

Unravelling seasonal dynamics: Inter-station correlations and hydrological assessments of Topľa river in the Bardejov basin

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Abstract. The study delves into the complex seasonal dynamics of water levels in the Topľa River, strategically positioned within the Bardejov basin. Hydrological assessments, aided by the water-bearing coefficient, classify the hydrological situation into Wet, Normal, or Dry conditions, creating a robust framework for clustering water levels across different years. The measurement stations, strategically located in Bardejovská Dlhá Lúka (stream Kamenec), Bardejov (river Topľa), Kľušovská Zábava (stream Šibská voda), and Gerlachov (river Topľa), contribute unique insights. Notably, Gerlachov and Bardejov represent different locations of the same stream, while Šibská voda and Kamenec are spatially proximate to Bardejov, experiencing similar meteorological conditions. Results from statistical analyses showcase distinctive seasonality patterns at each location and how the correlation between these stations evolves across different hydrological conditions. Intriguingly, the findings reveal an insignificant spatial relationship of correlation between station locations and seasonality, challenging conventional expectations. The implications of these results for water management and resources are discussed, emphasizing the need for a nuanced understanding of seasonality dynamics in optimizing water resource planning.

1 Introduction

Slovakia, a landlocked nation in Central Europe characterized by diverse landscapes, from soaring mountain ranges to fertile lowlands, faces significant challenges in managing its water resources. This complexity is largely influenced by the country's dynamic climate and topographic variations, which shape surface runoff dynamics. Understanding these dynamics and their seasonal variations is crucial for effective water resource management in Slovakia [1, 2].

Surface runoff, the flow of water across land surfaces, is a fundamental component of the hydrological cycle, impacting groundwater recharge, landscape erosion, and aquatic ecosystem health. In Slovakia, surface runoff patterns exhibit distinct seasonality driven by a complex interplay of climatic and geographic factors. Spring snowmelt dominates the

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annual discharge regime, leading to pronounced peaks typically occurring in March and April, extending into early summer in mountainous regions. Conversely, lowland streams experience minimal spring increases, transitioning rapidly into a period of low water content, coinciding with crucial agricultural water demands. Understanding these seasonal discharge patterns is vital for effective water resource management [1 – 3].

The threatening spectre of climate change further complicates surface runoff dynamics in Slovakia. Rising temperatures accelerate snowmelt rates, altering the timing and magnitude of spring runoff peaks. This shift leads to earlier peak flows, particularly in mountainous regions where snowpack acts as a vital water reservoir. Changes in precipitation patterns, including increased frequency of extreme events or shifts in seasonal distribution, further contribute to runoff variability. This complex interplay underscores the urgency of comprehensive research and adaptive strategies to mitigate risks and ensure long-term water security [3 – 6].

Beyond surface runoff dynamics [7] and climate change impacts, a comprehensive understanding of water resource vulnerability in Slovakia requires the analysis of droughts and the application of hydrological classification systems. Drought events, characterized by prolonged periods of below-average precipitation and water deficits, pose significant challenges to water resource management and societal resilience. Assessing the frequency, duration, and intensity of droughts, along with their spatial distribution, provides valuable insights into hydrological variability and informs drought mitigation strategies. Integration of drought analysis and hydrological classification enhances our understanding of water resource dynamics and supports informed decision-making for sustainable water management practices [8 – 10].

In this study, we undertake a comprehensive analysis of surface runoff dynamics in Slovakia, exploring the factors driving seasonality, the challenges posed by climate change, and the importance of drought analysis within the context of water resource vulnerability. By integrating these crucial elements, our research aims to contribute to a deeper understanding of water resource dynamics and inform the development of sustainable management practices in Slovakia amidst a changing climate landscape.

2 Study area

The study area includes the Topľa River basin, a prominent watercourse situated in eastern Slovakia. The Topľa River, a right tributary of the Ondava River, meanders for approximately 129.8 km within the boundaries of the Prešovský and Košický regions. This basin drains an area of roughly 1,544 km² [2], characterized by a diverse landscape blending agricultural lands with forested areas [3] (Figure 1.).

The basin exhibits a complex topographic variety, transitioning from lower elevations in the south to mountainous terrain in the north. This variation significantly influences climatic patterns within the basin, which falls within the temperate climate zone. The basin can be classified into three distinct climatic regions. The southern portion experiences a warm climate, with over 50 summer days and daily highs surpassing 25°C. Conversely, the northern and north-western regions fall within the cool climatic zone, with July mean temperatures remaining below 16°C. Valleys, uplands, and foothills in the central regions boast a moderately warm climate, with average July temperatures exceeding 16°C [3].

Annual precipitation within the basin varies considerably, reflecting the diverse topography. Lower elevations typically receive between 600-700 mm of annual precipitation, while mountainous regions can expect up to 1000 mm. This variation plays a crucial role in shaping the hydrological regime of the Topľa River [2, 3].

The hydrological behaviour of the Topľa River exhibits distinct seasonal patterns, with spring snowmelt and summer rainfall events contributing to peak discharge periods. Long-

term discharge data from key gauging stations, such as Bardejov (catchment area 325.8 km²), offer valuable insights into the hydrological characteristics of the river. Analysis of discharge data from the Bardejov station reveals a mean daily discharge of 2.978 m³ · s⁻¹. Understanding these spatial and temporal variations in the hydrological regime is paramount for effective water resource management strategies within the Topľa River basin [1 – 3].

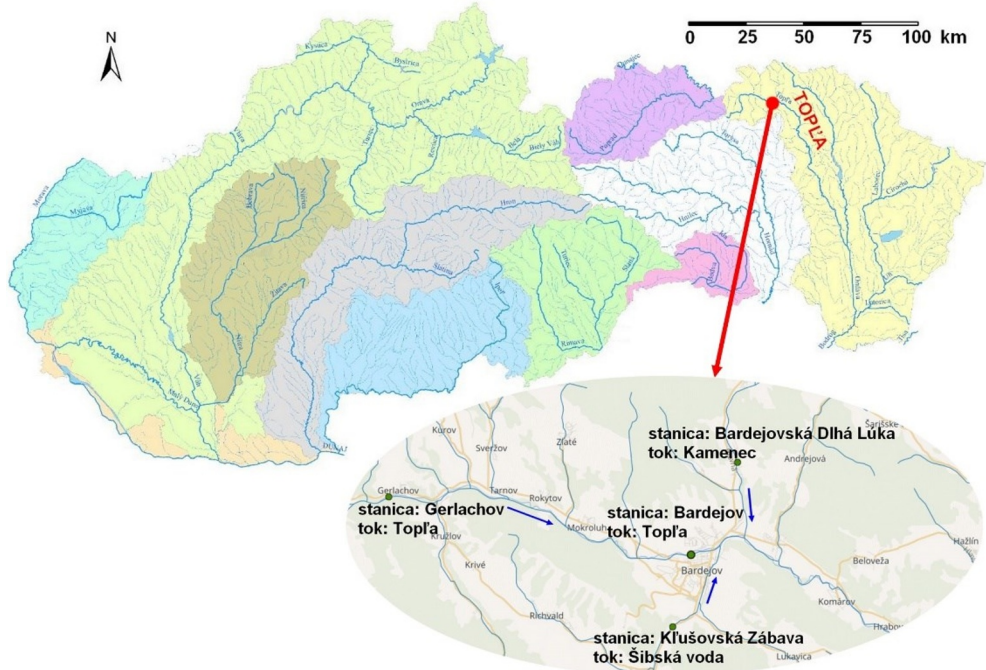


Fig. 1. The location of the Topľa River basin and the distribution of the gauging stations.

2.1 Data and Stations

In this study, four key gauging stations (Figure 1.) were instrumental in analyzing the hydrological dynamics of the Topľa River basin [11].

- Bardejov (Topľa River): Monitoring discharge patterns since 1988, this station offers a strategic vantage point for assessing basin-wide flow dynamics.
- Gerlachov (Topľa River): Situated downstream, this station provides valuable insights into discharge variations. Data collection commenced in 1992, and the data was meticulously processed for accurate analysis.
- Bardejovská Dlhá Lúka (Kamenec stream): Located on a tributary, this station offers unique perspectives on hydrological patterns within the Kamenec catchment. Data collection began in 1988. For the duration of this study, this station will be referred to by the name of the respective stream (Kamenec).
- Kľušovská Zábava (Šibská voda stream): Situated on another tributary, this station contributes to a holistic understanding of hydrological variations. Data collection commenced in 1988. Throughout the study, this station will be identified using the name of the associated stream (Šibská voda).

The data were collected and provided by the Slovak Hydrometeorological Institute (SHMI). Any year exhibiting a data gap exceeding two months is excluded from the database utilized in this study. Standardized and advanced statistical techniques were applied to

analyze the processed data, unraveling the complex interplay of hydrological variables and facilitating meaningful interpretations of discharge patterns within the Topľa River basin.

3 Methods and Analysis

3.1 Hydrological Droughts: The Water-Bearing Coefficient

To gain a deeper understanding of drought characteristics within the Topľa River basin, this study utilizes the well-established water-bearing coefficient (WBC) method. This technique offers a straightforward approach to quantifying water availability. It calculates a ratio, expressed as a single number, by dividing the average annual discharge (Q_{avg}) of the river by its long-term average discharge (Q_a). By comparing these values, the WBC provides a simple index that allows for easy comparison across different hydrological conditions [2, 12].

In this study, we leverage a classification scheme that categorizes WBC values into five distinct drought severity levels (Table 1.). This classification system goes beyond simply identifying periods of drought; it allows us to gauge their intensity, ranging from "extreme drought" to "normal" or even "extreme wet" conditions. While the WBC method is a powerful tool, its limitations are acknowledged [12]. Factors such as precipitation patterns, land-use changes, and water demands can significantly influence the vulnerability of water resources in the Topľa River basin. Therefore, the aim is to incorporate these additional aspects into a comprehensive analysis of the basin's hydrological characteristics.

Table 1. Standard values of water-bearing coefficient.

Standard Intervals	Hydrological Situation
10 - 29	Extreme Drought
30 - 49	Severe Drought
50 - 69	Moderate Drought
70 - 89	Mild Drought
90 - 110	Normal
111 - 130	Mild Wet
131 - 150	Moderate Wet
151 - 170	Severe Wet
171 - 180	Extreme Wet

3.2 Decomposing Time Series: Seasonal and Trend Decomposition using Loess (STL)

Understanding the complex relationship between trends and seasonality within the discharge data of the Topľa River requires employing sophisticated analytical methods. One such method, the Seasonal and Trend Decomposition using Loess (STL) technique serves as a valuable tool in this endeavor. This method deconstructs the time series into three fundamental components: the seasonal variation, the trend component, and the residual component. The Seasonal Whisper unveils the recurring annual pulse of the river, primarily driven by seasonal fluctuations in precipitation. Meanwhile, the trend is primarily shedding light on potential shifts in water availability over time. Lastly, the residual component captures the variability within the data not accounted for by the seasonal or trend components.

In practical terms, the STL method utilizes Loess, a smoothing technique, to effectively separate the underlying trends and seasonality from the background noise present in the data. By subtracting the seasonal and trend components, we can isolate the residual signal, which represents the "fingerprint" of drought events within the discharge record. Integrating these residual signals with drought periods identified using methods like the WBC technique offers valuable insights into the manifestation of droughts in the river's flow patterns.

While the STL method's window size is set to one year to capture annual variations accurately, it's crucial to acknowledge its limitations. Achieving a comprehensive understanding of water resource dynamics necessitates considering various factors beyond trends and seasonality, including precipitation patterns and land-use changes. By combining the STL and WBC methods, this study attempts to uncover a deeper understanding of the Topľa River's hydrological complexities, facilitating more informed and nuanced water resource management strategies [13 – 15].

3.3 Statistical analysis and testing

This study employs a suite of statistical analyses to analyze the complex relationships within the hydrological dynamics of the Topľa River.

- **Pearson or Spearman Correlation Test:** This test quantifies linear associations between variables, allowing us to explore correlations among streamflow variables across different locations within the Topľa River basin. Additionally, we can investigate connections between streamflow and influencing factors like precipitation or temperature, providing insights into hydrological variations [16].
- **Chi-Square Contingency Test:** This technique assesses relationships between categorical data, such as the occurrence of drought events across different zones within the Topľa River basin. Understanding these connections is vital for developing effective drought management strategies tailored to regional vulnerabilities [16].

By integrating these statistical tools, we aim to unravel the complex relationships and dynamics within the Topľa River's hydrological system, ultimately enhancing our understanding of its response to environmental changes.

3.4 Analysis

The analysis was conducted in several stages to examine the hydrological characteristics of the Topľa River basin under varying hydrological conditions and locations. Initially, the data were classified into three distinct groups based on the water-bearing coefficient method: dry, normal, and wet conditions. This classification facilitated the comparison of hydrological patterns across different levels of water availability for four key locations within the study area.

Subsequently, (STL) method was applied to each classified group separately to extract the discharge seasonality under different hydrological conditions. The STL decomposition enabled the separation of seasonal patterns, trends, and residual components from the hydrological time series data. Figures illustrating the discharge seasonality in dry, normal, and wet conditions for each of the four locations were generated, providing insights into the variability of discharge patterns across different hydrological scenarios.

Furthermore, correlation analysis was conducted to explore the relationships between the four different locations under varying hydrological conditions. Correlation heat maps were generated to visualize the correlation coefficients between discharge variables at each location, allowing for the identification of potential spatial dependencies and patterns. The correlation analysis provided valuable insights into the degree of association between

hydrological variables across different locations and hydrological conditions, facilitating a deeper understanding of the interconnections within the Topľa River basin.

Overall, the analysis revealed significant variations in discharge seasonality and spatial correlations across different hydrological conditions and locations within the study area. These findings contribute to a comprehensive understanding of the hydrological dynamics of the Topľa River basin and provide valuable insights for water resource management and decision-making processes. Further details and visual representations of the analysis results are presented in the following sections.

4 Results

4.1 Dry Hydrological Conditions

Under dry conditions, all four locations within the Topľa River basin exhibit distinct seasonal patterns characterized by fluctuations in discharge levels throughout the year. Despite variations in magnitudes attributed to differences in stream capacities, common trends in seasonality are observed among the locations.

From the onset of the year until March/April, there is a noticeable increase in seasonality across all locations. This rise in discharge levels can be attributed to p which contributes to precipitation increased runoff and streamflow. As the winter season progresses, precipitation events intensify, leading to heightened discharge levels and peak seasonality.

Subsequently, from mid-April onwards, a decline in seasonality is observed until May, followed by another peak in discharge. This secondary peak is primarily attributed to snow melting, particularly in higher-elevation areas. The gradual thawing of accumulated snowpack results in increased runoff and streamflow, leading to elevated discharge levels during this period.

Following the May peak, a gradual decline in seasonality is observed throughout the remainder of the year, albeit with small peaks occurring in June and October. Notably, the peak observed in June is particularly significant in Bardejov compared to the earlier peak in March/April. This disparity in peak magnitudes suggests variations in local hydrological dynamics and highlights the influence of geographic factors on discharge patterns within the Topľa River basin.

Overall, under dry conditions, the seasonalities of all four locations follow a similar trajectory, characterized by distinct peaks corresponding to precipitation and snow melting events (Figure 2.). These findings underscore the complex interplay of climatic, geographical, and hydrological factors shaping discharge patterns within the study area.

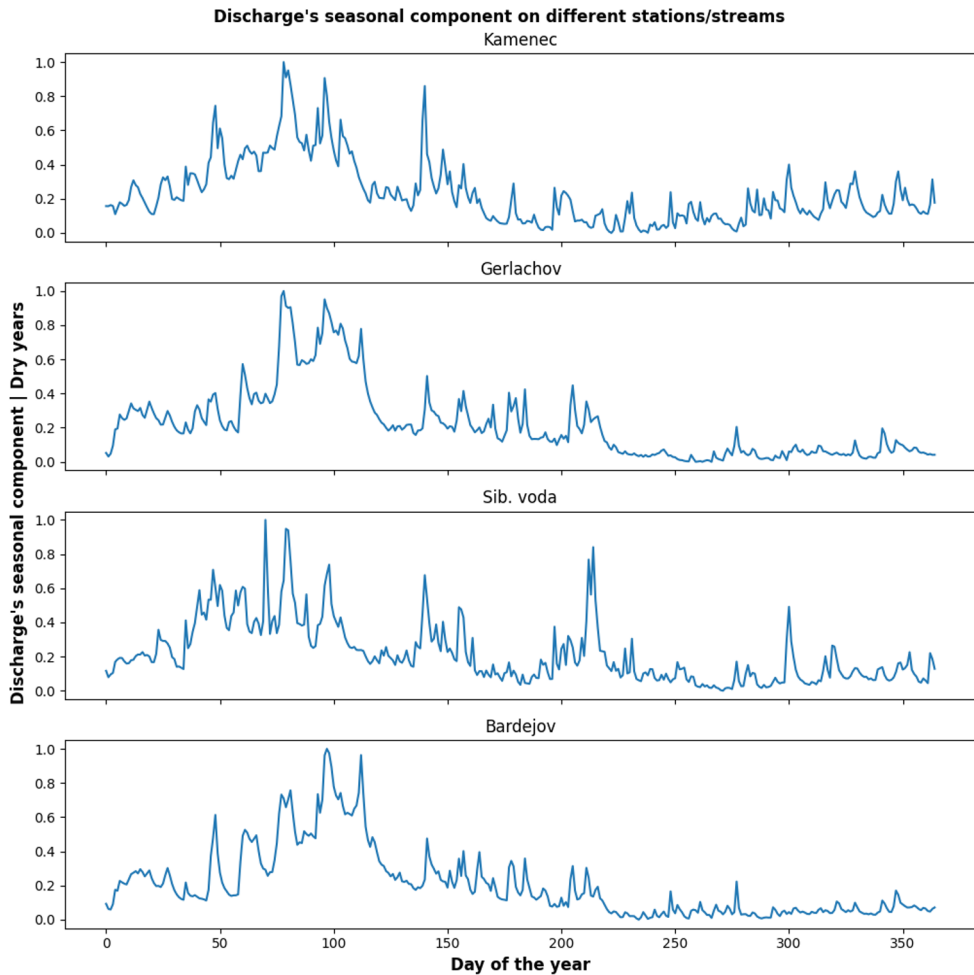


Fig. 2. Comparison of the seasonal discharge components over 365 days at four gauging stations under dry classified conditions.

The analysis of discharge seasonality under dry hydrological conditions revealed fascinating patterns of correlation between the gauging stations (Figure 3.). Interestingly, a strong correlation in seasonal discharge patterns was observed between Gerlachov and Bardejov, despite them being the furthest apart geographically within the basin. This finding suggests that large-scale climatic factors and regional precipitation patterns might exert a dominant influence on discharge seasonality in these locations during dry periods.

Furthermore, Bardejovská Dlhá Lúka station, situated on Kamenec stream, also exhibited a significant correlation with Bardejov station. This observation highlights the potential influence of upstream processes or shared hydrological characteristics, even across tributaries, during dry conditions. Conversely, the correlation between Šibská voda and Topľa in Bardejov appeared to be the weakest, despite their relative proximity. This contrast might be attributed to local factors specific to the Šibská voda catchment, such as variations in topography, vegetation cover, or groundwater interactions, that influence discharge dynamics differently compared to the other stations.

These findings underscore the complex interplay between spatial proximity, climatic drivers, and local catchment characteristics in shaping discharge seasonality patterns within the Topľa River basin, particularly during dry periods.

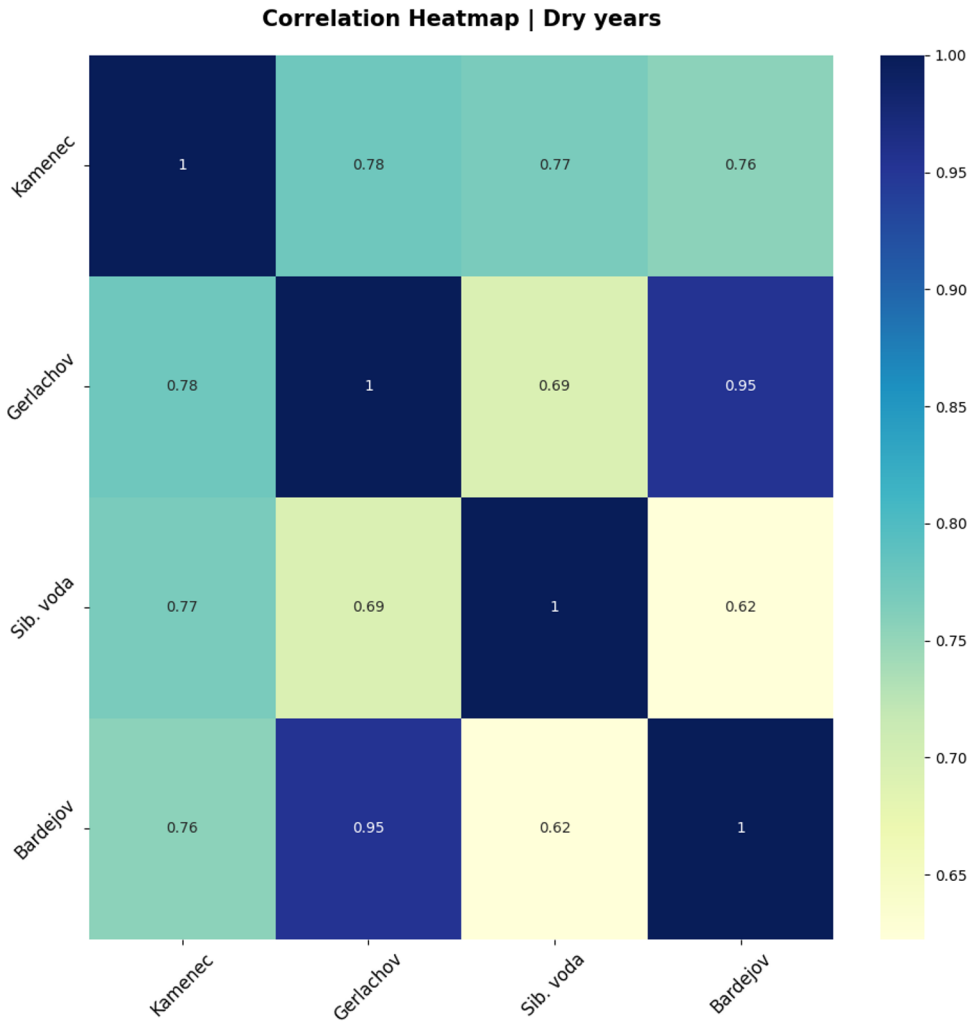


Fig. 3. Heatmap depicting Pearson correlation coefficients between the seasonal discharge components among four distinct locations during dry hydrological conditions.

4.2 Normal Hydrological Conditions

Under normal hydrological conditions, the seasonal patterns of all four locations within the Topľa River basin display similar trends, albeit with variations in magnitudes reflecting differences in stream capacities.

From the beginning of the year until March/April, there is a consistent increase in seasonality across all locations, primarily driven by Precipitation. Precipitation events during this period contribute to elevated runoff and streamflow, resulting in peak seasonality levels. The increase in discharge is particularly pronounced during the winter months, reflecting the cumulative effects of precipitation over the preceding months.

Following the peak in March/April, a gradual decrease in seasonality is observed across all locations from mid-April until May. However, in May, a secondary peak in discharge occurs due to snow melting, especially in higher-elevation areas. This phenomenon leads to

a temporary increase in streamflow as accumulated snowpack begins to thaw, contributing to elevated discharge levels during this period.

Subsequently, from May onwards, a gradual decline in seasonality is observed until the end of the year, with one significant peak occurring in June across all locations. However, notable variations are observed in the magnitude of the May peak in Kameneč, where it is considerably smaller compared to the other locations. This discrepancy can be attributed to local factors such as differences in elevation and snow accumulation patterns. Additionally, in Kameneč, the June peak is more significant than the March peak and exhibits the largest peak for this location. This observation may be attributed to specific local hydrological characteristics, such as watershed size or geological features, which influence discharge dynamics differently compared to other locations.

In contrast, in the other locations, the peaks in June are comparable in magnitude to those in May and March, indicating consistent discharge patterns throughout the normal hydrological conditions period. Overall, the seasonalities of the four locations under normal hydrological conditions exhibit common trends with variations in peak magnitudes, reflecting the complex interplay of climatic, geographical, and hydrological factors within the Topľa River basin (Figure 4.).

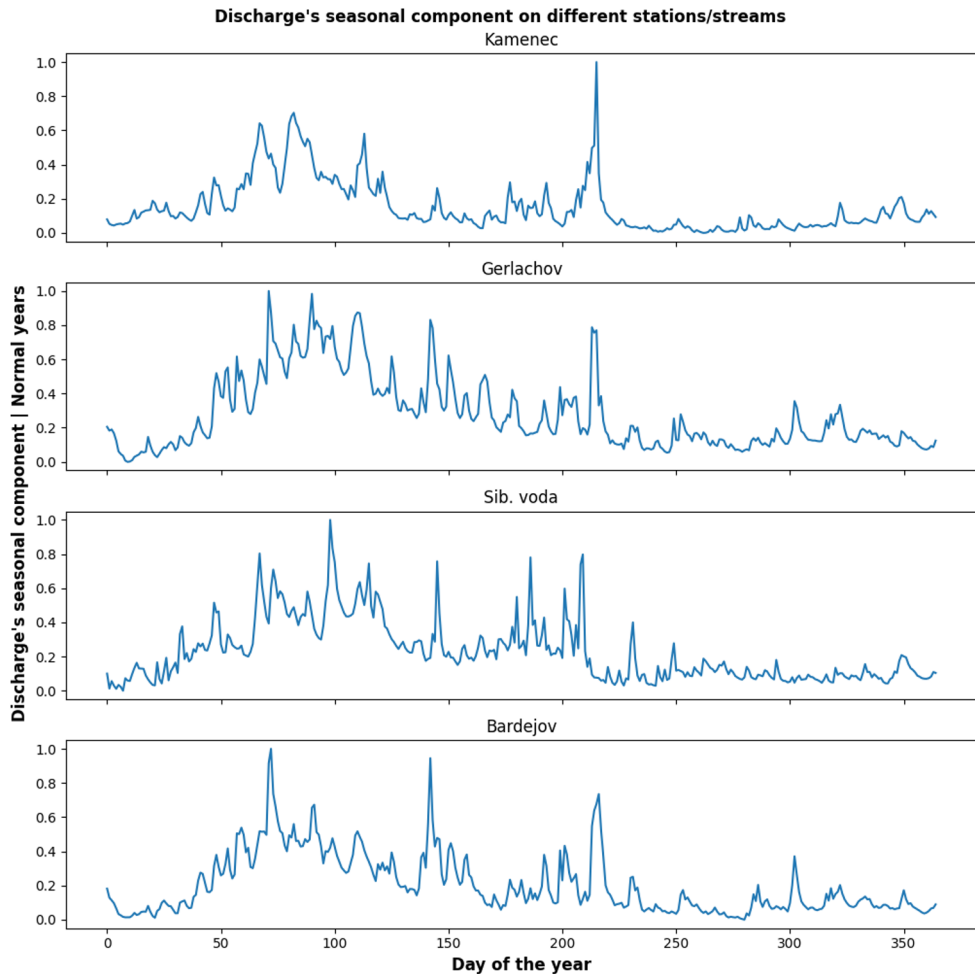


Fig. 4. Comparison of the seasonal discharge components over 365 days at four gauging stations under normal classified conditions.

The analysis of discharge seasonality under normal hydrological conditions revealed a noteworthy shift in the correlation patterns observed during dry periods. Notably, the strong correlation previously observed between Bardejov and the other stations weakened. This weakening correlation could potentially be attributed to several factors:

- Increased influence of local factors: With more abundant precipitation during normal conditions, the influence of local catchment characteristics, such as topography, soil properties, and vegetation cover, might become more pronounced, leading to greater divergence in discharge patterns between stations.
- Variability in snowmelt contribution: The timing and magnitude of snowmelt runoff can vary across different elevations and aspects within the basin. Under normal conditions, this variability might play a more significant role, causing deviations in discharge seasonality even among geographically close stations.

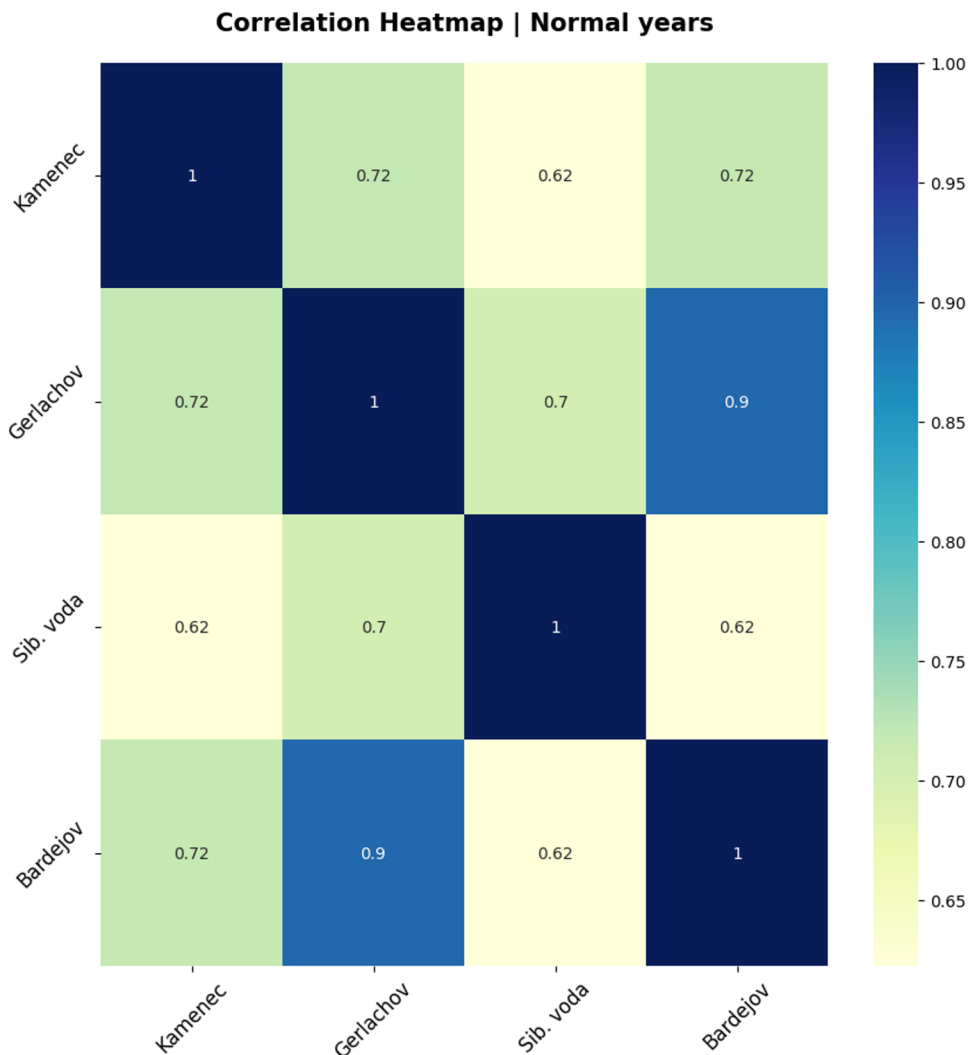


Fig. 5. Heatmap depicting Pearson correlation coefficients between the seasonal discharge components among four distinct locations during normal hydrological conditions.

Despite the weakened overall correlation, the ranking from strongest to weakest correlation remained consistent, with Gerlachov exhibiting the highest correlation with Bardejov, followed by Kamenec and then Šibská voda (Figure 5.). This suggests that some large-scale climatic drivers and regional influences might still exert a moderating effect on discharge seasonality, even as local factors become more prominent.

Furthermore, the overall correlation in the seasonal component of discharge appears to be weaker compared to dry conditions. This observation highlights the complex interplay between regional climatic forcing, local hydrological processes, and the influence of snowmelt dynamics in shaping discharge seasonality patterns within the Topľa River basin, with normal conditions exhibiting a stronger influence of local factors and snowmelt variability.

4.3 Wet Hydrological Conditions

Under wet hydrological conditions, all four locations within the Topľa River basin exhibit unique seasonal patterns characterized by variations in discharge magnitudes, influenced by differences in stream capacities (Figure 6.).

From January to March/April, there is a consistent increase in seasonality across all locations, primarily attributed to winter rainfall. This period sees heightened precipitation levels, resulting in increased runoff and streamflow, with the peak seasonality observed in March/April. Notably, this peak is most significant in Kamenec, which experiences the highest overall discharge levels among the four locations during wet conditions.

Following the peak in March/April, a gradual decrease in seasonality occurs from mid-April until June. However, in June, a secondary peak in discharge is observed across all locations, attributed to snow melting. This peak is particularly significant for Gerlachov, Šibská voda, and Bardejov, where the seasonal discharge reaches its highest point. This phenomenon reflects the influence of snowmelt from higher elevation areas, contributing to elevated streamflow during this period.

Subsequently, from June onwards, a gradual decline in seasonality is observed until the end of the year, with one significant peak occurring in July across all locations. This peak in July signifies a temporary increase in discharge levels, followed by a subsequent decline in seasonality for the remainder of the year. Notably, starting from July, the seasonality continues to decrease until the end of the year, indicating a gradual return to lower discharge levels and more stable hydrological conditions.

Overall, under wet hydrological conditions, the seasonalities of the four locations exhibit common trends with variations in peak magnitudes, reflecting differences in stream capacities and local hydrological characteristics. These findings highlight the complex interplay of precipitation, snowmelt, and other hydrological processes shaping discharge patterns within the Topľa River basin during periods of elevated water availability.

Wet hydrological conditions unveiled a fascinating shift in the correlation patterns observed between the gauging stations. Notably, the correlation between Bardejov and both Kamenec and Šibská voda stations significantly increased, reaching values as high as 0.83 and 0.81, respectively (Figure 7.). This pronounced rise in correlation suggests that the spatial location of stations plays a more dominant role during periods of abundant precipitation.

Several factors could potentially explain this observation:

- Dominant influence of regional precipitation: During wet periods, widespread and intense precipitation events likely become the primary driver of discharge across the basin. This basin-wide influence could lead to more synchronized discharge patterns among stations, regardless of their specific location within the catchment.

- Increased connectivity within the river network: With higher discharge levels, the connectivity between different parts of the river network might become more pronounced.

This enhanced connectivity could allow for a more unified response to regional precipitation events, fostering stronger correlations between stations.

While Bardejov maintained the highest correlation with Gerlachov, it's noteworthy that the correlation during dry conditions was even stronger. Additionally, the correlation under normal conditions was very close to the wet conditions value. This suggests that under drier conditions, local factors and potentially variations in snowmelt play a more significant role in differentiating discharge patterns at Gerlachov compared to Bardejov. However, when abundant precipitation dominates, the basin-wide response becomes more synchronized, leading to a stronger correlation even between geographically distant stations.

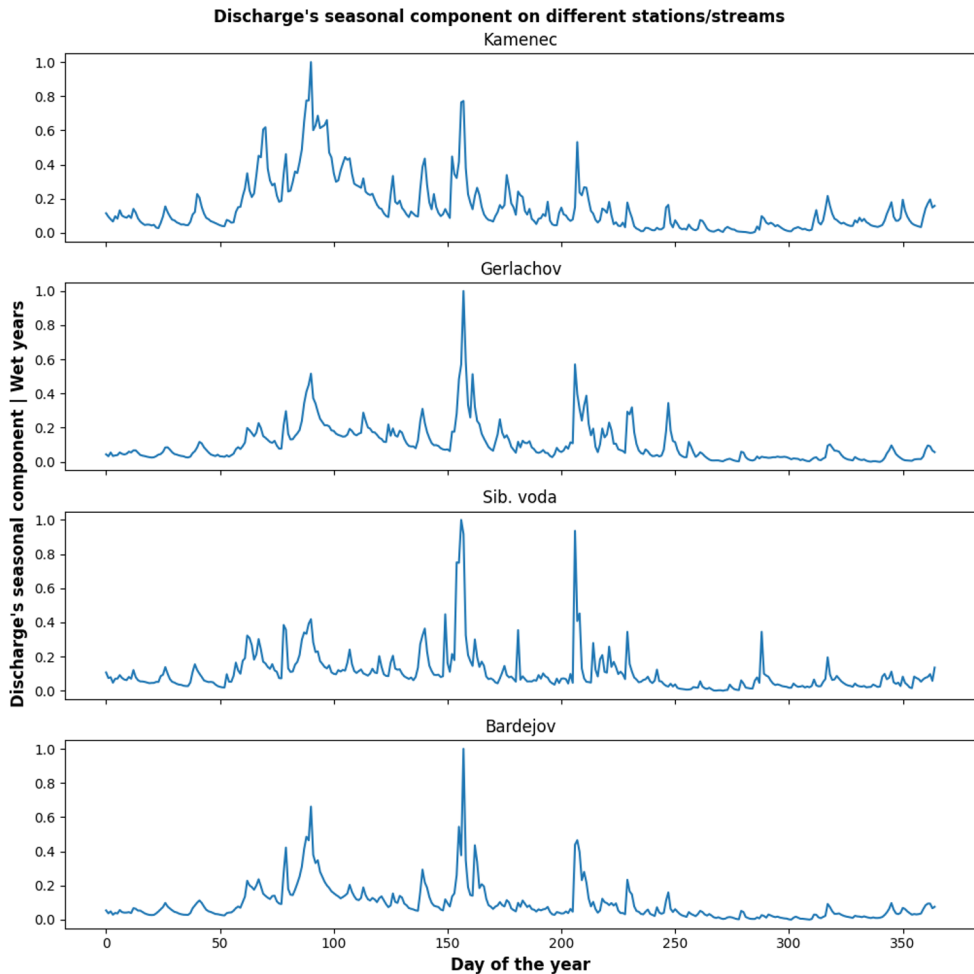


Fig. 6. Comparison of the seasonal discharge components over 365 days at four gauging stations under wet classified conditions.

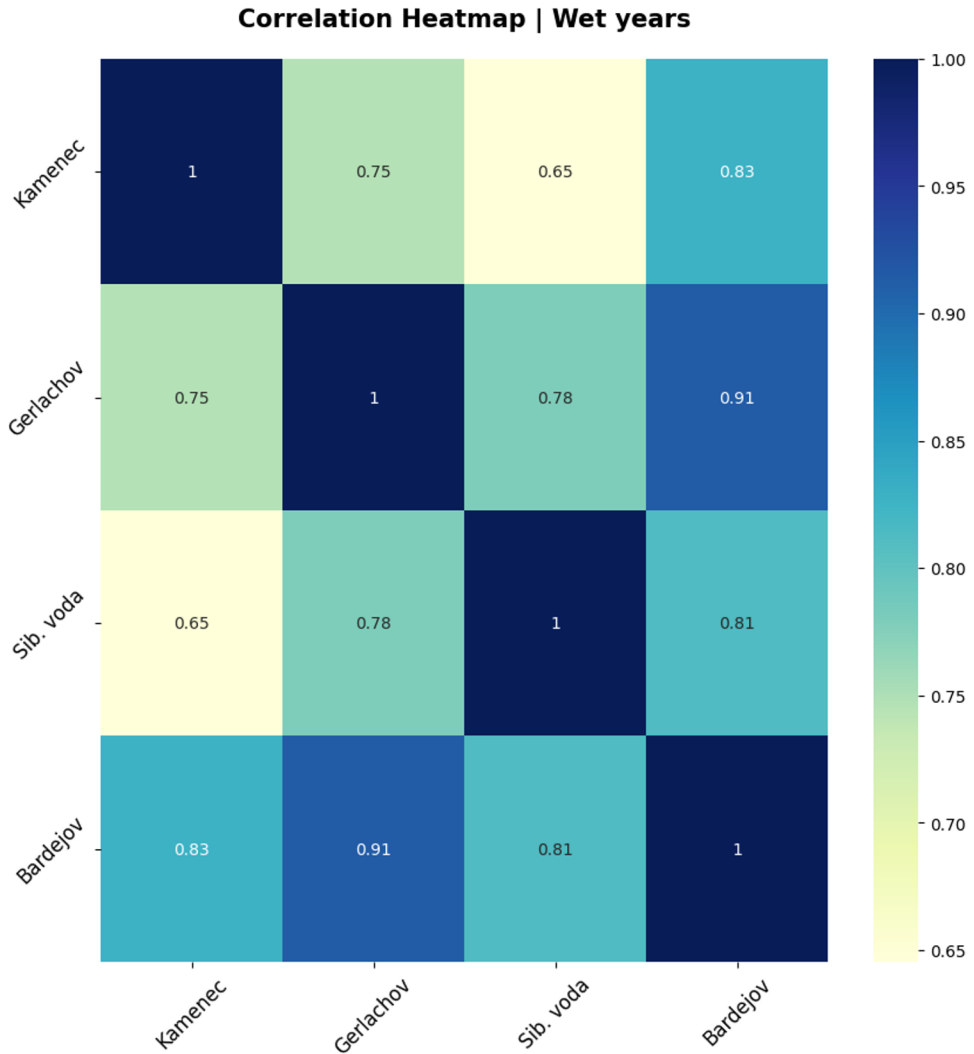


Fig. 7. Heatmap depicting Pearson correlation coefficients between the seasonal discharge components among four distinct locations during wet hydrological conditions.

5 Conclusion

This study meticulously explored the intricate relationship between seasonality, hydrological conditions, and local factors shaping discharge patterns within the Topľa River basin. Through detailed analyses across four key locations under varied conditions, we unveiled distinct yet interconnected seasonal fingerprints characterizing each scenario.

Seasonality emerged as a dominant driver of discharge dynamics across all hydrological conditions, with variations in magnitude and timing attributed to differences in stream capacities and local hydrological characteristics. Notably, precipitation, particularly winter rainfall and snowmelt, played a pivotal role in shaping these patterns, emphasizing the basin's vulnerability to potential shifts in precipitation regimes.

Unique insights emerged, particularly from Kamenec, where deviations from common trends suggested specific local influences like larger snow-covered areas or distinct

catchment response dynamics. Similarly, Bardejov's pronounced June peak under dry conditions highlighted the significance of considering geographical nuances in interpreting discharge patterns.

Considering the potential impact of climate change is crucial. Rising temperatures may alter snowmelt timing and magnitude, while increased precipitation variability could exacerbate extreme events during wet periods and worsen dry conditions, amplifying the importance of snowmelt contributions.

These insights form a robust foundation for developing resilient water resource management strategies. By comprehensively considering seasonality, hydrological conditions, local factors, and the potential influence of climate change, we can move towards sustainable practices ensuring the river's health and supporting the well-being of surrounding communities.

In conclusion, this study provides valuable insights into seasonal discharge patterns within the Topľa River basin and highlights the need for ongoing monitoring and adaptation efforts. By integrating climate change considerations into management strategies, stakeholders can enhance resilience and promote the long-term sustainability of water resources in the basin and beyond.

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