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Understanding the impact of drought on Topľa River discharge seasonality

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This study examines the effect of drought on the discharge seasonality of the Topľa River from 1988 to 2020. Each year is classified into dry, normal, or wet years using the water-bearing coefficient as a drought index. The Seasonal and Trend decomposition using the Loess time series decomposition method was used to compare discharge patterns between these groups. The results demonstrate a significant impact of drought on the seasonal discharge of the Topľa River, with substantially lower discharge and affected seasonality during dry years. The study findings demonstrate that the impact of the drought is altering the seasonal discharge pattern of the river. This highlights the importance of considering the effects of drought in water management and resource planning, particularly in the face of climate change and increasing water scarcity. These findings provide valuable insights for informing water management policies and practices in the region and can guide future research on the impact of drought on river systems.

KEY WORDS: time series decomposition, drought analysis, seasonality analysis, climate change, water resources

Introduction

Climate change has had a profound impact on water resources and water management strategies globally, with hydrological drought being a particular challenge. There is growing evidence to suggest that climate change is exacerbating hydrological drought conditions in many regions of the world. As temperatures rise, evapotranspiration rates increase, leading to higher rates of water loss from soils and vegetation (Vicente-Serrano et al., 2014). This, coupled with changes in precipitation patterns, can lead to reduced water availability and increased frequency and severity of hydrological drought. Climate change can also alter the frequency and intensity of extreme weather events such as hurricanes, floods, and heat waves, which can further exacerbate the impacts of hydrological drought. Addressing climate change through mitigation and adaptation measures is essential for reducing the risks associated with hydrological drought and ensuring sustainable water management for present and future generations (Gu et al., 2022).

Hydrological drought is a significant issue in Europe, affecting many regions and posing challenges for water management and adaptation (Vicente-Serrano et al., 2014). The changing climate in Europe has led to a more frequent occurrence of drought events, and the recent decades have seen a significant increase in the duration, severity, and spatial extent of hydrological drought in many parts of the continent (Spinoni et al., 2018; Sýs et al., 2021). In Slovakia, the impacts of hydrological drought have been particularly severe, with the country experiencing multiple episodes of low river discharge, reduced groundwater levels, and agricultural losses in recent years (Zeleňáková et al., 2018; Fendeková et al., 2018a). These impacts have been attributed to a combination of factors, including climate change, land-use changes, and water abstraction for various purposes. The hydrological drought situation in Slovakia highlights the need for effective monitoring and management of water resources, as well as the development of drought-resilient infrastructure and policies. It also underscores the importance of international cooperation and coordination to address the transboundary nature of water resources in Europe (Özerol et al., 2016).

Slovakia's surface runoff regime exhibits a notable increase in spring runoff, with the mountainous regions at higher altitudes experiencing slower snowmelt and consequently, delayed enhanced spring runoff when compared to lowland streams (Fendeková et al., 2018b; Velísková et al., 2017). During the summer-autumn season, most streams in Slovakia exhibit low water content, with the months between August and October being a crucial period for the growing season. In mountainous regions, the winter low-water period is of significant importance, particularly during the months of December to February (Almikaeel et al., 2022). Snowfall is a contributing factor to the low-water season, which does not immediately generate runoff during periods of sub-zero temperatures resulting from partial or complete freezing of the stream (Wang, 2019).

Understanding seasonal patterns of river flow is crucial for sustainable water management and agriculture (Serrano et al., 2020; Duchan et al., 2022). It can impact the quality and quantity of available water resources, affecting water supply, agriculture, and other water-dependent industries (Serrano et al., 2020; Khan et al., 2009). Hydrologists and agriculture can optimize their water use by comprehending seasonal changes in river flows, reducing losses, and increasing productivity, particularly in regions with limited water resources (Khan et al., 2009). A better understanding of the seasonality of river flows can also inform climate adaptation strategies (Laizé et al., 2016) and drinking water demand (Varga and Velísková, 2021). Seasonality can exacerbate drought conditions as precipitation patterns correlate with water availability, amplifying the effects of low rainfall or prolonged drought (Romano et al., 2020). This can result in reduced water availability during times of high demand, such as during the growing season for crops. Similarly, seasonality plays a role in exacerbating flood disasters, as seasonal patterns of precipitation and snowmelt can concentrate high-flow occurrences at particular times of the year, increasing the likelihood and severity of flooding (Serrano et al., 2020; Sivapalan et al., 2005).

Climate change has had a profound impact on water resources and water management strategies globally, with hydrological drought being a particular challenge (Vicente-Serrano et al., 2014; Rao and Patil, 2016). Changing precipitation patterns, increasing temperatures, and altered seasonal cycles have resulted in more frequent and severe drought events, leading to reduced water availability and quality (Rao and Patil, 2016). Moreover, innovative approaches that account for the impacts of climate change on water resources, including changing precipitation patterns, temperature, and water availability, are crucial in developing sustainable water management strategies that can cope with the increasingly frequent and severe drought events resulting from climate change (Rao and Patil, 2016).

Effective water resources management under extreme climate conditions requires an understanding of seasonal flow discharge patterns. The influence of water management can be significant as it extends beyond borders, and this is due to the fact that water does not recognize boundaries. Climate change has led to alterations in seasonal cycles and precipitation patterns, resulting in more frequent and severe hydrological droughts (Van Loon et al., 2014; Tomaszewski, 2014). Consequently, understanding the timing and variability of water flows in different seasons has become critical for managing water resources sustainably. By considering seasonal flow discharge patterns, water resources management strategies can be designed to catch and store water during high-flow periods, improving water availability during low-flow periods, particularly during droughts (Van Loon et al., 2014).

Study area

The study area – Topľa River in eastern Slovakia, falls within these administrative divisions of Slovakia: Prešovský, and Košický region, and comprises agricultural land and forested areas. It is a right-hand tributary of the Ondava River, and it is classified as an upland/lowland type of river, with a catchment drainage area of 1,544 km² (Vodohospodárska bilancia SR, 2014) and a length of 129.8 km (Fig. 1). The annual rainfall in the Topľa River basin ranges from 600 to 700 mm in lower elevations to approximately 1000 mm in mountainous areas, and it is situated in the temperate climate zone. It falls within three different climatic regions of Slovakia, based on the classification by Lapin. The warm region covers the lower-lying areas, mostly in the southern part of the basin, and is characterized by an average annual number of summer days of over 50 and a daily temperature maximum of over 25°C. The moderately warm region covers most of the study area and spreads mainly in valleys, uplands, and foothills, with an average July temperature of 16°C or more and an average annual number of summer days of less than 50. The cool region covers the northern and northwestern parts, represented by mountains, with a July mean temperature of less than 16°C (Garaj et al., 2019). According to the available data, July is identified as the month with the highest precipitation rate in the eastern region of Slovakia in period 1997–2017 (Predbežné hodnotenie povodňového rizika, 2018).

According to data from the period 1931–2015, the long-term mean daily discharge amounts in Hanušovce nad Topľou (the lowest gauging station on the Topľa River) station was 8.1 $m^3 \cdot s^{-1}$, with a maximum discharge of 449 $m^3 \cdot s^{-1}$ occurring on 06.04.1932. The seasonal variation of the discharge is the dominant characteristic of the Topľa River's hydrological regime, with the highest discharge usually recorded during the spring snowmelt period and summer rainfall events. On the other hand, low flows and occasional ice cover are witnessed during the winter months. For the purposes of this study data from the Bardejov gauging station (103.5 rkm, catchment area of 325.8 km^2) were used. The Slovak Hydrometeorological Institute (SHMI) reported a mean annual discharge of $Q_{a\ 1967\text{-}2000}$ = 2.978 $m^3\ s^{-1}$ for the Bardejov gauging station (Frandofer and Lehotský, 2014). An in-depth understanding of the hydrological characteristics of the Topľa River is critical for effective water management and the mitigation of extreme events like floods and droughts.

Material and methods

Drought analysis

Drought assessment approaches that are hydrological in nature are valuable tools for detecting potential water shortages, and their use is particularly important in the implementation of drought response strategies. To identify, monitor, and evaluate the severity of drought

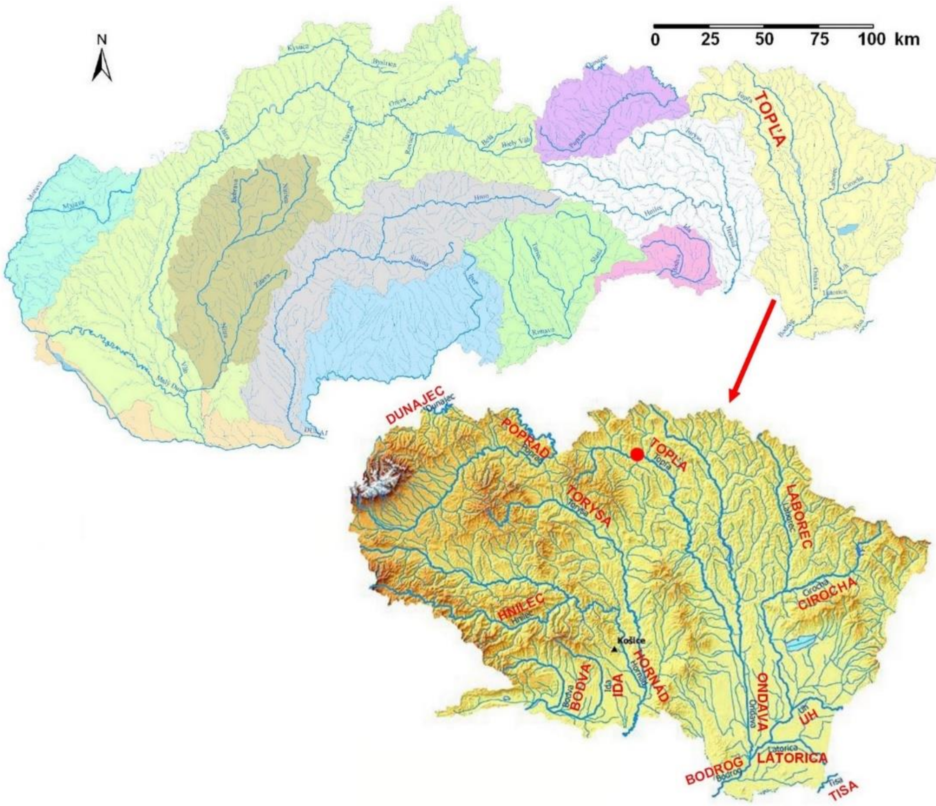

Fig. 1. Map of Slovak Republic – in yellow basin of Bodrog River with subbasin of Topľa River (Plaveniny, 2020), red dot represents gauging station in Bardejov.

events, indices have been developed by researchers worldwide, using several years of meteorological data, including precipitation, air temperature, evapotranspiration, runoff, and soil moisture. Indices provide a way to quantify drought and monitor wet and dry periods. They help to understand the severity, duration, location, and timing of drought events, and they make it easier to communicate this information to diverse audiences. Different indices can be used for various purposes, such as the Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Soil Moisture Anomaly Index (SMAI), Standardized Runoff Index (SRI), and Vegetation Condition Index (VCI). These indices can be used to assess the impact of droughts on agriculture, water resources, and communities and promote sustainable development. Therefore, the use of drought indices is crucial in mitigating the negative effects of drought and providing critical information to manage drought impacts effectively (WMO, 2008; Zhu et al. 2018).

Various hydrological drought indices are utilized to assess and characterize the severity of droughts on water resources. The indices allow for the monitoring of drought's effects on hydrological variables such as streamflow, discharge, and water storage. Standardized Runoff Index (SRI) and the water-bearing coefficient are two frequently utilized hydrological drought indices when only discharge data are available. The SRI is a drought index based on the standard deviation of discharge from the long-term mean, whereas the water-bearing coefficient estimates the available water resources relative to the long-term mean. The water-bearing coefficient is used as the drought index in this study to evaluate the hydrological drought in the study area (Almikaeel et al., 2022, Zhu et. al, 2018).

The water-bearing coefficient method is frequently employed to assess drought. This method calculates the ratio of the annual mean discharge (Q_{avg}) to the long-term mean discharge (Q_a), represented by Q_{avg}/Q_a. The annual mean discharge, Q_{avg}, refers to the average flow of water through a river or stream within a year, while the long-term mean discharge, Q_a, is the average flow of water over a more extended period. This method was applied also in this study for the Topľa River. This coefficient establishes standard values to determine the proportion of mean discharge during a particular period relative to the long-term average. The standard intervals are categorized into three primary groups to identify whether the year is dry, normal, or wet, and subcategories determine the severity of drought and wet years. While the water-bearing coefficient is a useful tool for analyzing drought conditions, other factors such as precipitation patterns, land-use changes, and water demand should be considered to evaluate water availability and management fully (Almikaeel et al., 2022; GWP, 2013). The classification intervals utilized by the Water-Bearing Coefficient method to assess the severity of drought are presented in Table 1.

Table 1. Hydrological status categories according to the water-bearing coefficient values

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 More	Extreme Wet

Time series decomposition

In various fields such as business, economics, engineering, environment, medical, earth sciences, hydrology, climatology, and meteorology, time series data are frequently collected through repeated measurements. These data can be discrete values of a variable, averaged over a particular time interval, or continuously recorded across time. Hydrological time series data often contain a deterministic component, which can be a trend, a jump, a periodic component, or a combination of these, placed on a random component. These data are typically collected at regular intervals, such as hour, day, week, month, season, or year. An example of hydrological time series is streamflow or river-stage readings collected hourly, daily, weekly, monthly, or annually. To decompose a hydrological time series into its level, trend, and seasonality, a time series decomposition method is used (Liu et al., 2021).

Seasonal and Trend Decomposition using Loess (STL)

Seasonal and Trend Decomposition using Loess (STL) is a popular method for time series analysis that decomposes a given time series into three main components: a seasonal component, a trend component, and a remainder or residual component. The seasonal component represents the repeating patterns of the time series that occur over a fixed time interval, such as a year or a month. The trend component represents the overall direction or trend of the time series over time. The remainder component represents the random fluctuations in the data that are not accounted for by the seasonal or trend components.
The STL method involves smoothing the time series using a locally weighted regression method called Loess. The Loess method fits a curve through the data points using a weighted average of neighbouring points. The weights are determined by a tuning parameter, which determines the amount of smoothing. The seasonal component is estimated by taking the moving average of the time series after removing the trend component. The trend component is estimated by taking the moving average of the time series after removing the seasonal component. The remainder component is estimated by subtracting the seasonal and trend components from the original time series.
The STL method can be expressed mathematically as follows. Given a time series y_t, the seasonal component S_t, trend component T_t , and remainder component R_t can be estimated by the following equations:

$$S_t = \sum_{i=1}^{m} w_i \left(m_j y_{t+i-m/2}\right) \quad (1)$$

$$T_t = \sum_{i=1}^{n} w_i \left(n_j y_{t+i-n/2}\right) \quad (2)$$

$$R_t = y_t - S_t - T_t \quad (3)$$

where
m – odd window size for the seasonal component,
n – odd window size for the trend component,
w_i – the weights assigned to each data point,
m_j, n_j – the number of non-missing data points in the *j*-th window.

The weights w_i are determined by the distance between the *i*-th data point and the central point of the window, with closer points receiving higher weights. The tuning parameters for the method include m, n, and the degree of smoothing for the Loess method (Liu et al, 2021; Theodosiou, 2011; Dokumentov and Hyndman, 2015).
The window size utilized in this study is 365 days, which has been chosen to signify an entire year and satisfy the requirement of an odd-sized window.
The STL method is useful for examining the dynamics of drought as it can separate the underlying trends and seasonal patterns from the noise in the data, which can help identify drought periods and their severity by analyzing the residuals from the decomposition.

Results and analysis

Drought analysis

Further analysis of the Topľa River's discharge data reveals important information about the hydrological situation of the river over the period of 1988 to 2020 (Fig. 2). By using the water-bearing coefficient, each year was assessed into three main categories: wet, normal, and dry. The results of the analysis confirm that the river experienced wet hydrological status during 8 years (1989, 2001, 2005, 2006, 2008, 2009, 2010, and 2017), with water bearing coefficients ranging between 110% to 196%. Meanwhile, normal hydrological status was observed during 7 years (1991, 1992, 1997, 1999, 2004, 2014, and 2019), with water bearing coefficients ranging from 89% to 104%. On the other hand, the river experienced dry hydrological status during 18 years (1988, 1990, 1993, 1994, 1995, 1996, 1998, 2000, 2002, 2003, 2007, 2011, 2012, 2013, 2015, 2016, 2018, and 2020), with water-bearing coefficients ranging from 53% to 88%. It can be concluded from Fig. 2 that the year 2003 was the worst in terms of drought. This statement is also confirmed in the "Preliminary Assessment of Flood Risk" report from 2018. Furthermore, it was the year with the most severe meteorological drought in Slovakia since 1881.

Overall, the results indicate that the hydrological situation of the Topľa River tended to be dry during the study period, with a maximum 3 sequential years of wet or normal years. However, the period between 2004 and 2010 was the best period in terms of the level of discharges. Interestingly, even though 2007 is considered as a dry year, the water-bearing coefficient was around the boundaries of the normal level. For further analysis, the discharges of each year were grouped according to the hydrological situation. This grouping allows for a more detailed examination of the discharge data and can help in developing appropriate strategies to manage and optimize the use of water resources in the Topľa River basin.

Seasonality analysis

Seasonality analysis is a useful tool to understand the pattern and trend of a time series. In the current study, the STL method was used to perform time series decomposition on four groups of data, including the general data set over the period 1988–2020, dry years data set containing discharges of 18 years, normal years data set containing discharges of 8 years, and wet years data set containing discharges of 7 years. The seasonal decomposition function was used from the statsmodel library, and the period was set to be 365 to represent a whole year, and the model was chosen to be multiplicative. This enabled the study to determine the seasonal pattern of each hydrological group on an annual basis. The seasonal pattern was extracted from each group and then compared to the seasonality over the whole period. The results showed that the seasonal pattern of the general data set was characterized by a clear peak in discharge during the spring season, followed by a gradual decrease during the summer and autumn seasons, and a relatively low discharge during the winter season. In contrast, the seasonal pattern of the dry years data set showed a gradual increase in discharge from the winter season to the spring season, followed by a sharp decrease during the summer and autumn seasons. The normal years data set showed a seasonal pattern similar to that of the general data set, with a clear peak in discharge during the spring season, followed by a gradual decrease during the summer and autumn seasons, and a relatively low discharge during the winter season. Finally, the wet years data set showed a seasonal pattern with a clear peak in discharge during the spring season, followed by a gradual decrease during the summer season, and a relatively low discharge during

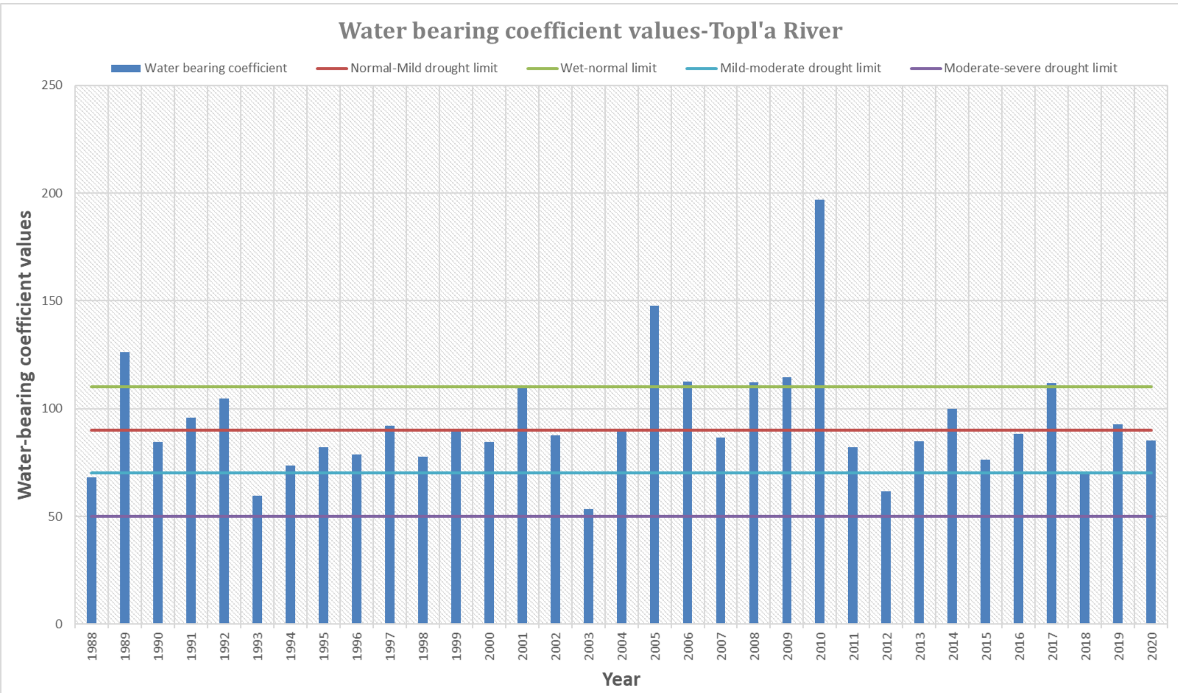

Fig. 2. Water bearing coefficient and its standard values for Topľa River, period 1988–2020.

the autumn and winter seasons. These results indicate that the seasonal pattern of the discharge data varies depending on the hydrological situation of the year.

Based on the analysis of the seasonal discharge of the dry years compared to the general seasonal discharge, it can be concluded that the seasonality of the two groups is very similar. Both groups have relatively low seasonal discharge during the first two months of the year, followed by a steady increase that reaches its peak in mid-April, which is most likely due to the onset of the spring snowmelt in the catchment area. From mid-April to mid-May, the seasonal discharge component decreases slowly, followed by two peaks in May and June, where a significant increase in the seasonal discharge component is observed. However, it is uncertain whether the increase in June can still be attributed to ice melting, as summer storms may especially contribute to the increase in discharge during this time. Additionally, the seasonal discharge component decreases slightly after mid-June, reaching another significant peak in the last week of July and the first week of August, which dominates the discharge component during this period. Following this peak, the seasonal discharge component decreases until it reaches its minimum in October, with a slight increase observed in November and December. The main difference between the dry and general seasonality seems to be the peak in mid-June, which is slightly higher in the general seasonality, and a small peak of discharge in July for the dry seasonality seems to be shifted to August in the general one. Furthermore, the seasonal discharge in late April or the first of May seems to be higher in the general seasonality compared to the dry seasonality (Fig. 3).

The seasonal discharge patterns of the normal and general data sets are quite similar, with some slight differences. Both seasonalities show a relatively low seasonal discharge during the first two months of the year, which can be attributed to low precipitation and snow accumulation during this period. After mid-February, the seasonal discharge component increases slowly, reaching its first peak in late February for the normal seasonality, while in the general seasonality, this peak is less significant. There is a large peak in late February in the normal seasonality, which is absent in the general seasonality, indicating a higher rate of precipitation during this month in normal years than the average rate during the study period. From late February to mid-April, the seasonal discharge component decreases slowly, followed by a significant increase in mid-April that reaches its peak in the first week of May. This peak is most likely due to the onset of the spring snowmelt in the catchment area.

Moreover, there are two significant peaks in seasonal discharge in the normal seasonality, occurring in late April and the beginning of August. These peaks have a higher magnitude compared to the general seasonality, indicating a higher rate of precipitation during these periods. The late April peak is likely related to the spring snowmelt and heavy rainfall, while the August peak may be correlated to summer storms. From mid-May to mid-June, the seasonal discharge component decreases slightly, followed by a peak in late June, which is higher in the general seasonality compared to the normal one. After mid-June, the seasonal component of the discharge decreases slightly, reaching another significant peak in the last week of July and the first week of August, which dominates the discharge component during this period. The seasonal discharge component then decreases until it reaches its minimum in October, with a slight increase observed in November and December. These results demonstrate the impact of precipitation and snowmelt on

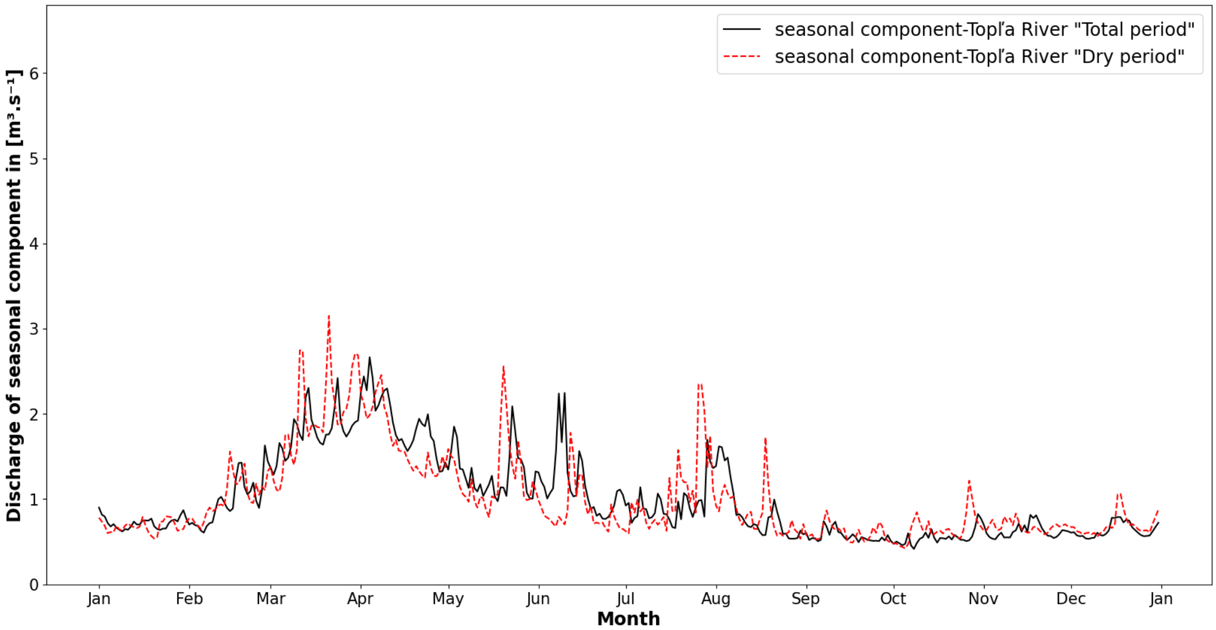

Fig. 3. Comparison of seasonal discharge patterns in dry years and over the whole study period.

the seasonal discharge patterns of both normal and general data sets but also highlight the significance of certain peak periods in the normal seasonality that indicate higher precipitation rates during those periods (Fig. 4).

A comparison of the wet seasonality to the general seasonality indicates significant differences in the seasonal discharge patterns. Although February and late March exhibit slightly higher seasonal discharge in the general period, the wet seasonality shows extremely high seasonal discharge peaks in April and June, significantly higher than those in the general seasonality. The June peak, slightly higher than the April peak in the wet period, demonstrates the combined effect of snow melting and summer storms on the seasonal discharge, affecting the hydrological situation of the river. Additionally, mid-April and mid-July show relatively larger peaks of seasonal discharge in the wet period compared to the general seasonality. Overall, these results emphasize the significance of understanding the hydrological dynamics of the river catchment and the role of precipitation and snow melting in predicting the seasonal discharge patterns. The wet seasonality's analysis highlights the impact of precipitation and snowmelt rate on the seasonal discharge pattern, exhibiting a distinct pattern of seasonal discharge with significant differences in the magnitude and timing of the peaks. While February and late March exhibit slightly lower seasonal discharge components in the wet seasonality, April and June exhibit extremely higher seasonal discharge peaks, suggesting the importance of snow melting and summer storms in shaping the seasonal discharge pattern. Mid-April and mid-July also show relatively larger peaks of seasonal discharge in the wet seasonality, indicating a higher rate of precipitation during these periods. These findings suggest that the wet seasonality of the river is highly influenced by hydro-climatic conditions such as snow accumulation, precipitation, and temperature, affecting the rate of snowmelt and onset of summer storms (Fig. 5). Findings of this study correlates with results stated in other studies dealing with hydrological aspects of Slovak streams, e.g. (Predbežné hodnotenie povodňového rizika, 2018).

The results of the hydrological assessment of the Topľa River over the period 1988–2020 indicate that most of the years can be classified as dry hydrological, as compared to the long-term average discharge of the river. However, it is worth noting that the drought situation in 79% of these dry years is considered as mild drought, with only 21% being classified as a moderate drought. This finding suggests that although the river tends to have a lower-than-average discharge in most years, the severity of drought is not extreme. Nevertheless, the shift of the long-term average towards the dry situation can be correlated to the increasing effect of climate change, and the lack of precipitation and snow in the area. This trend is consistent with the findings of other studies that indicate an overall decrease in water resources in many parts of the world due to climate change. It is essential to continue monitoring the hydrological status of the Topľa River and other water resources in the region to evaluate the impacts of climate change and identify appropriate adaptation measures. The results of this study can provide valuable information for water resource management and planning in the region and could help to mitigate the potential impacts of climate change on water availability.

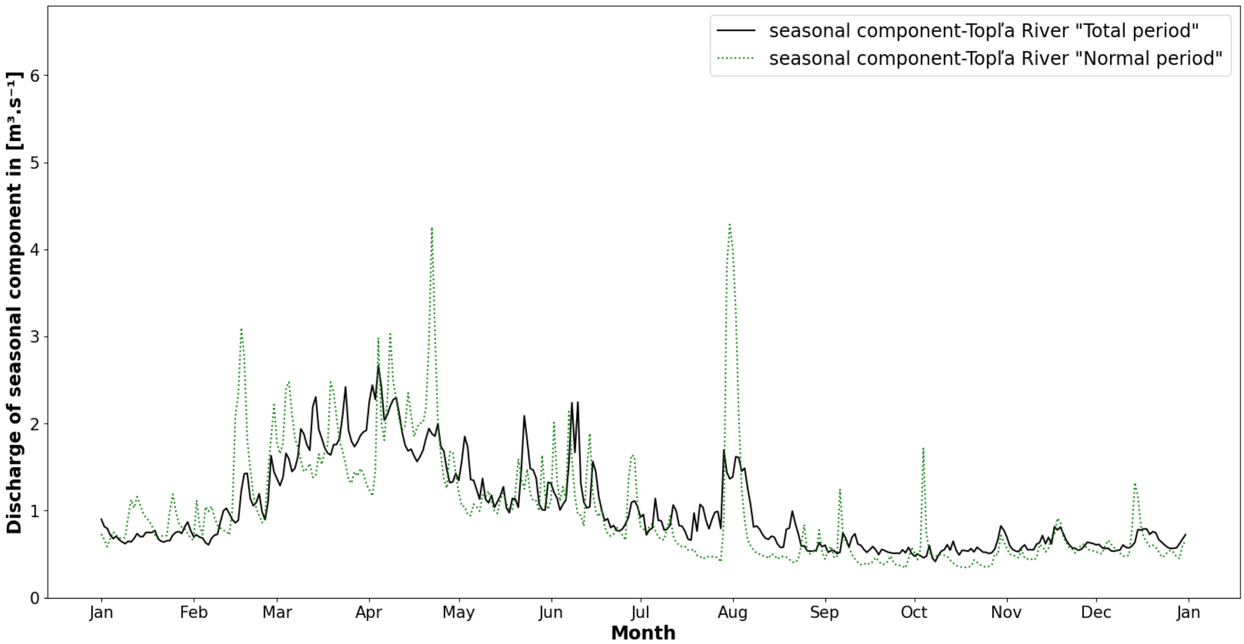

Fig. 4. Comparison of seasonal discharge patterns in normal years and over the whole study period.

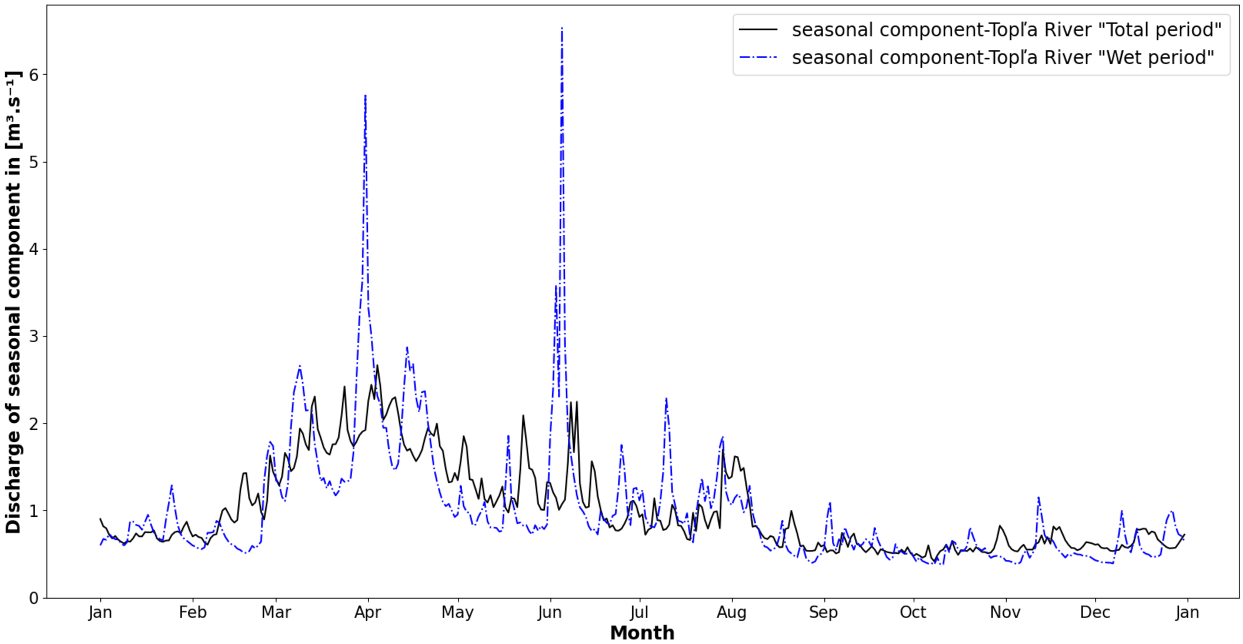

Fig. 5. Comparison of seasonal discharge patterns in wet years and over the whole study period.

Conclusion and discussion

In conclusion, the analysis reveals that the Topľa River's seasonality is undergoing a gradual shift towards dry seasonality, and the results suggest that perhaps changes in the magnitude of precipitation, snowmelt, and summer storms are the key factors behind the changes in seasonal discharge patterns, but these data were not available to assess. The drought analysis supports these findings, with more than half of the study period classified as dry. This shift towards dry seasonality raises concerns about the potential impacts of climate change and global warming on hydrological systems, as rising temperatures can affect snow accumulation and snowmelt, causes heavy storms or flash floods, leading to changes in the distribution of discharge throughout the year. Therefore, further research and monitoring of the hydrological dynamics of the Topľa River and other river systems are essential to better understand the effects of climate change on water resources and to develop effective management strategies to mitigate and adapt to these changes.

It is worth noting that the data set used in this study is imbalanced due to the unequal number of dry, wet, and normal years. While this may limit the conclusions drawn from analyzing the wet and normal groups, the results of the dry group analysis are more reliable due to its homogenous data set and good size. Therefore, the findings related to the dry hydrological status should be given more weight and considered in decision-making processes related to water resource management in the study area. However, future studies should aim to increase the number of wet and normal years to provide a more balanced data set for analysis by adding simulated data.

Very important is to have appropriate data from a long time period, except discharges, it means other hydrological data such as temperatures, precipitations, evaporation, evapotranspiration, snow cover correlated to geology, to terrain slopes, basin agricultural utilization, land cover, water management measures (reservoirs) etc. But these are often not available, or only short time of observation is accessible. This is mostly problem, data insufficiency of small basins, but their influence on the hydrological assessment in larger scale is not negligible. Therefore, in term of these statements, understanding of changed hydrological cycle in climate change conditions is important for the planning of water management strategies.

Such management strategies may include improving water storage and management practices, promoting water-efficient technologies, and reducing greenhouse gas emissions to limit the effects of climate change on hydrological systems. The shift towards the dry seasonality of the Topľa River also highlights the significance of studying other environmental indicators such as groundwater level, precipitation, temperature, and other relevant factors to achieve a comprehensive understanding of the hydrological dynamics of the river. The implications of the shift towards dry seasonality for the ecology of the river and the surrounding environment, as well as for human activities such as agriculture and hydropower generation, are substantial and require immediate attention. Therefore, it is necessary to develop effective policies and management strategies to ensure the sustainable use and management of the river systems in the face of changing climate and hydrological conditions.

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