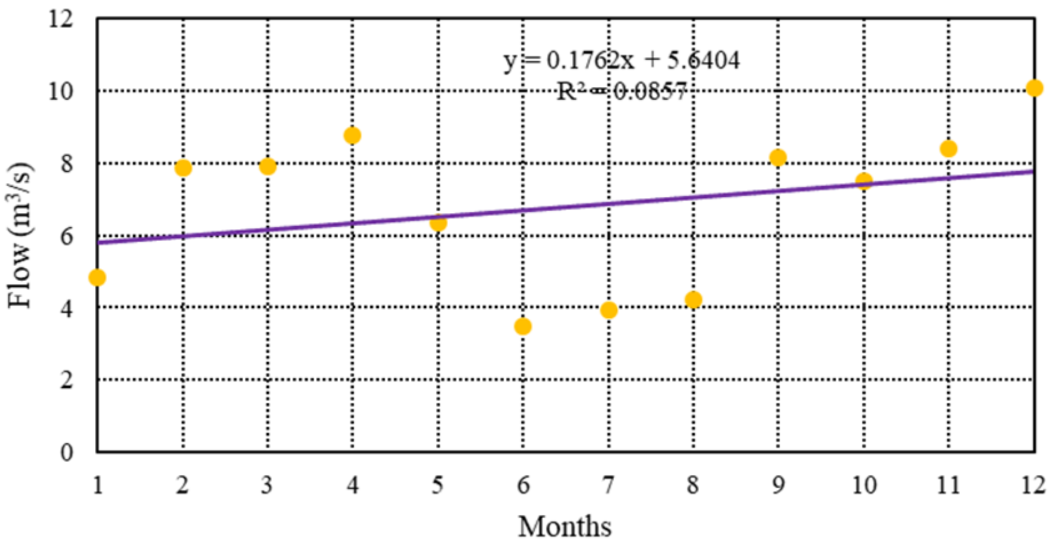

Figure 19. The standard deviation of the mean flows per month for the Turkovići water measurement station on the Gornja Dobra River from 1999 to 2019

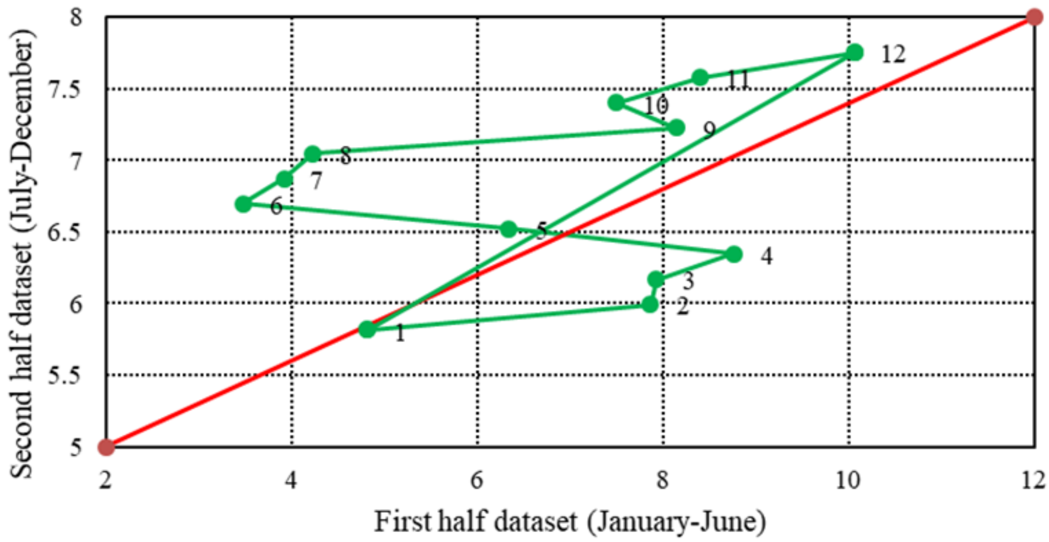

Figure 20. IPTA method for the linear trend of the monthly values of the standard deviation of mean flows at the Turkovići water measurement station on the Gornja Dobra River from 1999 to 2019

6 Conclusions

The analysis provided an algorithm to determine the possible homogeneity and isotropy of the flow time series in two analysed hydrological systems: alluvium and karst. This study showed the variability in the observed time series and monthly unit levels.

The most commonly used procedure, linear trend analysis, is unreliable despite its widespread use. RAPS was applied to detect fluctuations in the analysed time series of the average daily flow values. This was determined by the overlap of the RAPS patterns of the Bednja and Gornja Dobra rivers.

The application of the IPTA method proved to be justified as at the level of monthly average daily flows, certain months in the year were extracted as a 'border,' which shows periods in which the status of homogeneity and isotropy exists. This is crucial for determining the part of the year during which drastic changes in the water regime may occur. This approach is applied

in the context of the more pronounced fluctuations in river flow resulting from significant climate changes of recent decades. It is a well-known fact that climate changes affect the reliability of the forecasted values. Extreme events do not go hand in hand with these events.
This research will form the basis for further and more specific analyses, which will also include all other hydrometeorological parameters, as well as other watercourses and hydrological measurement stations.

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