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Analysis of trends of low flow in river stations in Ipeľ with respect to Málinec reservoir

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The Málinec reservoir plays a key role in the region's drinking water supply and energy stability. However, like any reservoir, Málinec faces a number of challenges that can affect its efficiency and sustainability. One of the critical issues that may affect it is the minimum flows, i.e. the lowest flows that need to be maintained in order to maintain the ecological balance and ensure a reliable water supply. Minimum flows play a crucial role in the protection of aquatic ecosystems by ensuring sufficient oxygen and nutrients for life in rivers and streams, thus contributing to the maintenance of biodiversity. In addition to the ecological aspects, minimum flows are also important from an economic point of view, as they have an impact on water quality and its availability to the population. The Málinec Reservoir on the Ipeľ River was completed in the early 1990s as part of the Slovak Republic's comprehensive water management system. With increasing climatic changes and changes in hydrological cycles, maintaining optimal flows is becoming an increasingly difficult task. This paper focuses on the analysis of minimum flows in the tributaries of the Málinec reservoir. Specifically, we will discuss the use of the lfstat package in the R programming language, which allows a comprehensive analysis of hydrological data. The aim of the paper is to provide an overview of the current state of minimum flows in the Málinec reservoir. Based on the analysis of minimum flows, it will be possible to better understand the dynamics of flows and their implications for management and monitoring.

KEY WORDS: low flow, Ipeľ, water reservoir, lfstat package

Introduction

Reservoirs are a significant source of drinking water worldwide. Construction of reservoirs has shifted from developed countries to these regions in recent years. Reservoirs are an important source of drinking water worldwide. There are currently more than 1 million artificial reservoirs, covering between 6% and 11% of the world's total area of standing water (Feldbauer et al., 2020; Lehner et al., 2011; Połomski and Wiatkowski, 2023). These reservoirs allow water to be stored in catchments, which helps to ensure sufficient water for the regions. In addition to water supply, artificial reservoirs have other benefits such as flood protection, energy use, recreational opportunities and drought control. Asia has the largest number of artificial reservoirs, followed by Africa, Asia and South America (Zhang and Gu, 2023). In recent years, the construction of artificial reservoirs has been shifting from developed countries to these regions.

Nowadays, people are more conscious of environmental issues than ever before, leading to a growing preference for projects that minimize their ecological footprint. However, restricting the construction of multi-purpose reservoirs may not align with the needs of many countries, particularly given the rising demand for water. Worldwide, reservoirs increase water supplies in rivers by more than 700%. These reservoirs are very important because there is not enough water to meet demand, and demand is expected to exceed supply by 40% by 2030. So it is important to take steps to make sure we can keep some water in the region's river basins, and the best way to do this is to build special reservoirs. These reservoirs can help deal with the problems caused by the climate change, but they need to be managed in a clever way to deal with different situations.(Men et al., 2019; Sahoo et al., 2016).

The impact of climate variability on artificial reservoirs is manifested by the deterioration of physical parameters, such as an increase in surface water temperature or a change in stratification. Increases in temperature and changes in the ecosystem exacerbate problems associated with mixing, dissolved oxygen content and the release of nitrogen and phosphorus. Climate variability also increases the risk of cyanobacterial blooms and eutrophication processes. For example, an increase in water temperature causes a rapid increase in plant biomass (Varga et al., 2023; Velísková et al., 2023; Weyhenmeyer et al., 2008). From a drinking water perspective, increases in water temperature and changes in algal blooms degrade water quality and threaten system reliability. Investigating reliability and variability

indicators is important for water utilities, and analysing the vulnerability and adaptability of reservoirs can aid in improving system performance. It is also important to consider future rainfall increases when planning reservoir construction (Chernet et al., 2014).

Several studies have been conducted on low flows in river stations in eastern Slovakia, specifically in the Hornád, Poprad, Bodrava, and Bodrog basins (Zeleňákova et al., 2012). Some studies have shown a decreasing trend in low flows in certain basins over the past few decades. The impact of drought on seasonal flow changes in specific Slovak rivers, such as the Topľa River, has been investigated, highlighting the significant effects of dry years on flow (Almikaeel et al., 2023). The Slovak Hydrometeorological Institute (SHMÚ) plays a crucial role in monitoring drought conditions and low flows across Slovakia, providing monthly flow data and drought monitoring reports. Slovak researchers have contributed to a better understanding of regional hydrology and the characteristics of low flows in Slovak rivers (Grešková, 1999). Water management plans in Slovakia address aspects related to low flow management by considering water availability and ecological flows. The Water Research Institute (WRI) in Slovakia actively conducts research on low flow and ecological flows. Guidelines have also been established to determine minimum ecological flow requirements in Slovak rivers to protect aquatic ecosystems during periods of low flow. Slovakia has been experiencing periods of drought, resulting in significant drops in water levels in rivers such as the Rajčanka and Topľa. The Danube, a major waterway, also experiences low water levels during extended dry periods, impacting navigation and other uses. Fish kills in Vadičovský Brook have been attributed to low flows, high water temperatures, and pollution. Several river basins in eastern Slovakia, including the Hornád, Poprad, Bodrog, and Bodva, are susceptible to declining flows. Meteorological droughts have led to soil moisture deficits across much of the country, causing hydrological droughts characterized by reduced flows and groundwater levels. These hydrological droughts have been officially recognized in Slovakia. Major European rivers, including the Danube, have also experienced low water levels, affecting sectors like river transport. Historical climate studies suggest that Central Europe has faced severe mega-droughts in the past, raising concerns about future events and climate change. With Southern and Central Europe at risk for water scarcity and drought, managing low flows in Slovak rivers has become a critical issue.

The aim of the article was to answer questions concerning the minimum flows on the tributaries to the reservoir as well as downstream, with regard to the main purpose, namely the supply of drinking water. With declining water resources and persistent climatic variability, research on artificial reservoirs for drinking water is important. Although the work primarily focused on drought assessment, a crucial issue was overlooked: the impact of low water levels on artificial reservoirs. Our research aims to address this oversight by providing a comprehensive evaluation of water quantity and quality in such circumstances. The paper concludes by low flow emphasizing the importance of maintaining flood storage at the reservoir and ensuring sufficient drinking water for the population. The operation of the reservoir is focused on maintaining the required flow and water supply.

Material and methods

The present study focuses on the inflow and outflow to the Málinec Reservoir and the regime thereof (Fig. 1). The reservoir was constructed between 1986 and 1993, with the primary function being the provision of drinking water to surrounding districts, in addition to its role as a regulator of the upper Ipeľ River. In addition to its primary function, the feasibility of constructing a pumped storage hydroelectric power plant is currently under consideration; however, this aspect will not be million [m^3] and a surface area of 1.38 [km^2]. The length of the dam is 620 m and its height is 48 m. It has been in operation since 21 January 1994.

Data from four water gauging stations were utilized. (Fig. 1, Table 1). The stations Málinec Smolná 1 and 2 and Málinec – Ipeľ that flow into the water reservoir and Málinec – Ipeľ below the water reservoir. All these stations, have been mounted after construction of the water reservoir itself. We have used daily flow data [Q, $m^3 s^{-1}$] from the 1 November 1994 to 31 October 2022 (Fig. 2). These data were used based on the definition of hydrological year in Slovakia.

The lfstat package (Koffler and Laaha, 2012) is a tool in *R* (R Core Team, 2022) specifically designed for low-flow analysis using daily discharge data. Developed based on the World Meteorological Organisation's publication on low flow estimation, its primary objective is to provide users with functions to compute low flow statistics and produce consistent graphical output. The package serves as a standardised and efficient tool

Table 1. List of used water gauging stations

Hydrological Station	River	Station ID	Latitude (◦N)	Longitude (◦E)	Elevation [m a.s.l.]	Data Availability Flows [Q]	Catchment Area [km^2]
Málinec nad VN	Ipeľ	7398	48.5462	19.6834	348.96	1994–2022	54.24
Málinec	Smolná II	7399	48.5469	19.6657	-	1994–2022	13.28
Málinec	Smolná I	7400	48.5425	19.6679	-	1994–2022	0.1
Málinec pod VN	Ipeľ	7402	48.5358	19.6697	291.41	1994–2022	85.21

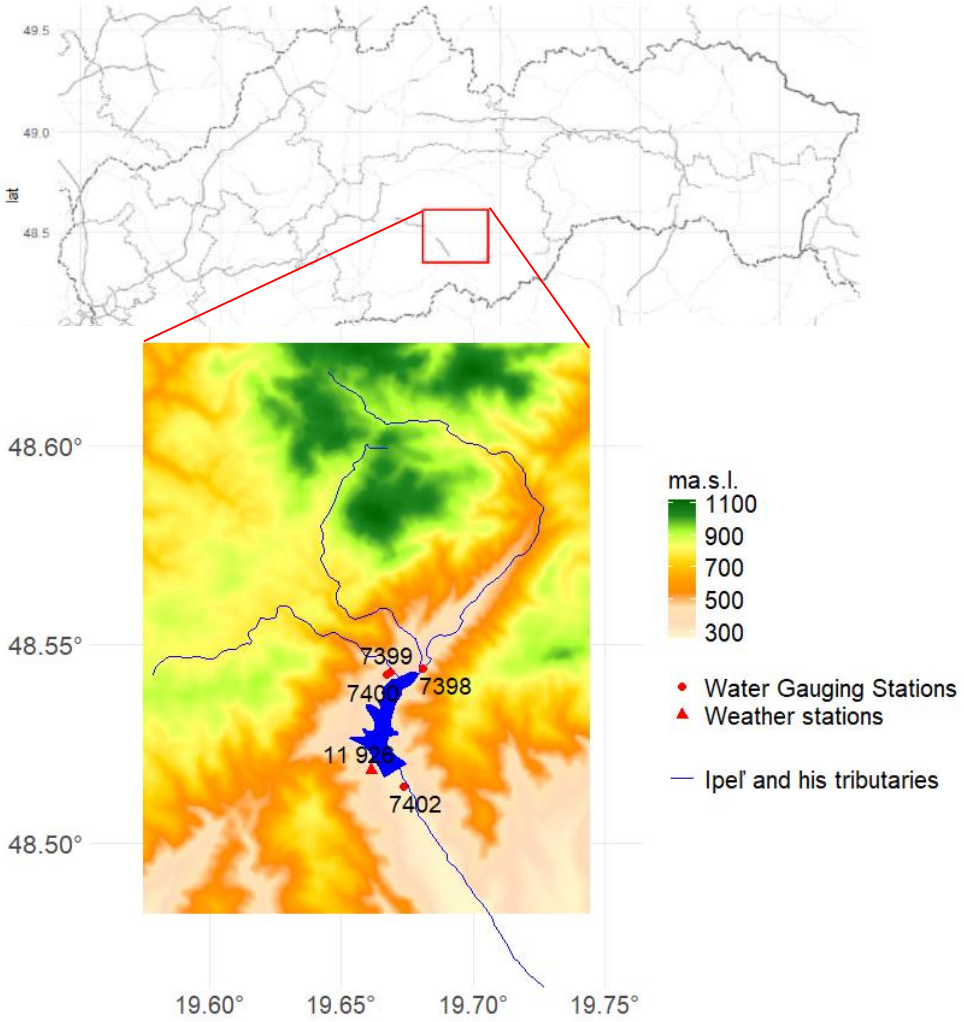


Fig. 1. Location of the area of interest within the Slovak Republic.

for analysing hydrological droughts and low flows, benefiting professionals in hydrology, ecohydrology and water management. Since its release in 2013, the package has been updated to ensure compatibility with the latest versions of R and to address identified shortcomings. The package's integration with the WMO manual (Organization (WMO), 2008) enhances its credibility and facilitates its adoption by the hydrological community. Ongoing maintenance and updates ensure that users always have access to an up-to-date and reliable tool.

The lfstat package introduces the *lfobj* (Low-Flow-Objects) class, which is a special data structure for handling flow data. The lfobj format is implemented as a special data frame with required columns including day, month, year, flow and *hyear*. Optional columns can include *baseflow*. The day, month and year columns identify the date of measurement, the flow column contains the measured flow values and the baseflow column can contain calculated baseflow values. The concept of the hydrological year (*hyear*) is important for the calculation and visualisation of annual indices. The *createlfobj* function is used to create an *lfobj* object, and the readlfdata function allows direct retrieval of data in specific formats. Additional functions such as *hyear_start* and *water_year* are provided to determine the starting month of the hydrological year and to calculate the hydrological year for a given date. The package also includes functions for setting and retrieving flow units, checking for missing values and interpolating missing values. The introduction of the lfobj class provides a structured approach to low flow analysis and the flexibility of the package allows integration into existing workflows.

The package provides a set of functions to calculate various indices and statistics that are key to characterising low flows. Basic statistics include the calculation of mean flow using the *meanflow* function and the calculation of various flow quantiles, such as the 95 percent quantile (*Q95*), the 90 percent quantile (*Q90*) and the 70 percent quantile (*Q70*), which can be obtained using the *Qxx* function. Another important statistic is the Mean Annual Minimum (MAM), calculated using the *MAM* function. To analyse the base flow component of the total discharge, the package provides a *baseflow* function to calculate the base flow of the river and a *BFI* function to calculate the base flow index (BFI). For visualisation of the base flow, the *bfplot* function is provided, which displays the flow hydrograph

together with the calculated base flow hydrograph.
Flow recession analysis is another important part of the package. The recession function allows the recession constant to be determined using the Master Recession Curve (MRC) method or the Individual Recession Segments (IRS) method. The *recessionplot* function produces a diagnostic recession analysis plot to help identify peaks and visualise periods of recession. The *seglenplot* function produces a bar chart of recession segment lengths, which can be useful in selecting the appropriate segment length for analysis. For flow deficit analysis and drought identification, the package originally included a *streamdef* function, but this has been marked as obsolete in recent versions. A recommended alternative is the find_droughts function, which identifies periods of low flow based on a user-defined threshold. The *streamdefplot* function visualises the characteristics of flow deficits, such as duration, occurrence and volume, for a given hydrological year. The lfstat package is primarily designed to process daily flow data. The input data can be in the form of a data frame containing columns with date and flow value, or as a time series (objects of class ts, zoo or xts). For users working with data in specific hydrological formats such as GRDC, HZB (Austria), LFU (Germany, Bavaria) and TU (Technical University of Vienna) formats, the package provides a *readlfdata* function that allows direct loading of data from these sources. The basic function for creating an object of class *lfobj*, which is required for most of the analyses in the package, is *createlfobj*. This function can process data frames and time series and transform them into the desired *lfobj* format. The focus on daily flow data as the standard input format reflects the common availability of these data in hydrological practice and their suitability for low flow and drought analysis.

Flow duration curves (FDCs)

Flow duration curves (FDCs) provide an important insight into the hydrological regime of a watercourse before and after reservoir construction. In this case (Fig. 3), we compare the a) FDC, which represents the flows at the station ID 7398 upstream from the reservoir, and the b) FDC, which captures the condition in station ID 7402 downstream from the reservoir. The curve above the reservoir (left graph) shows the natural flow regime without regulation. The distribution of flows is more variable, i.e. high flows occur less frequently, while low flows occur more frequently. This condition is typical of unregulated rivers, where flows vary according to meteorological and hydrological conditions. The curve below the reservoir (b) reflects the influence of water management and regulation on the flow regime. We observe a more pronounced stabilisation of flows – extremes are moderated, high flows are reduced and low flows are increased compared to the natural regime above the reservoir. This effect is due to reservoir management, where water is stored during high flows and then gradually released into the river during low flows, reducing seasonal variability.
The obtained data (Table 2) provide detailed information on average flow, average annual minimum 7-day flow

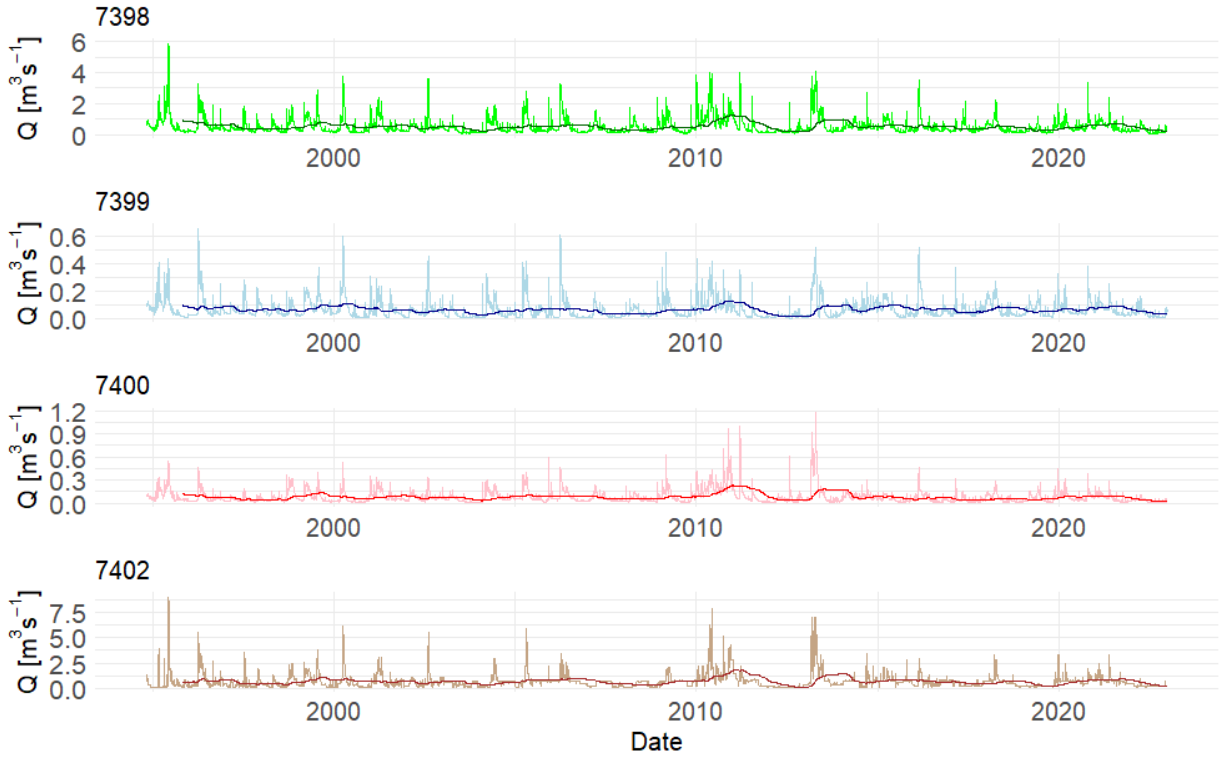


Fig. 2. Average daily flows from selected stations for the period 1995–2022. Daily values (light colour) and 1 – year moving average (dark colour).

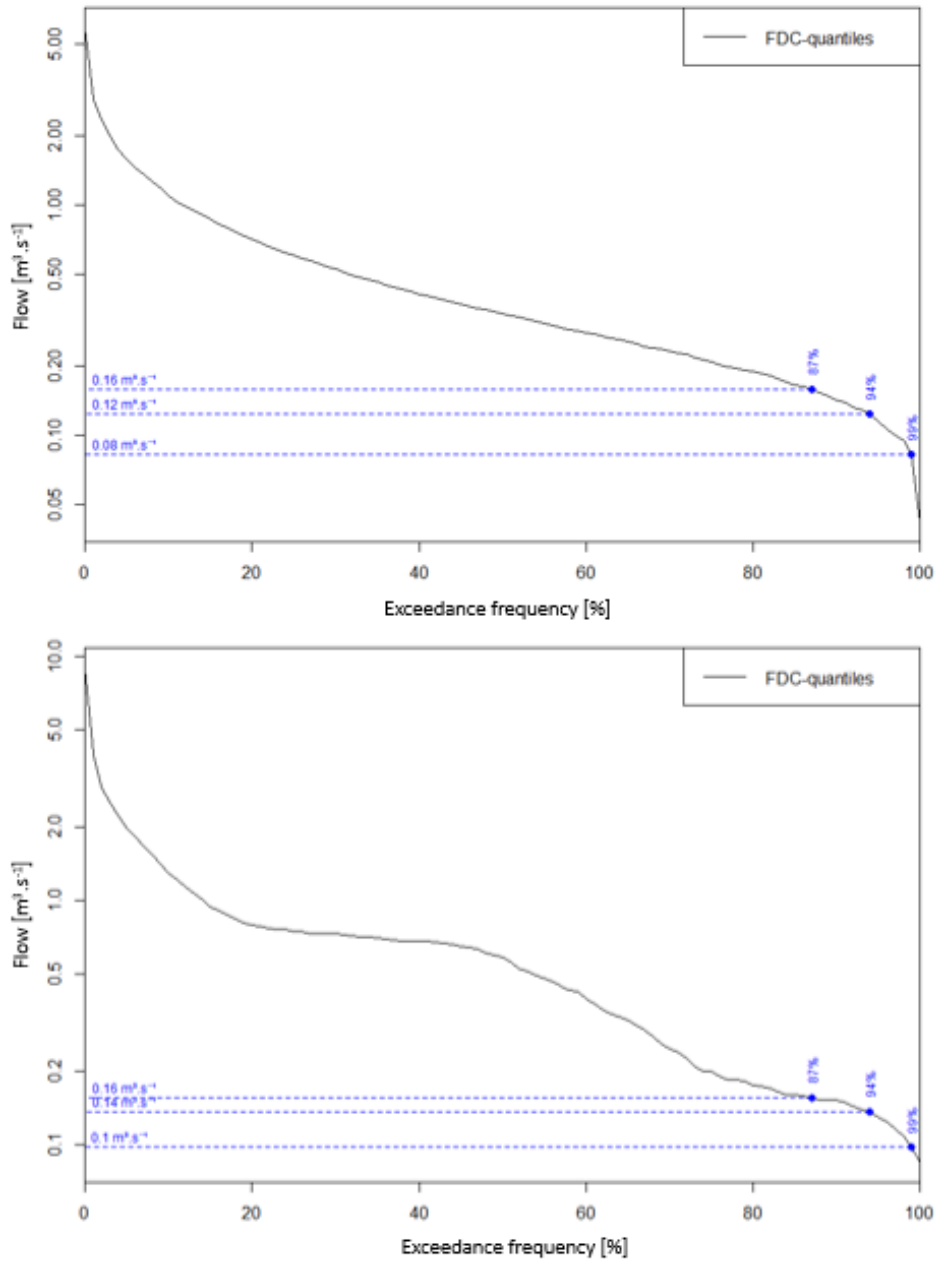


Fig. 3. Flow duration curves for the stations 7398 (a) and 7402 (b).

Table 2. List of hydrological features of water gauging stations used

Station ID	Mean flow [$m^3.s^{-1}$]	Mean Annual Minima 7 – day [$m^3.s^{-1}$]	Base Flow Index	*Q87*	*Q95*	*Q99*
7398	0.5174	0.1316	0.702	0.158	0.114	0.082
7399	0.0635	0.008806	0.691	0.012	0.007	0.003
7400	0.0802	0.01309	0.7206	0.019	0.013	0.006
7402	0.6775	0.1643	0.6958	0.15	0.13	0.098

and the proportion of groundwater to total flow represented by the Base Flow Index (BFI).

Mean flows show considerable variation between monitoring stations. For example, it reaches 0.5174 at station 7398, but only 0.0635 at station 7399, indicating different hydrological regimes within the study areas. Mean annual minimum 7-day flow is also an important parameter, which determines the average minimum flow over a 7-day period and helps to analyse the occurrence of extremely low flows, which are important for

assessing the water stress of ecosystems. The contribution of groundwater to total streamflow is quantified by the Base Flow Index (BFI), which reaches 0.7206 at station 7400, indicating a significant dependence of surface flow on groundwater.

In the next part of the paper we analyse the monthly changes in water flows Q [m^3. s^{-1}] in the Málinec reservoir basin, the calculations were performed using the *Qxx()* function from the lfstat package. This function calculates quantile values, namely 1%, 5% and 13%, which provide important information on extreme and typical values of flows at different time periods. The graphical representation in (Fig. 4) includes data from gauging stations 7398, 7399, 7400 and 7402 and includes three datasets, X13, X5 and X1, representing the individual quantiles. The results indicate a distinct seasonal dynamics of flows, with the highest values systematically occurring in the months of April at the stations at the inlet to the water reservoir. For station 7402 this is May and June. This phenomenon is likely related to the period of snowmelt in the mountainous areas of the watershed and the increase in precipitation that typically occurs in the spring. During the summer months, flows stabilize at lower values, which can be attributed to increased evaporation and decreased precipitation.

The marked differences between sites indicate specific hydrological and geomorphological conditions in different parts of the catchment. Water Gauge stations 7398, 7399 and 7400, located at the inlet to the reservoir,show higher variability in flows. In contrast, the flows downstream of the reservoir (station 7402) are regulated, which is reflected by a smaller range of seasonal variations and a shift in maximum values. This trend highlights the importance of water management in stabilizing reservoir outflows, thereby minimizing the risk of extreme flood events and ensuring consistent availability of water resources. Curves X13, X5 and X1 show the distribution of flows based on quantile values. The X13 value (13th percentile) represents the higher flows that occur in only about 13% of the observations, while X5 (5th percentile) shows flows in the lower part of the distribution. X1 (1st percentile) then represents the lowest outliers of flows that occur in only 1% of the observations. This method allows a more accurate analysis of extreme hydrological situations such as low or high water episodes.

Droughts

The analysis of hydrological drought, based on the find_droughts function of the lfstat package, enables the identification of periods when discharge falls below the *Q95* threshold. This method offers a comprehensive view of dry episode dynamics within the studied catchments. The results illustrated in Fig. 5 highlight significant differences between stations situated upstream of the reservoir and station 7402, positioned downstream. The presence of the reservoir plays a crucial role in flow regulation, effectively reducing

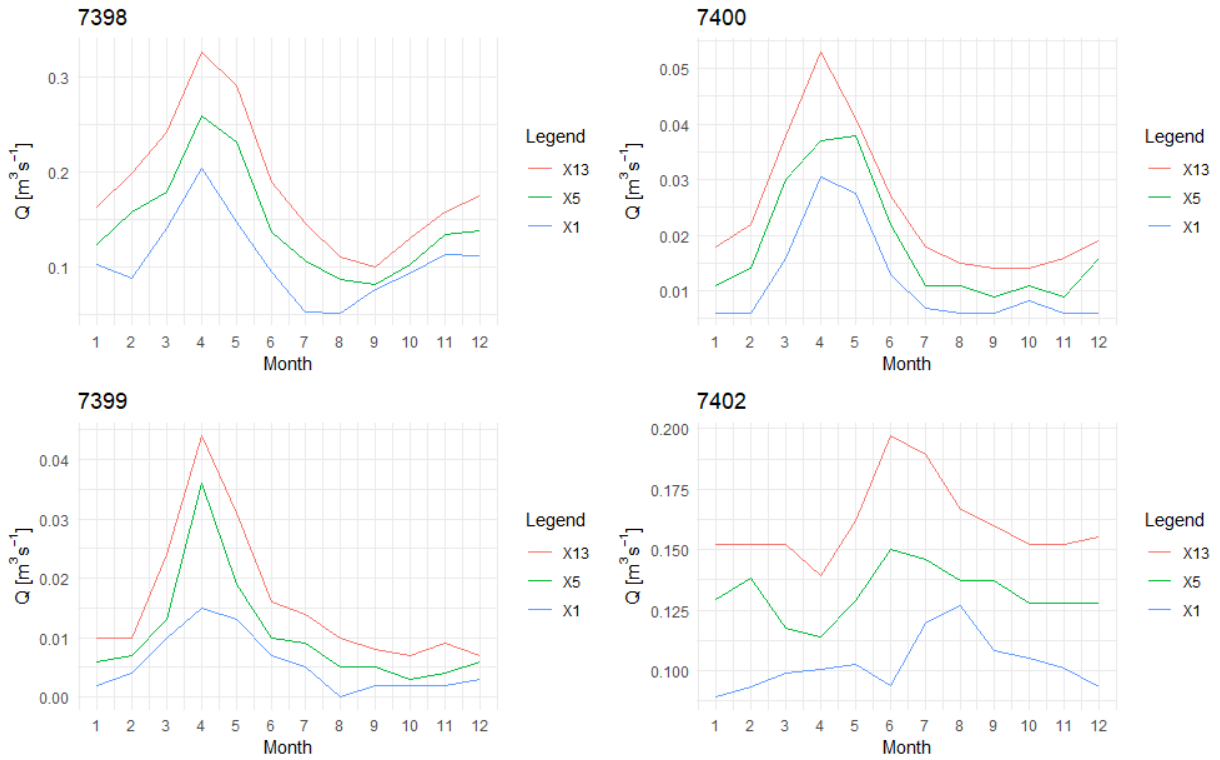


Fig. 4. Monthly variability of flow ***Q [m³·s⁻¹]*** *for selected stations. The graphs display flow values for three different non-exceedance probabilities (**0.87, 0.95, and 0.99**). The curves represent individual probabilities: Red (X13) – probability 0.87, Green (X5) – probability 0.95 Blue (X1) – probability 0.99.*

the occurrence of extreme low flows. This regulatory effect substantially influences the hydrological regime in the lower portion of the catchment. A noticeable variability exists in both the duration and frequency of droughts across stations, indicating that local hydrogeological conditions significantly shape extreme flow scenarios. At certain locations, dry periods are becoming longer, possibly reflecting long-term climatic changes and evolving runoff patterns. The *qmin* values displayed in the graphs represent minimum flows recorded during identified drought periods. Most upstream stations exhibit relatively low variability in qmin, suggesting similar responses to drought events among these catchments. In contrast, station 7402, located downstream, shows higher minimum flows than other sites, reinforcing the reservoir's stabilizing effect and its role in mitigating extreme drought impacts.

The Mann-Kendall trend test further examines long-term changes in *qmin* values across selected stations. The findings reveal that station 7398 exhibits a statistically significant downward trend, indicating a gradual decline in minimum flows over time. Meanwhile, stations 7399 and 7400 show no significant trend, suggesting relatively stable minimum flows. For station 7402, updated results indicate no significant trend (p = 0.1382), implying that minimum flows downstream of the reservoir might be more stable than previously expected. While the reservoir effectively regulates

Table 3. Results of the Mann-Kendall Trend Test for Minimum Flow (*qmin*) at Selected Stations

Station ID	*Z*- value	*p*-value	S	varS	Tau	significance of trend
7398	-2.5321	0.01134	-210	6812.67	-0.2867	Significant downward trend
7399	0.40166	0.6879	25	3570.33	0.0563	No significant trend
7400	-0.48749	0.6259	-29	3299	-0.0682	No significant trend
7402	1.4824	0.1382	57	1427	0.228	No significant trend

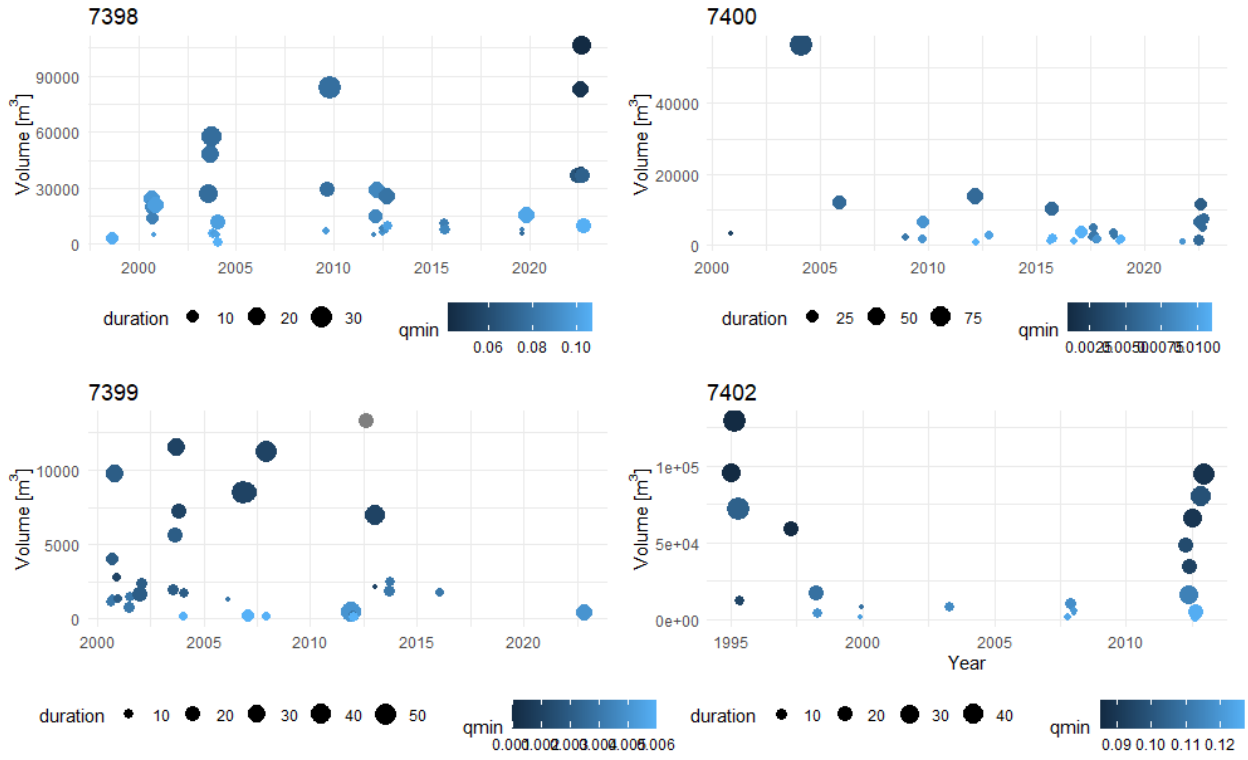


Fig. 5. Occurrence of drought events in selected station identified using the function "find_droughts". The graph displays drought volume [m³] on the Y-axis, while the X-axis represents the years in which the events occurred. The size of the circles indicates the duration of the drought event (in days), and the color of the circles represents the minimum flow recorded during the event.

extreme low-flow conditions, it does not necessarily contribute to a long-term decline in *qmin* at this site.Overall, a distinct trend toward longer dry periods is observed upstream of the reservoir, where prolonged drought durations and low *qmin* values point to an increasing water deficit. The lowest *qmin* values suggest that, in certain years, extended drought periods could pose critical challenges for maintaining the ecological stability of watercourses. These patterns may have significant implications for aquatic fauna, water quality, and water resource availability.

Conclusion and Results

The hydrological analysis of the Málinec reservoir and surrounding gauging stations offers valuable insights into the long-term effects of water management on flow regimes and drought occurrence. The presence of the reservoir plays a crucial role in moderating extreme flows, reducing peak discharges while sustaining higher minimum flows, effectively stabilizing hydrological variability in the lower part of the catchment. Flow duration curves (FDC) highlight the differences between upstream and downstream stations, showing greater variability in natural conditions versus a more regulated flow regime below the reservoir. Drought analysis using the find_droughts function from the lfstat package reveals an increasing trend in drought duration and decreasing minimum flows (*qmin*) at stations upstream, indicating a growing water deficit. The Mann-Kendall trend test confirms a statistically significant downward trend in *qmin* at station 7398, while stations 7399 and 7400 show no significant trend. Station 7402, located downstream, benefits from the stabilizing effect of reservoir releases, mitigating the impact of extreme droughts. Seasonal flow variations display peaks in April-May for upstream stations, while May-June peaks occur at station 7402, likely influenced by snowmelt and spring precipitation in the mountainous areas. Summer months exhibit lower flow stability, emphasizing the need for adaptive management strategies. The regulation of reservoir outflows ensures more consistent water availability, reducing seasonal extremes and preventing hydrological stress. Overall, while reservoirs provide crucial stabilization, emerging drought risks in upper catchments necessitate long-term monitoring and adaptive water management strategies to mitigate future deficits. Addressing these shifting hydrological dynamics through sustainable water governance will be key to ensuring resilience in river systems amid ongoing climatic variations.

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