Changes in Selected Low-Flow Characteristics in the 2001–2015 Period Compared to the 1961–2000 Reference Period in Slovakia

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Abstract: This research is focused on the assessment of drought on surface watercourses in Slovakia. Low-flow characteristics and their changes in the 2001–2015 period in comparison with the 1961–2000 reference period were evaluated at selected representative water-gauging stations. Two different methods were used to calculate the flow duration curves (FDCs): the standard method, based on mean daily discharge data series for the whole evaluated period in descending order, and the alternative method, based on first calculating the values of FDCs for each year of the assessed period and then averaging the corresponding percentile values. The changes were evaluated for selected percentiles of the FDCs (330-, 355-, and 364-day discharge). The number of days with the mean daily flow below the set limits and the seasonality of their occurrence were assessed. The results show significant changes in cases of both methods in the compared time periods, while differences in individual regions of Slovakia were also found. The weakness of the standard method is in allowing the values of the smallest quantiles to be influenced by a small number of long-lasting drought episodes. The alternative method eliminates the aforementioned shortcoming and could be used to determine the ecological flows in Slovakia.

Keywords: low flow; drought; flow duration curve

1. Introduction

Drought and water scarcity is a topic that has always been considered a serious problem in water management in many countries. However, it resonates even more in previous years due to the increasing evidence of climate change impacts on the hydrological regime. The air temperature from 2015 to 2021 was the warmest on the record [1] and is continuously predicted to rise [2–4], which will possibly lead to increased rate of evapotranspiration, thus escalating the continuous deterioration of river ecosystems and the risk of increased appearance of low flows and droughts [5,6].

Low flows and droughts are being studied from various points of view, e.g., statistical test and trend analysis [7–10], variations of flow duration and flow duration frequency analysis [11–13], and the use of indicators of hydrological alteration [14].

The assessment of the changes in the runoff regime, especially in the area of low flows, is also important for appropriate setting of the so-called ecological flows [15]. Ecological flow is a governance threshold for maintaining the sustainable status of river ecosystems while managing the increasing demands of human consumption, as the projected global water demand increase is 55% between 2000 and 2050 [16]. The establishment of such a threshold widely varies from country to country by definition and resulting methodology, and there are still a number of questions and uncertainties to be addressed [17–22].

Even though droughts and low flows have also been studied in Slovakia [23–27], the methodology for nationwide implementation of ecological flows is still being discussed by Slovak experts in various fields (e.g., management of dams, fisheries, energy consumption, ecology, etc.).

Therefore, this work is part of a broader study conducted by the Slovak Hydrometeorological Institute (SHMI), focused on the assessment of drought on surface watercourses in Slovakia [28]. The article is focused on the methods driven mainly by the statistical analysis of the hydrological data: the flow duration curves (FDCs) in the area of low flows and the assessment of non-flow characteristics of drought (number of days below a selected threshold and the seasonality of their occurrence). The characteristics of the 2001–2015 period were also compared to those of the 1961–2000 reference period to identify the potential changes in the hydrological regime. The outputs of these analyses are important for water management, setting the design hydrological characteristics for water management decisions, planning and proposals of appropriate measures, and are intended to be used as a hydrological basis for the development of a new methodology for setting the values of ecological flow limits in Slovakia.

2. Materials and Methods

We selected 42 representative water-gauging stations (WSs) in Slovakia with a period of observation since at least 1961 and with little or no anthropogenic influence on discharges. For a more even coverage of the territory of Slovakia, we also added 21 stations with the hydrological regime partially influenced by human activities for evaluation because, especially in lowland areas, the regime at most WSs has been influenced by abstractions for agriculture and industry as well as by manipulations on water reservoirs. The results from these WSs were considered with respect to this fact and were not directly used to generalize the results. The spatial distribution of the selected WSs is presented in Figure 1 and the catchment characteristics are summarized in Table 1.
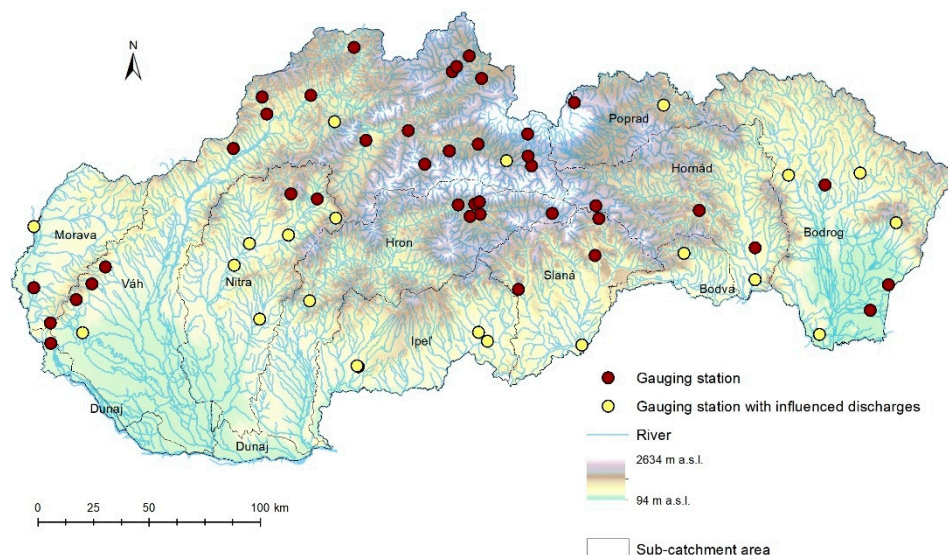
Figure 1. Location of the selected water-gauging stations.

For the selected stations, we evaluated the low-flow characteristics and their changes between the 2001–2015 and 1961–2000 periods.

In this work, we compared FDCs calculated using two methods:

1. Method 1: The standard method (covered by national Slovak Technical Standard STN 75 1410-1:2008 in Section 5.1.3) [29], is based on mean daily discharge (Q_d) data series for the whole evaluated period, sorted in descending order. Numerical values of the FDC are given for the average durations, when the mean daily discharge is reached

or exceeded. In Slovakia, the average durations are most commonly given as the number of days in the year; such a procedure can only be applied to a year and a multiannual period. In many other countries, the percentage of duration in a period is used more often. The numerical discharge values of the crossing line corresponding to the selected durations in days (M) are referred to as M-day discharges (Q_{Md}), e.g., the characteristic Q_{355d} (corresponds to 97.2%) is often used as a limit in water abstraction permits in water resource management in Slovakia.

2. Method 2: An alternative method (also mentioned in STN 75 1410-1:2008 in Section 5.1.9) of [29], is based on the calculation of FDCs for individual years of the evaluated period. Subsequently, the FDC for the multiannual period is determined by calculating the averages of the discharge values obtained from the FDCs of individual years, corresponding to the same values of M. The values calculated using this method were denoted as $Q_{Md,rr}$ in this contribution.

Table 1. Catchment characteristics of the selected water-gauging stations.

Sub-Catchment	Average Area (km²)	Average WS Altitude (m a.s.l.)	No. of WSs	No. of Influenced WSs
Morava	12,088.2	145.3	2	1
Dunaj	65,669.2	224.8	2	0
Malý Dunaj	40.6	217.2	4	1
Váh	252.5	528.2	19	2
Nitra	563.9	242.4	7	5
Hron	694.7	512.1	7	1
Ipeľ	351.8	157.9	4	3
Slaná	535.1	288.2	4	1
Hornád	1551.3	367.5	4	1
Bodva	90.2	310.2	1	1
Bodrog	2583.3	152.1	7	4
Poprad	648.7	707.6	2	1

The change was evaluated for both methods for the selected percentiles from FDCs: Q_{270d} (73.9%), Q_{330d} (90.3%), Q_{355d} (97.2%), and Q_{364d} (99.7%). These values of Q_{Md} and $Q_{Md,rr}$ computed for the 1961–2000 reference period were subsequently used as the thresholds for the evaluation of non-flow characteristics of drought episodes in assessed time periods.

The non-flow characteristics are another way to assess the low-flow hydrological regime. These characteristics include temporal and volume characteristics [30]. They relate to the time of occurrence of dry periods (occurrence dates, number of days of low-flow periods, and duration of drought episodes in the evaluated period) and deficit volumes (volumes of water missing on dry episode days for a given flow limit) [24].

We analyzed the number of days with mean daily discharges below the set limits and the duration of the longest drought episodes as well as their timing. The input parameters include the discharge threshold, minimum duration of a low-flow event (5 days), and maximum short-time interruption of a low-flow event (exceedance of the threshold; 3 days).

3. Results

3.1. Comparison of the Results of the Two Methods for Calculation of the FDCs ($Q_{Md,rr}$ vs. Q_{Md})

As a first step, the values of the FDCs were computed for both methods for the 1961–2000 period. The ratios between the M-day discharges in the low-flow area determined using Method 2 and their counterparts obtained using standard Method 1, commonly used in Slovakia (i.e., values $Q_{330d,rr}/Q_{330d}$ to $Q_{364d,rr}/Q_{364d}$), are significantly higher than 1, as shown in Figure 2. However, the differences vary in the individual sub-catchments as well as at the individual WSs.
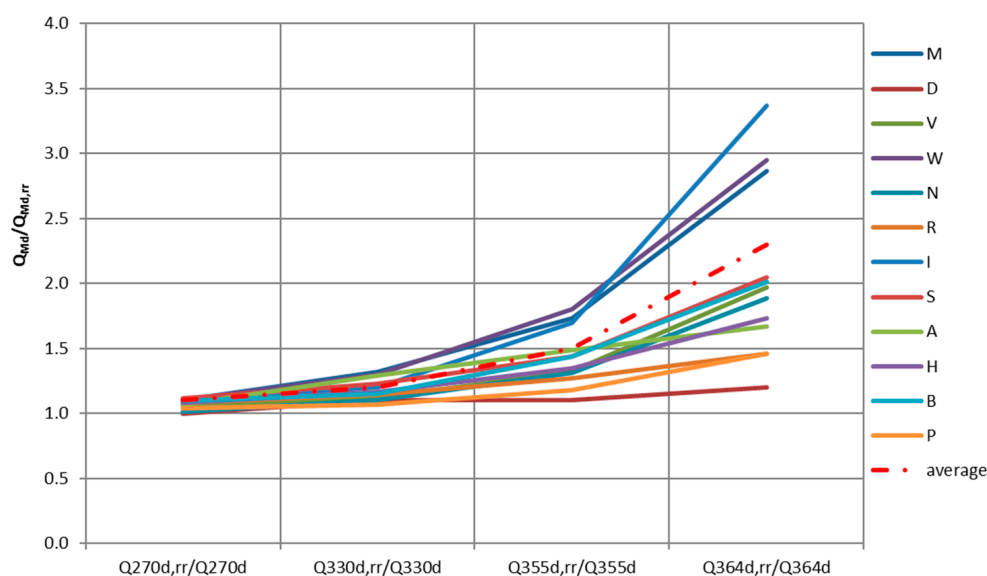
Figure 2. Comparison of Q_{Md} values calculated using both methods in the 1961–2000 period (M—Morava, D—Danube, V—Váh, W—Malý Dunaj, N—Nitra, R—Hron, I—Ipeľ, S—Slaná, A—Bodva, H—Hornád, B—Bodrog, P—Poprad).

After excluding a few outliers (e.g., a small stream in a Danube sub-catchment, where a little change in the value of Q_{364d} corresponds to a change of several hundred percent), the mean values of the ratio $Q_{Md,rr}/Q_{Md}$ for the 1961–2000 period were processed for the sub-catchments of Slovakia depicted in Figure 1. For $Q_{364d,rr}/Q_{364d}$, the highest values were detected in the Ipeľ (3.4), Malý Dunaj (2.9), and Morava (2.9) sub-catchments. The lowest values of $Q_{364d,rr}/Q_{364d}$ occurred in the Danube (Danube River; 1.2), Poprad (1.5), and Hron (1.5) sub-catchments. The average value of the ratios for the whole Slovak territory was 2.0.

For $Q_{355d,rr}/Q_{355d}$, the mean values of the ratios in the assessed sub-catchments (after the exclusion of the most significant outliers) were highest in the Malý Dunaj (1.8), Morava (1.8), and Ipeľ (1.7) sub-catchments. The lowest values of the ratio $Q_{355d,rr}/Q_{355d}$ were observed for the Danube River (1.1) and the Poprad River (1.2) sub-catchments. The average ratio for the whole Slovak territory was 1.4.

For $Q_{330d,rr}/Q_{330d}$, the mean values in the sub-catchments ranged from 1.1 (Danube sub-catchment) to 1.3 (Morava, Malý Dunaj and Bodva sub-catchments). For other quantiles (i.e., in the area of higher flows), the values from these two methods gradually approached each other; for Q_{270d}, the values for the sub-catchments remained in the range between 1.0 and 1.1.

The higher values of the M-day discharges in the low-flow area determined using Method 2 compared to the M-day discharges determined using standard Method 1 may indicate the weakness of the standard method used for low-flow water quantiles, especially for Q_{364d} and Q_{355d}. This method (No. 1) leads to lower values in the low-flow area because, in the series of sorted data, the smallest values often come from only few dry periods, sometimes only from one extremely dry period with a long duration [31]. Method 2 thus includes the inputs of the driest periods from each year, not just several extreme years of the evaluated period. However, it should be noted that the dry periods from individual years do not have to come from the same period of the year (same seasonality). This, however, applies to both methods used.

3.2. Selected Characteristics of the 2001–2015 Period Versus Those of the 1961–2000 Reference Period

The evaluation of data of selected water-gauging stations in the 2001–2015 period versus the 1961–2000 reference period by the standard method showed a higher number of stations with a decrease in $Q_{330d,2001-2015}$ compared to $Q_{330d,1961-2000}$ (Figure 3).
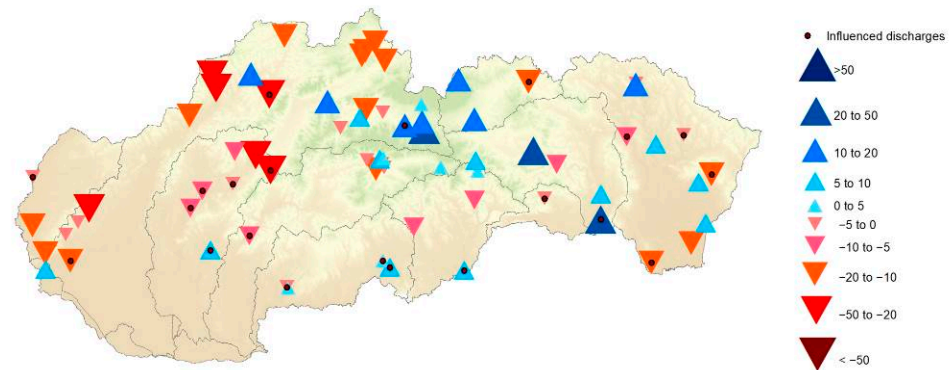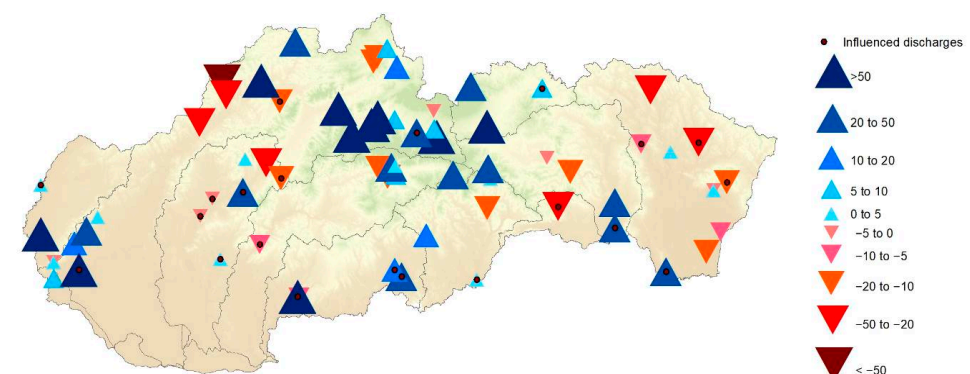

Figure 3. Changes in values of Q_{330d} from 2001–2015 vs. 1961–2000 (% of increase/decrease).

An increase in the values prevail in $Q_{355d,2001-2015}$ and $Q_{364d,2001-2015}$ in comparison with the corresponding reference values (Figures 4 and 5), with a more significant increase related to Q_{364d}. The increase for all quantiles is noticeable, especially in the area of the northern parts of central and Eastern Slovakia (upper parts of the Váh, Hornád, and Poprad sub-catchments). The decline is noticeable in the eastern part of Slovakia (Bodrog sub-catchment) and in the southern and western parts of Slovakia. For Q_{364d}, it is obvious that the number of stations with increasing values significantly exceeds the number of stations where the value of Q_{364d} decreased in the evaluated period compared to the reference period (Figure 5).
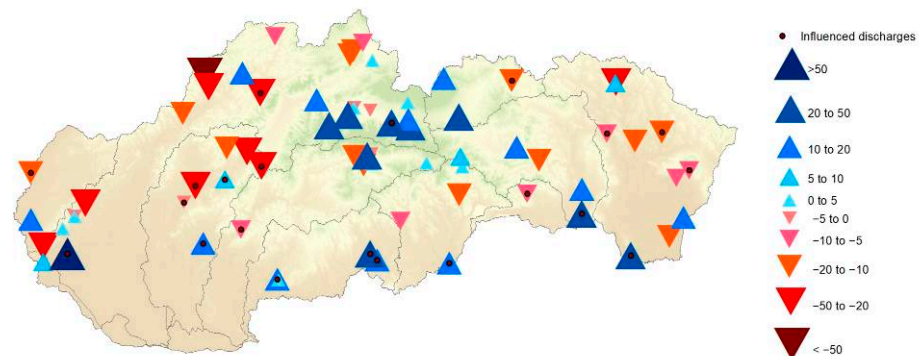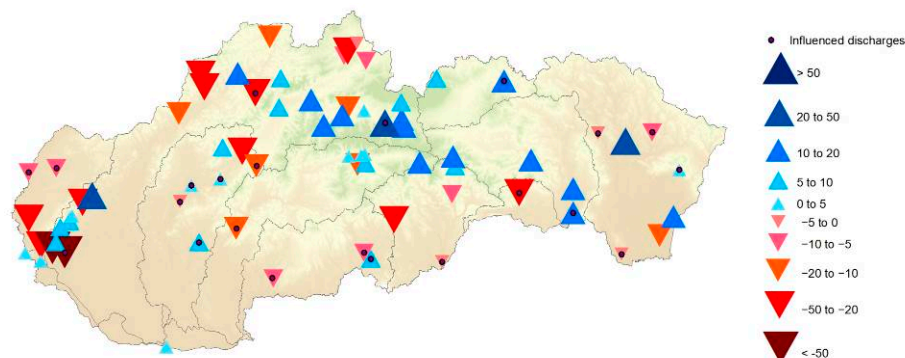

Figure 4. Changes in values of Q_{355d} from 2001–2015 vs. 1961–2000 (% of increase/decrease).

Figure 5. Changes in values of Q_{364d} from 2001–2015 vs. 1961–2000 (% of increase/decrease).

The results differ for the alternative method in comparison with the standard method. The number of stations with an increase in the values of the evaluated quantiles $Q_{Md,rr}$ in the 2001–2015 period compared to the 1961–2000 reference period prevails for all quantiles. For the Q_{364d} quantile, the increases in the evaluated period are more significant for the standard method than for Method 2 (Figure 6).

Figure 6. Changes in values of $Q_{364d,rr}$ from 2001–2015 vs. 1961–2000 (% of increase/decrease).

The increase in the values for all quantiles for the representative stations in comparison with the reference period is manifested mainly in the east of Slovakia, in the Hornád, Slaná and, Poprad sub-catchments. The decrease in the values of $Q_{330d,2001–2015,rr}$ compared to $Q_{330d,1961–2000,rr}$ is most numerous in the Morava and Váh sub-catchments.

3.3. Non-Flow Characteristics

In this study, we assessed the non-flow characteristics based on the number of days with a mean daily discharge below the specified limits. We set the following Q_{Md} values as the limits: Q_{270d}, Q_{330d}, Q_{355d}, and Q_{364d}, calculated using both methods mentioned above. The limits were set for the 1961–2000 reference period. We analyzed the number of days of low-flow episodes in the 1961–2015 period, as well as the change in the occurrence between the 2001–2015 period and the 1961–2000 reference period.

The total number of days with mean daily discharge under individual limits varied in relatively wide ranges (Table 2), while the differences also occurred at WSs within one sub-catchment.

Table 2. The number of days with $Q_d <$ limit (1961–2015); statistics from all WSs.

Limit	Q_{270d}	Q_{330d}	Q_{355d}	Q_{364d}	$Q_{270d,rr}$	$Q_{330d,rr}$	$Q_{355d,rr}$	$Q_{364d,rr}$
mean number of low-flow days	5163	1896	556	66	5886	2941	1745.5	1183
minimum number of low-flow days	3367	832	107	6	5011	1999	1015	566
maximum number of low-flow days	6992	2663	1196	266	8843	6066	5043	3821
mean number of low-flow days/year	93.9	34.5	10.1	1.2	107	53.5	31.7	21.5
mean number of days of longest low-flow event	200	126	73	26	212	159	124	101
minimum number of days of longest low-flow event	92	67	42	6	92	76	53	48
maximum number of days of longest low-flow event	304	248	178	72	372	273	270	236

The differences are higher in connection with low values of limit discharges (Q_{364d} and Q_{355d}). When comparing the number of days of low-flow events for the limits defined by Method 1 to the results of Method 2 (Table 2, Figure 7), higher numbers of such days can be seen for the M-day discharges evaluated by Method 2. This results from the fact that the values of these limits are higher. The ratios of the average number of days (per year) of low-flow events for the limits of Method 2 to the average number of days for the limits of Method 1 are as follows:
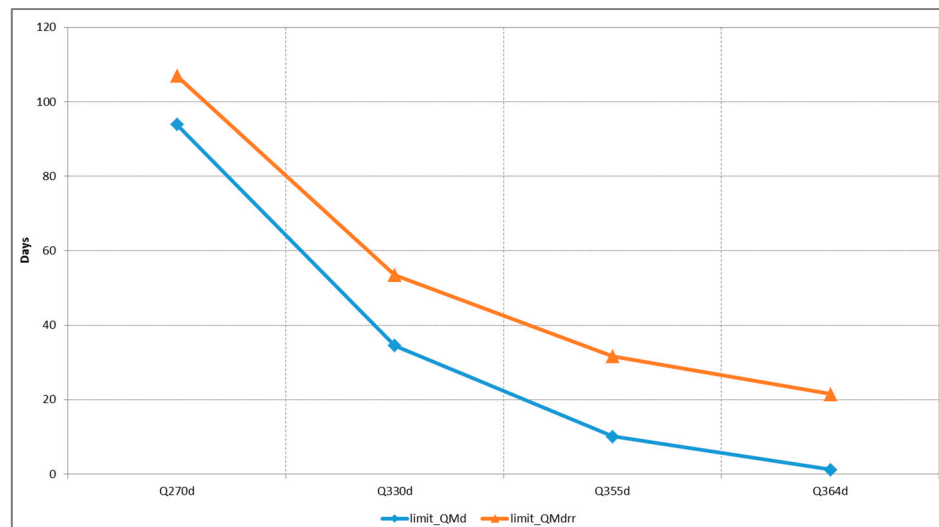
Figure 7. Average number of days with Q_d < limit from 1961–2015 (comparison for limits Q_{Md} and $Q_{Md,rr}$).

Days for limit $Q_{364d,rr}$/days for limit Q_{364d}: 17.9
Days for limit $Q_{355d,rr}$/days for limit Q_{355d}: 3.1
Days for limit $Q_{330d,rr}$/days for limit Q_{330d}: 1.6
Days for limit $Q_{270d,rr}$/days for limit Q_{270d}: 1.1

Significant differences due to the methods of calculation are also in the ratios of the number of days for $Q_{Md,rr}$ to the number of days for Q_{Md} for individual sub-catchments. After the exclusion of extreme outliers identified using more detailed analyses, we can see that for the Q_{364d} limits, the largest values of these ratios are in the sub-catchments of the Malý Dunaj (62.2) and Morava (49.6) rivers; the smallest ratios occur in the Bodva (5.7), Poprad, Nitra, Danube (only WS Bratislava—Danube considered), and Bodrog sub-catchments (Table 3).

Table 3. Comparison of the ratios of limit values $Q_{Md,rr}/Q_{Md}$ (1961–2000) and the ratios of related number of days of low-flow events; mean values for sub-catchments (1961–2015).

| Sub-Catchment	Q_{270}		Q_{330}		Q_{355}		Q_{364}	
	$Q_{270d,rr}/Q_{270d}$	Low-Flow Days Ratio	$Q_{330d,rr}/Q_{330d}$	Low-Flow Days Ratio	$Q_{355d,rr}/Q_{355d}$	Low-Flow Days Ratio	$Q_{364d,rr}/Q_{364d}$	Low-Flow Days Ratio
M	1.1	1.2	1.3	2.1	1.8	6.1	2.9	49.6
D	1.0	1.1	1.1	1.3	1.1	2.6	1.2	16.2
V	1.1	1.1	1.1	1.4	1.3	2.8	2.0	18.1
W	1.1	1.1	1.3	1.8	1.8	4.6	2.9	62.2
N	1.0	1.0	1.1	1.4	1.3	2.5	1.9	16.0
R	1.1	1.2	1.1	1.6	1.3	3.4	1.5	26.9
I	1.1	1.2	1.2	1.5	1.7	3.3	3.4	21.8
S	1.1	1.2	1.2	1.8	1.4	4.3	2.0	32.7
A	1.1	1.1	1.3	1.6	1.5	2.9	1.7	5.7
H	1.1	1.2	1.2	1.9	1.3	4.4	1.7	20.7
B	1.1	1.2	1.2	1.4	1.4	2.9	2.0	16.4
P	1.0	1.1	1.1	1.3	1.2	2.6	1.5	15.3

(M—Morava, D—Danube, V—Váh, W—Malý Dunaj, N—Nitra, R—Hron, I—Ipeľ, S—Slaná, A—Bodva, H—Hornád, B—Bodrog, P—Poprad).

Similarly, the analysis of the longest drought events at WSs (Figure 8) with mean, minimum, and maximum values determined, with the comparison of the results for both types of limits, shows the highest differences for the limits Q_{364d} ($Q_{364d,rr}/Q_{364d}$ = 3.9) and Q_{355d} ($Q_{355d,rr}/Q_{355d}$ = 1.7).
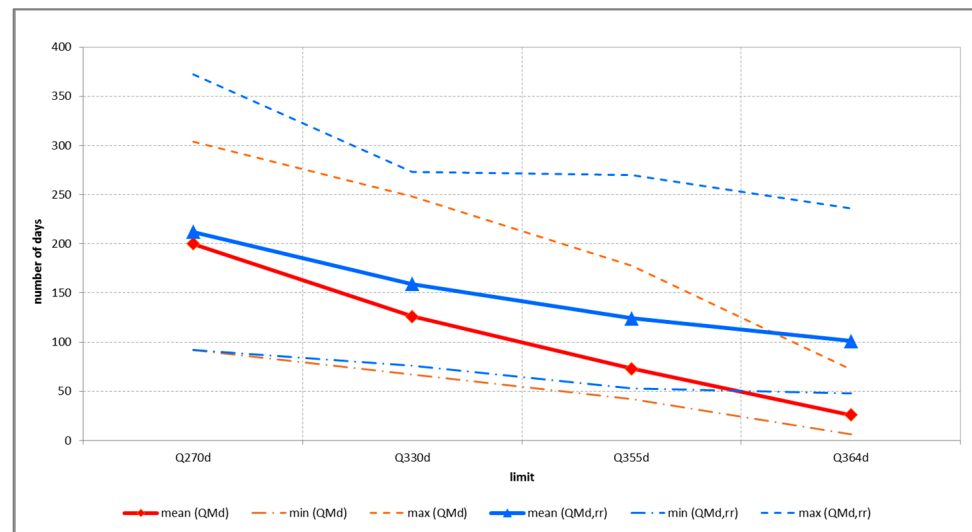
Figure 8. The longest drought event duration (mean and extremes of individual WSs), 1961–2015.

The comparison of the average number of days of low-flow events identified for individual flow limits at particular sub-catchments brings us an overview of the sub-catchments more prone to drought occurrence (colored in red and orange on the maps in Figures 9 and 10). Based on the analysis, we can state that the Nitra and Bodva sub-catchments are the most sensitive sub-catchments (with the largest number of days of dry periods) for the lowest limits of Q_{364d} and Q_{355d} (Figure 9). The numbers on the map represent the mean number of low-flow days in the individual sub-catchments.
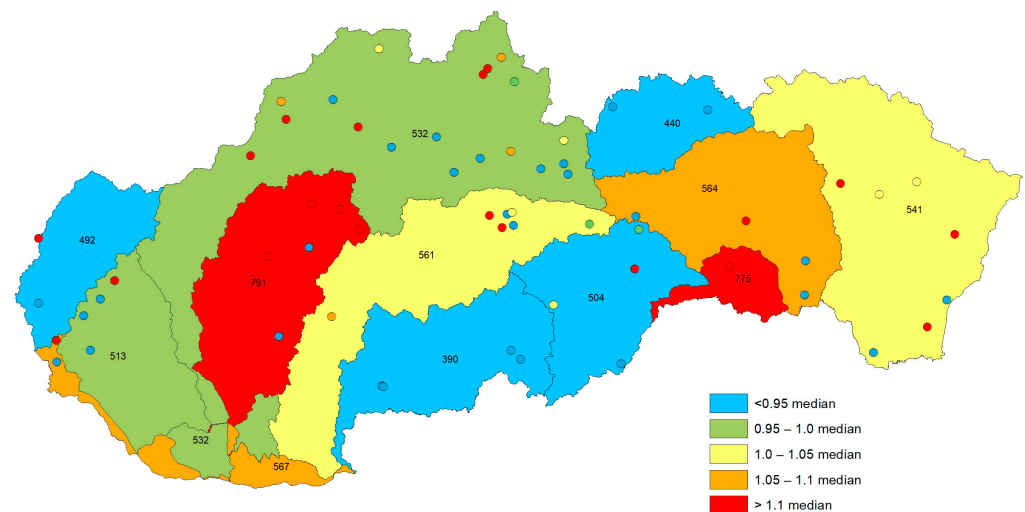
Figure 9. Sub-catchments in Slovakia colored according to the mean number of days with $Q_d < Q_{355d}$, 1961–2015. The dots represent the individual WSs and are colored using the same key as the sub-catchments.

For the $Q_{364d,rr}$ limit, the sub-catchments Morava, Bodva, and Malý Dunaj were detected as the most drought-prone. For the $Q_{355d,rr}$ limit, the Morava, Malý Dunaj, Bodva, and Slaná sub-catchments are the most sensitive sub-catchments with the highest number of days with Q_d lower than the set discharge limit (Figure 10). (Important note: The results in the Morava and Malý Dunaj sub-catchments do not represent the fully natural hydrological regime, so the results point to the effects of manipulation on water reservoirs and/or water use as well.)
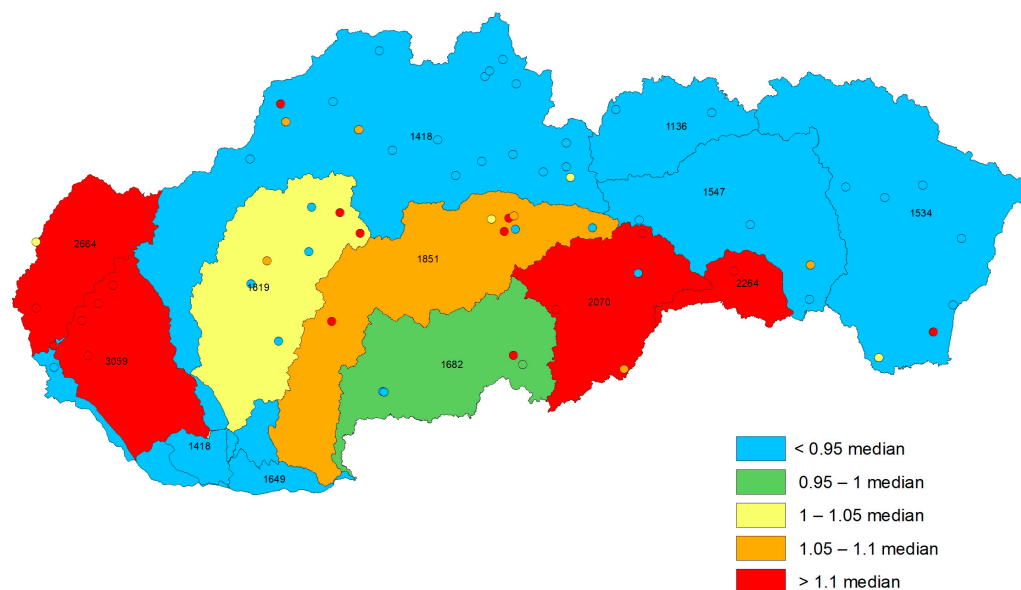
Figure 10. Sub-catchments in Slovakia colored according to the number of days with $Q_d < Q_{355d,rr}$, 1961–2015. The dots represent the individual WSs and are colored using the same key as the sub-catchments.

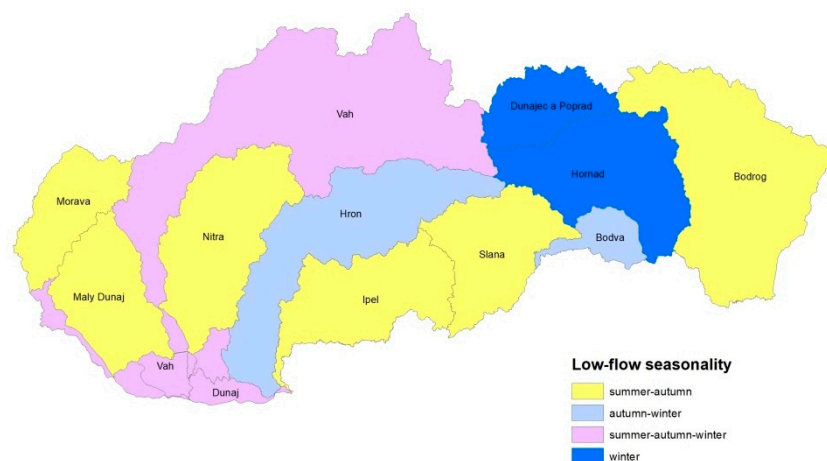### 3.4. Analyses of the Seasonality of the Five Longest Low-Flow Episodes at Evaluated WSs

Long periods of drought are the most severe in water management because they have significant negative economic and environmental impacts. Therefore, the seasonality of the longest low-flow events was assessed based on the five longest low-flow episodes in each evaluated profile for individual limit values in the 1961–2015 period. The mean and extreme lengths of the five longest periods for particular limits are listed in Table 4.

**Table 4.** The number of days with Q_d < limit for the five longest low-flow episodes at each WS.

Limit	Q_{270d}	$Q_{270d,rr}$	Q_{350d}	$Q_{330d,rr}$	Q_{355d}	$Q_{355d,rr}$	Q_{364d}	$Q_{364d,rr}$
mean	159	172	94	119	50	92	15	75
max	304	372	248	273	178	270	72	236
min	81	82	28	48	6	31	2	26

According to the timing of the five longest periods of drought at individual WSs, the overall situation of the sub-catchments was further analyzed. The occurrence of the longest low-flow events in the summer–autumn period (June to November) prevails in the evaluated profiles in Slovakia because it is visible, e.g., for the limit Q_{355d} (Figure 11). However, the occurrence in the winter period (December to February) is also significant (especially in higher mountain areas) with an overlap into the spring months (March to May).

At higher values of selected limit discharges, when the low-flow episodes have a longer duration, the summer–autumn and winter low-water periods may become interconnected. The sub-catchments of Ipeľ, Slaná, and Malý Dunaj (with the streams originating in the Malé Karpaty Mountains) were identified as the most sensitive areas with the low flows (Q_{364d}) occurring in the summer period (Figure 12). This can be considered a higher risk, e.g., for agriculture (deficit of water for irrigation in a growing season) or fisheries (negative effect of a combination of low flows and higher temperature on the river biota).

Figure 11. Sub-catchments in Slovakia according to the prevailing seasonality of the five longest low-flow episodes; 1961–2015, limit Q_{355d}.
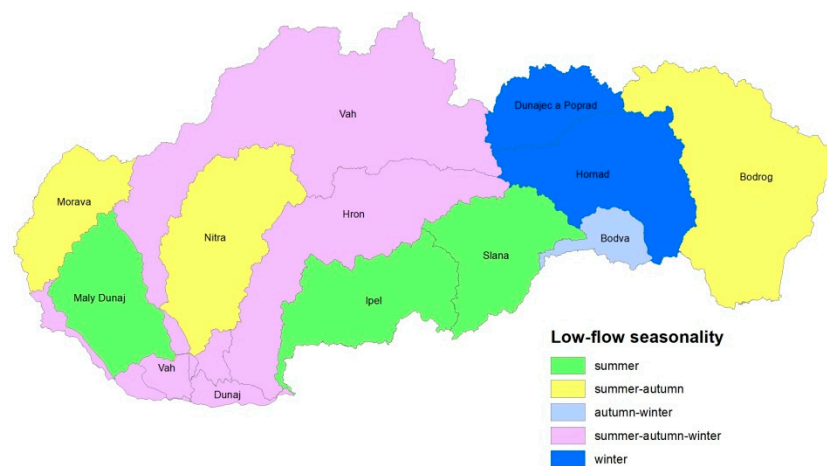
Figure 12. Sub-catchments in Slovakia according to the prevailing seasonality of the five longest low-flow episodes; 1961–2015, limit Q_{364d}.

According to the evaluation of the five longest low-flow episodes at the selected WSs with respect to the years of their occurrence, the following years appeared to be the most affected hydrological years for individual limits in the 1961–2015 period (Table 5):

Table 5. The driest hydrological years according to the sum of the occurrence of the five longest dry events at each WS.

Limit	Hydr. Years with the Highest Number of the Longest Dry Episodes Occurrence at WSs
Q_{270d}	1973–1974, 1983–1984, 1986–1987, 1992–1993, 2003–2004, 2011–**2012**
Q_{330d}	1961–1963(1994), 1986–1987, 1992–1993, 2003–2004, (2011)–**2012**
Q_{355d}	1961–1962, 1973, **1992**–1993, 2003, **2012**
Q_{364d}	1973, 1987, **1992**–1993, 2003, 2012
$Q_{270d,rr}$	1973–1974, **1983**–1984, 1986–1987, 2003–2004, 2011–2012
$Q_{330d,rr}$	1962–1963, 1983–1984, 1986–1987, 2003–2004, 2011–**2012**
$Q_{355d,rr}$	1961–1963, 1973, 1983–1984, 1986–1987, 1992–1993, 2003–2004, **2012**
$Q_{364d,rr}$	1961–1963, 1987, 1992–1993, **2003**, **2012**

bold highlights the maxima (years with the largest total number of low-flow events at evaluated stations).

These results are in line with the evaluation of dry years based on annual and monthly discharges in previous partial reports of the Hydrological Drought Assessment conducted at the SHMI [32,33]. In the evaluated period, the hydrological year 2012 was the most affected by drought (highest sum of low-flow events) with a longer duration. Of the other most frequently presented dry years, similar to the results of the assessments in previous partial reports, the 2003–2004, 1992–1993, and 1986–1987 periods were repeated.

3.5. Comparison of the 2001–2015 Period Versus the 1961–2000 Reference Period

For the analysis of changes in non-flow characteristics between the 2001–2015 period and the 1961–2000 reference period, we analyzed the number of days for the WSs with long-term observations in which the mean daily discharge fell below the specified limit. This comparison has only been made for the quantiles Q_{355d} and Q_{364d} (the low-flow area), set for the 1961–2000 reference period. In general, there was an increase in the number of days below the limit discharge (on average per year) in the 2001–2015 period compared to the reference period (Figure 13) but that was not the case for all WSs.
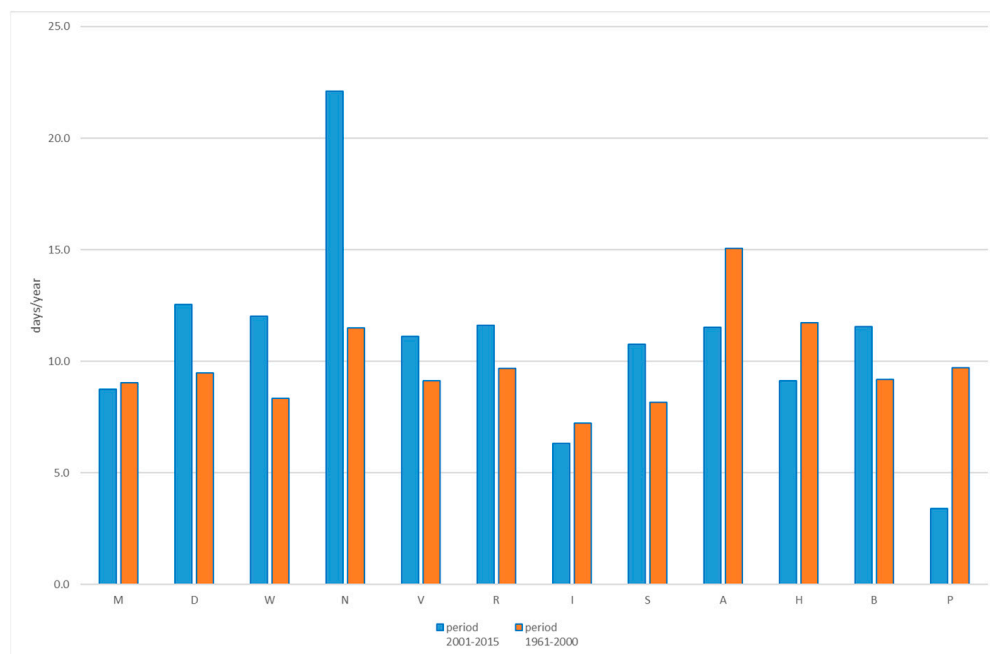
Figure 13. Mean number of low-flow event days from 2001–2015 compared to 1961–2000.

For the Q_{364d} limit, no low-flow period with $Q_d < Q_{364d}$ was detected at nearly half of the evaluated WSs in the 2001–2015 period. However, at a large portion of the rest of the WSs, an increase in the occurrence, compared to the 1961–2000 period, is visible.

For the Q_{355d} limit, at four of the evaluated WSs in the 2001–2015 period, there was no observed low-flow event below the specified limit (of which three WSs are considered to be anthropologically affected). On average, for the rest of the assessed stations, the increase in the number of days with low-flow events prevails in the 2001–2015 period compared to the reference period. When it comes to the sum of WSs with a decrease or with no change between the evaluated 2001–2015 period and the 1961–2000 reference period in terms of the duration of low-flow episodes expressed as the days with values below the limit per year, it is almost the same as the number of WSs with the increase.

Predominance of the stations with a decrease in the number of low-flow days in the evaluated period occurred in the Poprad, Bodva, Hornád, Ipeľ, and upper Váh sub-catchments.

4. Discussion

The two methods used for the calculation of FDCs in this study differ in their approach to the calculation of the quantiles. Method 1 allows the small number of long dry periods to influence the lowest quantiles of the FDC (Q_{364d} and Q_{355d}). This can lead to very low values of these characteristics, especially for small streams with high variability of flows (steep course of FDC). Method 2 brings higher values in the area of low flows ($Q_{330d,rr}$ (90.3%), $Q_{355d,rr}$ (97.2%), and $Q_{364d,rr}$ (99.7%)), while in the area of higher discharges (in the area of Q_{270d} (73,9%) and higher), the differences between Method 2 and Method 1 disappear. Method 2; however, to some extent, smooths out the extremity of the minimum flows. The extremely large percentage differences between the values of Q_{364d} calculated by these two methods are observed for the smallest streams, where the low flows can be close to zero. For large rivers, such as the Danube or the Morava at the Slovak territory, where the FDCs have more balanced courses, the relative differences of these values are smaller. For other evaluated rivers, the differences also vary due to the hydrological regime of the region, resulting from the local hydrogeological, morphological, and climatic conditions. These findings indicate that the results of Method 1 in the area of the lowest quantiles need to be handled with care for small streams. Therefore, Method 2 appears to be more suitable for the calculation of hydrological characteristics, applicable as the basis for setting the minimum ecological flows.

Changes of M-day discharges in the low-flow area in the 2001–2015 period show regional differences. The regions of Slovakia highlighted by the red ellipses in Figure 14 can be considered to be more sensitive. They are characterized by predominant negative changes in the Q_{355d} values at the assessed WSs. These regions cover the western, southwestern, and eastern parts of Slovakia. On the other hand, the middle blue ellipse in Figure 14 representing the upper, mountainous parts of the Váh, Hornád, Hron, Poprad, and Slaná sub-catchments shows positive changes in these values. These findings are in line with the results of previous studies [24,31]. For the threshold Q_{364d}, the increase in the values prevails at the assessed WSs more significantly than for Q_{355d}. We should keep in mind that the results are partially affected by the values from WSs with the anthropogenically influenced hydrological regime, especially in the southern, more lowland regions of Slovakia. The positive changes in some cases (mostly in these southern, downstream areas), to some extent, point to the effects of manipulation on water reservoirs.
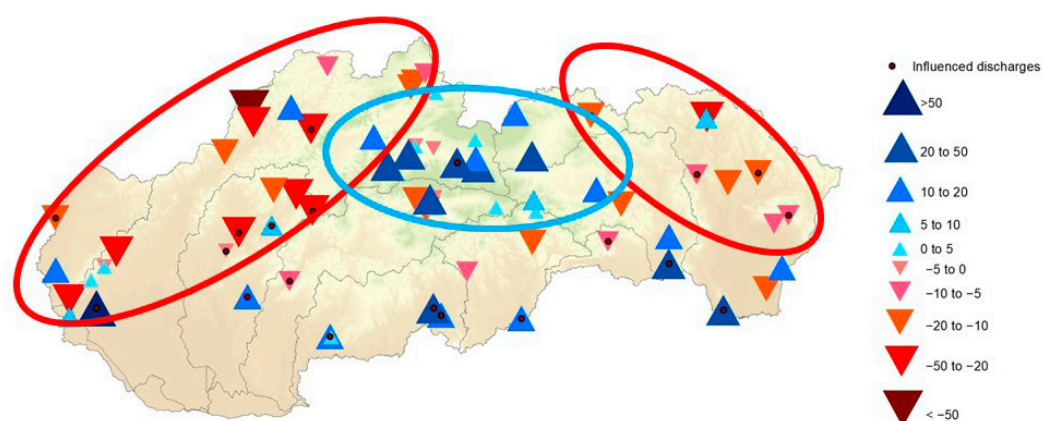
Figure 14. Areas of prevailing increases (blue) and decreases (red) of Q_{355d} from 2001–2015 compared to 1961–2000.

Concerning the seasonality of the longest periods of droughts, the evaluation of the main sub-catchments of Slovakia, based on the average status for all sub-catchments, can be partially misleading. Larger sub-catchments, such as Váh or Hron, have quite different physical-geographical conditions in the up- and downstream parts. While in the upper, mountain areas with higher altitudes, the winter season is typical for the drought

occurrence, in the lowland, it is the summer–autumn season where the drought typically occurs. Therefore, in the continuation of our work, we want to divide these sub-catchments into smaller sections for assessment. The sensitivity of the sub-catchments (local areas) to the occurrence of long-lasting drought periods in the growing season can also be important knowledge for agriculture, fisheries, etc.

5. Conclusions

In the article, we compared two methods for estimating values of FDCs using mean daily discharges from selected water-gauging stations located in Slovakia. The weakness of the standard method (No. 1) is that it allows the values of the smallest quantiles (Q_{364d} and Q_{355d}) to be influenced by a small number of long-lasting drought episodes [32]. This is also supported by the analysis of non-flow characteristics, which showed that in the 2001–2015 period that was evaluated using the standard method, the discharges at some stations did not at all fall under the Q_{364d} values determined using the standard method for the 1961–2000 reference period. The alternative method (No. 2) eliminates the aforementioned shortcoming of the standard method and, out of these two methods, it has a better precondition to be used as an input for determining the design values of ecological flows.

The seasonality of the longest low-flow episodes on Slovak rivers prevails in the summer–autumn period; however, in case of the mountain streams, the low-flow episodes with a longer duration also occur in the winter period, which is associated with the temporary freezing of watercourses and the entrapment of water in the form of snow and ice. For the summer period, the sub-catchments of the rivers Ipeľ, Slaná, and Malý Dunaj were identified as the most drought-prone areas in Slovakia (Q_{364d}).

According to the mean values of the number of days with Q_d < limit (limits set as Q_{270d}, Q_{330d}, Q_{355d}, and Q_{364d}) in the sub-catchments in Slovakia, we consider the Nitra, Bodva, Morava, and Slaná sub-catchments to be the most sensitive (with the highest number of dry days in the evaluated 1961–2015 period). According to the evaluation results, the choice of the threshold hydrological characteristic is of key importance for defining the low-flow periods. However, it has to be based on the purpose of intended use.

The subsequent analysis of the lengths of the low-flow periods in relation to the limits gives the necessary feedback for the assessment of the suitability of the limit, e.g., as a limiting flow value for the purposes of abstraction permits, while maintaining the flow in the stream for general water use and maintaining a good ecological status.

The next planned step is the assessment of selected limit values of discharges in low-flow areas by experts in the fields of biology and water resources management to see the possible impacts of the introduction of such limits into the river system.

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