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Front cover photography: Large avalanches like the January 2021 »twin avalanche« in the upper Soča Valley that reach the valley floor will be unavoidable in the Alps in the future, as climate warming actually triggers them, contrary to expectations (photograph: Jure Tičar).
Fotografija na naslovnici: Velikim snežnim plazovom, kakršen je bil »dvojček« januarja 2021 v Zgornjem Posočju, ki dosežejo dolinsko dno, se v Alpah tudi v prihodnosti ne bomo izognili, saj jih otoplitev podnebja, nepričakovano, celo povzroča (fotografija Jure Tičar).

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COMPREHENSIVE LOW-FLOW ANALYSIS OF THE VIPAVA RIVER

Mateja Jelovčan, Mojca Šraj

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Mateja Jelovčan[1], Mojca Šraj[2]

Comprehensive low-flow analysis of the Vipava river

ABSTRACT: The article presents the results of the analysis of low flows at 5 gauging stations on the Vipava River, which has a Dinaric pluvial-nival regime (catchment area of 590 km^2). The low-flow statistics show that the gauging station Vipava stands out with the lowest values. Baseflow index (BFI) values are comparable among the considered stations and are around 0.40. Relatively low BFI values indicate low soil permeability. A high similarity between the mean annual minimum 7-day flow (MAM7) and the 95th percentile exceedance discharge (Q95) at all gauging stations indicates a temperate climate. The highest flows values occur in spring and autumn, and the lowest in summer. In wet years there are relatively large fluctuations in flow, while in dry years the flow consists mainly of baseflow. This is also confirmed with the flow duration curves analysis. The seasonality analysis shows a predominant summer regime with low flows.

KEY WORDS: low-flow analysis, lfstat package, Vipava River, Vipava Valley, Slovenia

Analiza nizkih pretokov reke Vipave

V članku so predstavljeni rezultati analize nizkih pretokov na 5 vodomernih postajah na reki Vipavi, ki ima dinarski dežno-snežni režim (površina zaledja 590 km^2). Rezultati statistik nizkih pretokov kažejo, da z najnižjimi vrednostmi izstopa vodomerna postaja Vipava. Vrednosti indeksa baznega odtoka (BFI) so med obravnavanimi postajami primerljive in se gibljejo okoli 0,40. Relativno nizke vrednosti BFI kažejo na nizko prepustnost tal. Velika podobnost med srednjim letnim 7-dnevnim minimalnim pretokom (MAM7) in 95-odstotnim pretokom (Q95) na vseh vodomernih postajah kaže na zmerno podnebje. Največje vrednosti pretokov se pojavijo spomladi in jeseni, najnižje pa poleti. Za mokra leta so značilna relativno velika nihanja pretoka, v sušnih letih pa pretok predstavlja predvsem bazni odtok. To potrjuje tudi analiza krivulj trajanja pretokov. Analiza sezonskosti kaže prevladujoč poletni režim nizkih pretokov.

KLJUČNE BESEDE: analiza nizkih pretokov, paket lfstat, reka Vipava, Vipavska dolina, Slovenija

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1 Introduction

Low flows usually occur after periods of low precipitation. In addition, low precipitation over a prolonged period of time can lead to hydrological drought. Drought is a complex phenomenon that is difficult to define unambiguously, so there is no single, universally accepted definition of drought. Several types of drought can be defined, differing in both causes and consequences (e.g. Brenčič 2017). Mikoš et al. (2002, 134) define hydrological drought as »Period of abnormally dry weather sufficiently prolonged to give rise to a shortage of water as evidenced by below normal streamflow and lake levels and/or the depletion of soil moisture and a lowering of groundwater levels«.

Comprehensive low-flow analyses are critical for providing information for sustainable water management and planning (WMO 2009). However, flow data can be analysed in several ways using different indicators and methods to describe the low-flow regime of the rivers (e.g. Laaha and Blöschl 2006; Fiala, Ouarda and Hladný 2010; Beck et al. 2013; Petek, Kobold and Šraj 2014; Coch and Mediero, 2016; Sapač, Rusjan and Šraj 2020). To ensure consistent and appropriate analysis of time series of daily flows, the World Meteorological Organization has produced a guidance manual (2009) containing operational information for low-flow prediction and forecasting. In Slovenia, for example, Petek, Kobold and Šraj (2014) analysed low flows at 55 gauging stations of national hydrological monitoring. They found that low flow statistics are very strongly related to the size of the catchment area. The catchment area also affects the values of the recession constant. Sapač, Rusjan and Šraj (2020) analyse various low-flow indices in the hydrogeologically inhomogeneous Ljubljanica river catchment. They found that most of the low-flow indices are consistent with each other and that there are some rivers with specific hydrogeological properties influencing the values of some indices in an inconsistent way compared to other indices. They concluded that in order to correctly interpret the results of low-flow analysis, it is not sufficient to calculate different low-flow indices, but it is necessary to analyse and compare them also with respect to other catchment characteristics.

The main objective of the study is to analyse low flows at five gauging stations on the Vipava River in the Vipava Valley in order to obtain a comprehensive information on the dynamics of the river. The Vipava River has its own characteristics that distinguish it from other watercourses in Slovenia. When we talk about water and watercourses, the analysis of spatial distribution is not enough. We also need to study the temporal changes in the presence of water in watercourses, aquifers and soils, which we can do if we have an appropriate set of data (Brenčič 2013). Comprehensive low-flow analysis includes calculation of low-flow statistics, analysis of hydrographs with baseflow separation, analysis of recession curves and flow duration curves, calculation of baseflow index (BFI) and streamflow deficit, and analysis of seasonality.

2 Methods

2.1 Research area

The Vipava Valley extends in an east-west direction for about 40 km from the headwaters of the Močilnik stream near Razdrto to the Gorica Plain along the Soča River. Its area of 310 km^2 covers a wide strip of Eocene flysch between the high karst plateaus Trnovski Gozd and Nanos in the north and the low plateau Karst in the south. It has an average elevation of 216 m (Kladnik 2013).

The main watercourse in the Vipava Valley is the river Vipava. It originates in numerous springs along the impermeable flysch edge at the foot of the Nanos Mountain. The Vipava River has a Dinaric rain-snow regime with peaks in spring and autumn (Bat et al. 2008). It has the highest flows during snowmelt on the Nanos and partly Hrušica karst plateaus (Uhan and Krajnc 2003). Along its course, the Vipava River receives water from tributaries, that differ in hydromorphology and the amount of water they convey. More important are mainly the streams Hubelj and Lijak (Brenčič 2013). In addition to surface waters, groundwater in intergranular aquifers is also important in the Vipava Valley (Brenčič 2013).

2.2 Data

We analysed daily discharge data series at five gauging stations of the Vipava River (Table 1). Measured discharge data from the gauges Vipava I and Vipava II, Dolenje, Dornberk, Zalošče and Miren and Miren

I gauging stations were applied. The location of gauging stations is shown in Figure 1. The data were obtained from the Surface Water Archive of the Slovenian Environment Agency (http://vode.arso.gov.si/hidarhiv/pov_arhiv_tab.php). A 28-year long data set (1991–2018) was used for the analysis for the Dolenje gauging station, a 64-year data set (1951–2014) for the Dornberk gauging station and a 5-year data set (2014–2018) for the Zalošče gauging station. Due to the short set of data at this gauging station, it cannot be compared with the data at other stations. Therefore, in the chapter 3 Analysis and Results, we only present the results for the Zalošče station, but we do not include them in the discussion. In 2003, during the reconstruction of the bridge over the river Vipava, the Miren gauging station was moved slightly downstream towards the confluence of the Vipava and Soča rivers and the new station was named Miren I. Because the distance between both stations is small, the data set from both stations can be combined into a single set, hereinafter referred to as Miren. A 69-year long data set (1950–2018) was thus used in the analysis for the Miren gauging station. However, in the case of the Vipava and Vipava I gauging stations, the data cannot

Table 1: Main characteristics of the considered gauging stations (Surface Water Archive of the Slovenian Environment Agency).

Gauging station	Station code	Station elevation [m]	Catchment area [km^2]
Vipava	8550	97.4	132
Dolenje	8565	81.4	317
Dornberk	8590	53.9	466
Zalošče	8591	53.9	467
Miren	8600	37.0	590

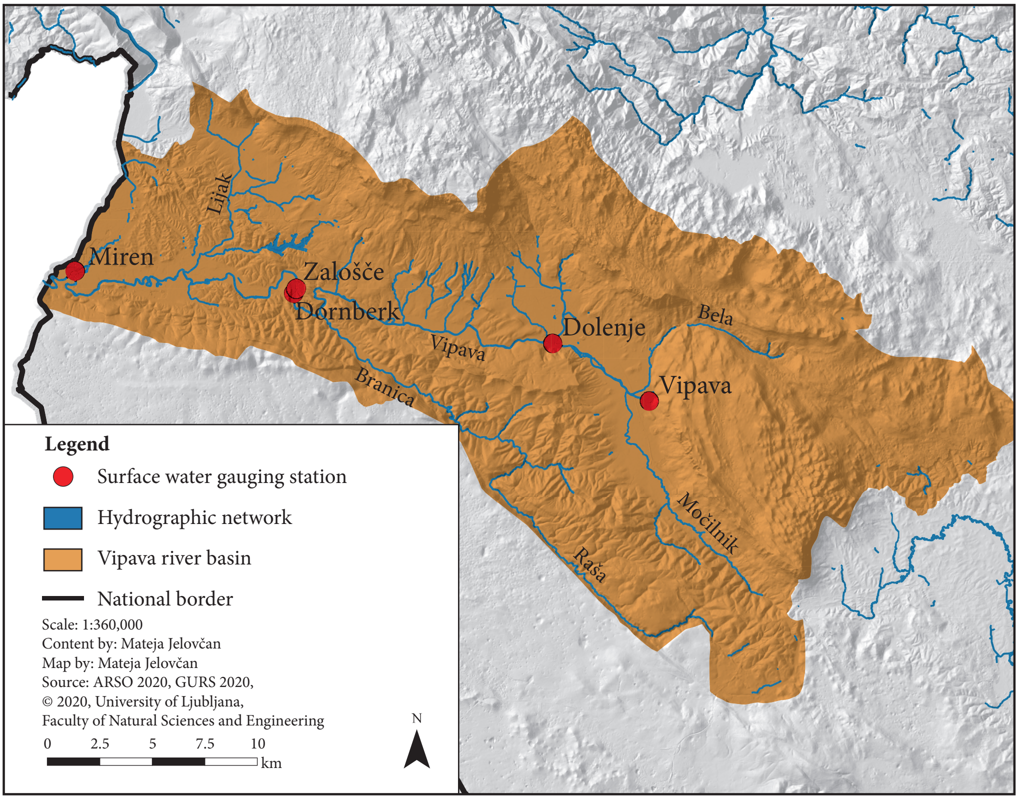

Figure1: Location of the gauging stations of the Vipava River at the Vipava Valley.

be combined. Both stations recorded flows in the area of the springs in Vipava, but the Vipava gauging station turned out to be unreliable, so it was abolished in 1965. As early as 1960, a new station Vipava I was built, which recorded the discharge data from most of the springs of the Vipava River. The Vipava I gauging station was in operation until 2015, when the Vipava II gauging station started operating. A combined set of 59-years of Vipava I and Vipava II gauging stations (1960–2018), hereinafter referred to as Vipava, was used for the analysis.

2.3 Methods

Data analysis and graphical representations were performed using the free and open source R software tool, developed by the R Core Team in 2018 (https://www.R-project.org/). It has been increasingly used for various hydrological analyses in the last decade (e.g., Omuto and Gumbe 2009; Šraj, Bezak and Brilly 2012; Bezak, Horvat and Šraj 2015; Petek, Kobold and Šraj 2014; Sapač, Rusjan and Šraj 2019; Sapač, Rusjan and Šraj 2020). The software allows the extension of existing functions by various packages, thus providing a wide range of different methods for analyses. For the analysis of low-flows, in 2016 Koffler et al. developed the lfstat package (https://cran.r-project.org/web/packages/lfstat/lfstat.pdf) which allows comprehensive analyses of low-flow indices according to the World meteorological organization (2009) recommendations. The analysis of the data in this article includes the calculation of low-flow statistics of the Vipava River, the analysis of hydrographs with baseflow separation, the analysis of recession curves and flow duration curves, the calculation of baseflow index (BFI), the streamflow deficit, and the analysis of seasonality.

The flow duration curve (FDC), allows us to determine the percentage of time that a certain flow value is equal to or greater than the selected value or the relationship between the amount of flow and the frequency of its occurrence (Mikoš et al. 2002). It gives us an overview of the flows in a watercourse and allows us to distinguish between low and high discharge. When analysing low flows, the useful part of the FDC is the one that defines low flows, i.e. flows that are reached in 50% or more of the time. If underground sources contribute substantially to the flow, the FDC in this part will be flat, and in the case of a small contribution from the baseflow, the curve will be steep (Smakhtin 2001). As part of the analysis, we plotted and analysed the FDC for the entire data set and for individual seasons for each gauging station.

Other typical low-flow statistics obtained from the FDC are Q70, Q90, and Q95, which represent a flow exceeded 70%, 90%, and 95% of the time, respectively. In the study, Q50, Q70, Q90, and Q95 were plotted for each gauging station by individual months, and all low-flow statistics were calculated for the entire considered period of each gauging station.

Mean annual minimum n-day flows (MAMn) are also commonly used as low-flow indices and can be calculated for different durations (Tallaksen and Van Lanen 2004; Sapač, Rusjan and Šraj 2019). For example, the mean annual minimum MAM7 represents the average of the minima of the 7-day series of measured flows. In temperate climates, MAM7 is similar to Q95 (WMO 2009). In the study, MAM1 and MAM7 were calculated for each gauging station considered.

Hydrograph separation methods generally divide total flow into the direct surface runoff (fast component) and the baseflow (lagged component). Baseflow originates from groundwater reserves or delayed water sources and thus accounts for most of the flow during the dry season (WMO 2009). The ratio between the baseflow and the total flow is the so-called baseflow index (BFI) (Gustard et al. 1992). BFI values vary with soil permeability, geology and other water-related storage indicators and range from 0 to 1. For impermeable soils, the BFI is less than 0.2, and as permeability increases, the BFI value also increases (WMO 2009). BFI was calculated for each gauging station in the study area. Furthermore, we also selected dry and wet years, visualised them using hydrographs and compared them with each other.

Streamflow deficit represents the period of time during which the flow in a watercourse is below a certain threshold value that defines drought (WMO 2009). To determine the deficit, the threshold level method should be applied defining drought or periods of low watercourse flows (Hisdal and Tallaksen 2000; Cunja, Kobold and Šraj 2020). The deficit begins when the flow falls below the threshold value and ends when it rises above it (WMO 2009). In the study, the flow Q70 was chosen as the threshold. Due to the shortcomings of the threshold level method, such as when daily discharge data are used, there may be an interdependence between droughts and the occurrence of minor droughts. This can be avoided by using other data classification methods (Petek 2014). In this study, a moving average procedure was used in the study. Several indicators can be determined in the context of streamflow deficit (WMO 2009), such as duration (d), deficit volume (V), intensity or volume to duration ratio (mi), minimum deficit flow (Qmin) and time of the event (t) (Figure 2).

The falling limb of the hydrograph is the so-called recession curve. By analysing recession curves, we can determine the change in flow over time and the relationship between them (e.g. Petek 2014; Sapač, Rusjan and Šraj 2019). There are two groups of methods for recession analysis, namely the master recession curve method (MRC) and the method with calculation of parameters for individual recession segments (IRS). The recession constant C is a value that illustrates the degree of recession/decline. It can be determined by both methods mentioned above. Sapač, Rusjan and Šraj (2019) state that both BFI and recession constant can be used to determine river basins characteristics. Both are indicators of water reserves in the river basin. Higher BFI values indicate a better correlation between surface water and groundwater reserves, which represent a larger part of the flow in the river during low flows and thus a higher value of the recession constant. At low BFI, this relationship is poorer thus so the recession constants are lower. In the study, the recession constant was calculated separately for each gauging station using the MRC and IRS methods (threshold value Q70). Different durations of the segments (seglength) were applied, i.e. for 4, 5, 6 and 7 days.

Seasonality ratio is the ratio between summer and winter flows. When the seasonality ratio values are greater than 1, the winter regime with low flows prevails, and when the values are less than 1, the summer regime prevails. In the study the year was divided accordingly with Sapač, Rusjan and Šraj (2020). April 1st was chosen for the beginning of the summer period and December 1st for the beginning of the winter period. The seasonality index is used to show the seasonal distribution of the occurrence of low flows. We determine the date of occurrence of the annual low flow in the Julian calendar (the first day is January 1st, the 365th day is December 31st) (Burn 1997). The dimensionless measure of data dispersion is the parameter r, which ranges between 0 and 1. High values of the parameter r indicate that most extreme drought events occurred on the calculated mean day of year D. High values of r also indicate little variability in the occurrence of low flows throughout the year. On the other hand, low values of the parameter r indicate high variability in the occurrence of extreme events (Young, Round and Gustard 2000).

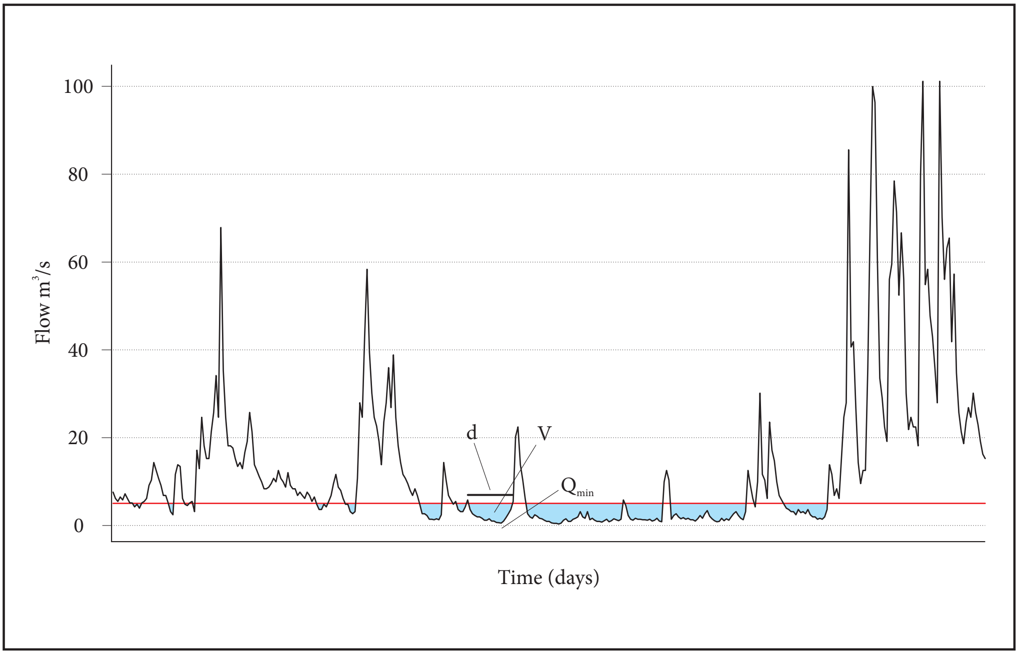

Figure 2: Display of streamflow deficit indicators (WMO 2009); the red line indicates the threshold value.

3 Analysis and Results

3.1 Low-flow statistics, baseflow index (BFI) and hydrographs

The low-flow statistics, i.e. BFI, MAM1, MAM7 and flows from FDCs with exceedances of 50, 70, 90 and 95% of the time for all gauging stations considered are presented in Table 2. The BFI values are comparable between the stations and vary around 0.40, with a slightly lower BFI value observed at the Miren gauging station. Relatively low BFI values indicate low soil permeability at the Vipava Valley. Considering all other low-flow statistics (MAM1, MAM7, Q50, Q95, Q90 and Q70), it is observed that the Vipava gauging station has the lowest values, which then increase along the Vipava River, which is evident from the calculations for the other gauging stations. The lowest value of the mean flow (6.53 m^3/s) belongs to the Vipava station, followed by the Dolenje, Dornberk and Miren stations, where mean flow reaches 17.73 m^3/s. There is also a great similarity between MAM7 and Q95 values at all gauging stations, indicating a temperate climate.

Kobold and Brilly (1994) analysed low flows of various watercourses in Slovenia, including the Vipava River at the Vipava gauging station for the period 1961–1988. The results of our calculations in the case of BFI values show an agreement with their calculation, and minor differences in the results occur in the case of Q50, Q95 and MAM1. Kobold and Brilly (1994) calculated BFI = 0.40, Q50 = 6.94 m^3/s, Q95 = 1.61 m^3/s and MAM1 = 1.26 m^3/s. Cunja, Kobold and Šraj (2019) studied the temporal and spatial analysis of the largest hydrological droughts in Slovenia at selected gauging stations in the period 1960-2016. The results of their MAM7 calculations at the gauging stations Vipava and Miren show slightly lower values compared to our calculations. MAM7 = 0.83 m^3/s was calculated for the Vipava gauging station and 1.21 m^3/s for the Miren gauging station. Petek, Kobold and Šraj (2014) calculated low flow statistics for several gauging stations in Slovenia, including Dornberk. The results of their calculations are comparable to ours. They calculated BFI = 0.38, MAM1 = 1.83 m^3/s, MAM7 = 2.0 m^3/s, Q50 = 14.9 m^3/s, Q70 = 4.6 m^3/s, Q90 = 2.7 m^3/s and Q95 = 2.2 m^3/s.

Figure 3 shows that at the Dornberk gauging station the first maximum low flow occurs in spring (April), and the second, slightly higher maximum low flow occurs in autumn (November). The same is true for

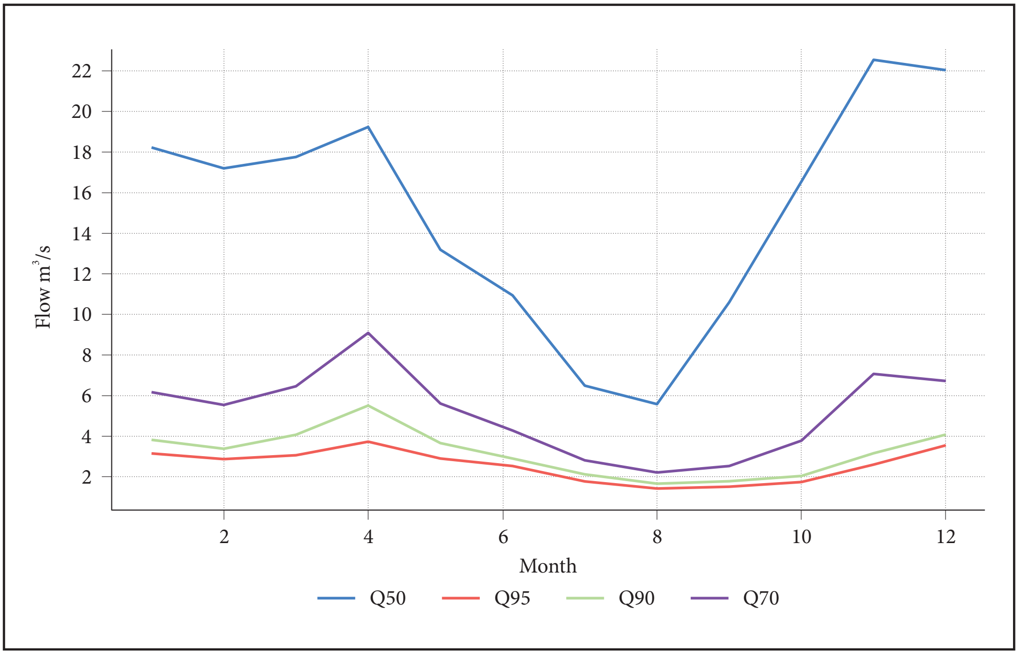

Figure 3: Q50, Q95, Q90 and Q70 by individual months for gauging station Dornberk.

Table 2: Low flow statistics for individual gauging stations in the considered period.

Gauging station	Vipava	Dolenje	Dornberk	Zalošče*	Miren
BFI [/]	0.40	0.40	0.38	0.34	0.35
MAM_1 [m^3/s]	1.17	1.76	1.85	1.77	1.89
MAM_7 [m^3/s]	1.21	1.87	1.99	1.87	2.06
Q_{50} [m^3/s]	6.53	12.19	15.01	15.25	17.73
Q_{70} [m^3/s]	2.20	3.64	4.48	4.12	5.00
Q_{90} [m^3/s]	1.35	2.24	2.46	2.38	2.64
Q_{95} [m^3/s]	1.14	1.91	1.98	2.00	2.08

* Due to the short data set (5 years) at the Zalošče gauging station, the results cannot be directly compared with the results for other stations.

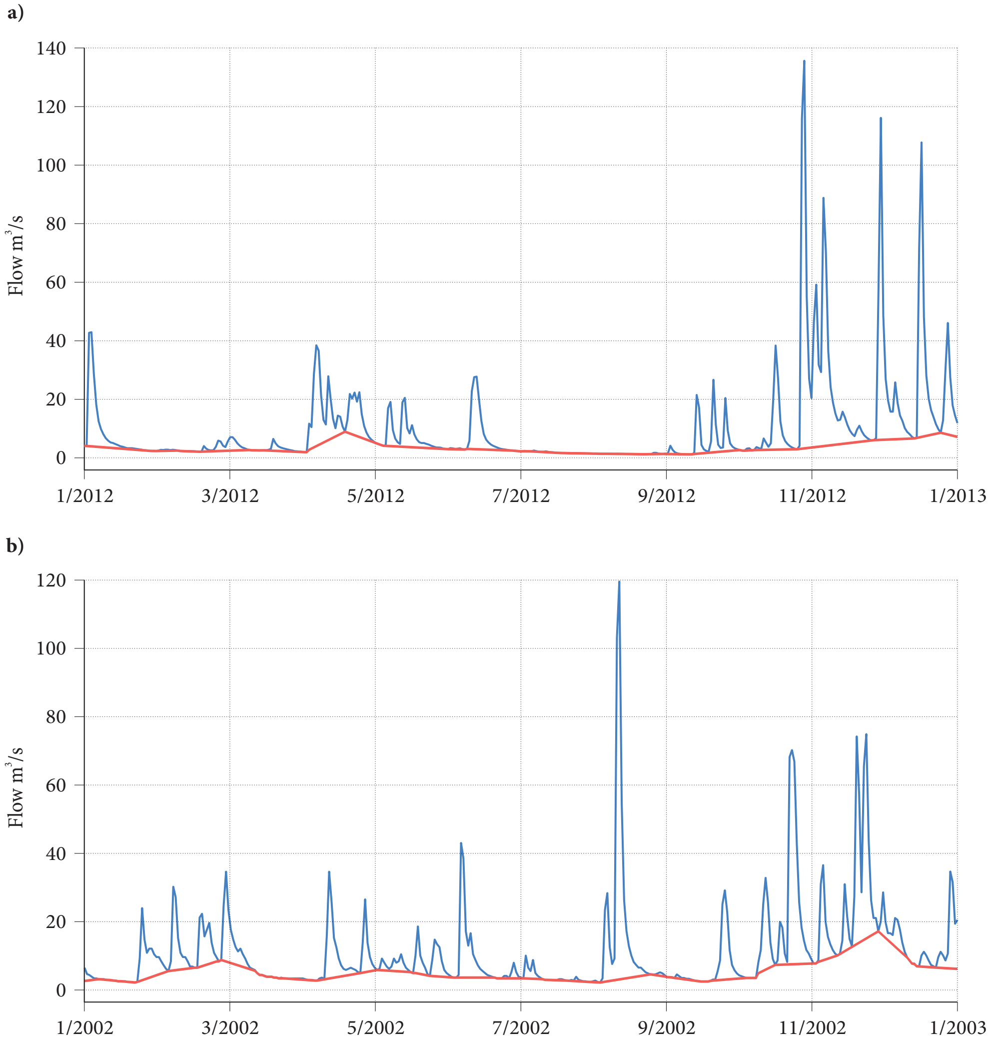

Figure 4: Hydrographs with separated baseflow (red line) for dry year 2012 (A) and wet year 2002 (B) at Dolenje gauging station.

the Vipava, Dolenje and Miren gauging stations. Minimum low flows at these stations are reached during the summer, in July and August. The autumn peak is the result of heavy autumn precipitation, and the spring peak is the result of snowmelt on the high Dinaric plateaus.

The hydrographs for wet years show relatively large fluctuations in flow throughout the year at all gauging stations. For example, Figure 4 shows hydrographs for a dry year (2012) and a wet year (2002) at the Dolenje gauging station. As we can see, the flow during precipitation can increase more than 10 times compared to the baseflow. The large fluctuations in flow are mainly due to the tributaries of the Vipava and the poorly permeable base along which the Vipava River flows. Hydrographs for dry years show higher flows at all gauging stations at the beginning and end of the year, while spring and summer flows consisted mainly of baseflow (red line) (Figure 4A). The drought is most pronounced at the Dolenje gauging station, where flow from mid-January to early April and from late June to mid-September is represented by baseflow (Figure 4A).

3.2 Flow duration curves

Flow duration curves show that in the case of the Vipava gauging station (Figure 5), the flow can increase by a factor 10 or more during extreme events, while at the Dornberk station (Figure 6), as well as the other gauging stations in the Vipava Valley, the flow can increase by a factor of 100 and the flow can reach values up to about 200 m^3/s. The duration curves are quite flat in the part representing the flow below Q50 for all gauging stations, indicating that karst underground sources contribute to the surface flow considerably. Sapač, Rusjan and Šraj (2020) also came to a similar conclusion regarding flow duration curves when analysing low flows in the Ljubljanica river catchment. They found that such shapes of the duration curve, which are also observed in the Vipava Valley, are characteristic of watercourses, whose flow increases greatly after precipitation events, while in non-precipitation periods flows are low and show little fluctuation. This is also confirmed by the large difference in Q90 and Q50 values.

Figures 5B and 6B show the duration curves for the gauging stations Vipava and Dornberk for each season separately, so that the change of flow in the different periods of the year can be observed. In both cases, the curves for spring, autumn and winter overlap more or less, indicating comparable flows in these seasons. However, the duration curve for the summer (red line) lies much lower than the other three, indicating the lowest flows occur in the summer. This curve is flattest in portion representing a flow of less than Q50, indicating that karst underground sources contribute the most to surface flow in the summer.

3.3 Streamflow deficit

The analysis of the streamflow deficit shows that among the identified drought events, the longest drought event lasted 153 days. It occurred at the Dornberk gauging station in 2003 (Figure 7, Table 3), in a year considered as one of the driest in Slovenia since 1960 (Cunja, Kobold and Šraj 2019). The drought event started in early May and lasted until October. It reached a minimum flow of 0.99 m^3/s. The other three

Table 3: Calculated indicators of streamflow deficit for gauging stations Dornberk and Miren.

Gauging station	d (days)	V (m^3)	mi (m^3/day)	Qmin (m^3/s)	Start of the deficit
Dornberk	12	811,963	67,664	3.30	February 18th, 2003
	7	180,045	25,721	4.02	March 20th, 2003
	153	34,396,729	224,815	0.99	May 5th, 2003
	7	1,244,432	177,776	1.72	October 11th, 2003
Miren	3	29,376	9,792	4.81	January 10th, 1950
	3	73,563	24,521	4.70	March 28th, 1950
	1	30,363	30,363	4.65	April 9th, 1950
	9	1,501,755	166,862	1.63	May 9th, 1950
	22	5,000,955	227,316	0.88	May 24th, 1950
	55	16,222,341	294,952	0.58	June 24th, 1950
	30	7,732,923	257,764	1.15	August 23rd, 1950
	16	2,877,861	179,866	1.79	October 9th, 1950

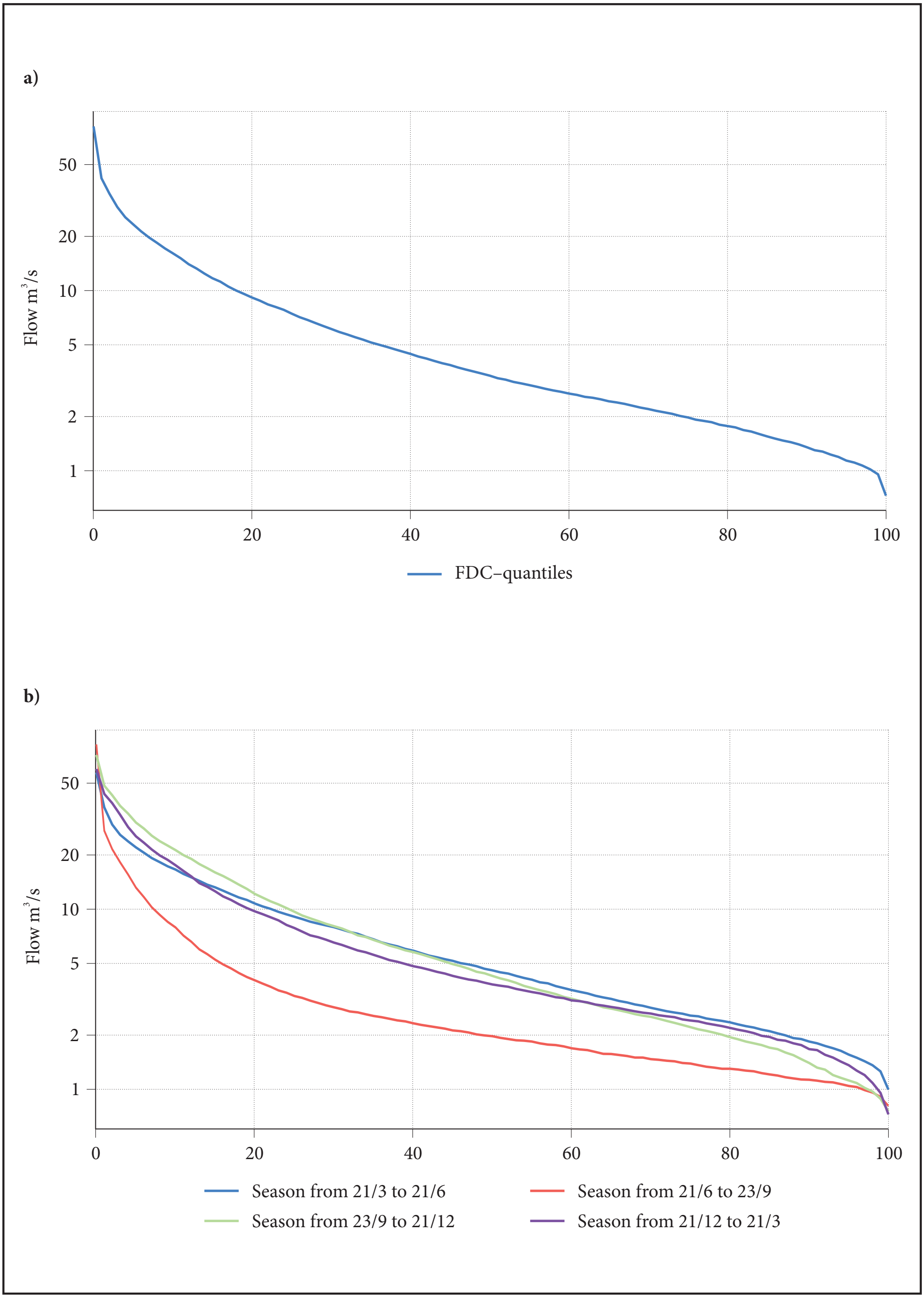

Figure 5: A: Flow duration curve for the whole data set (1960-2018) of the Vipava gauging station. B: Flow duration curves by individual seasons for the Vipava gauging station. The black, red, green, and blue lines represent the spring, summer, autumn, and winter seasons, respectively.

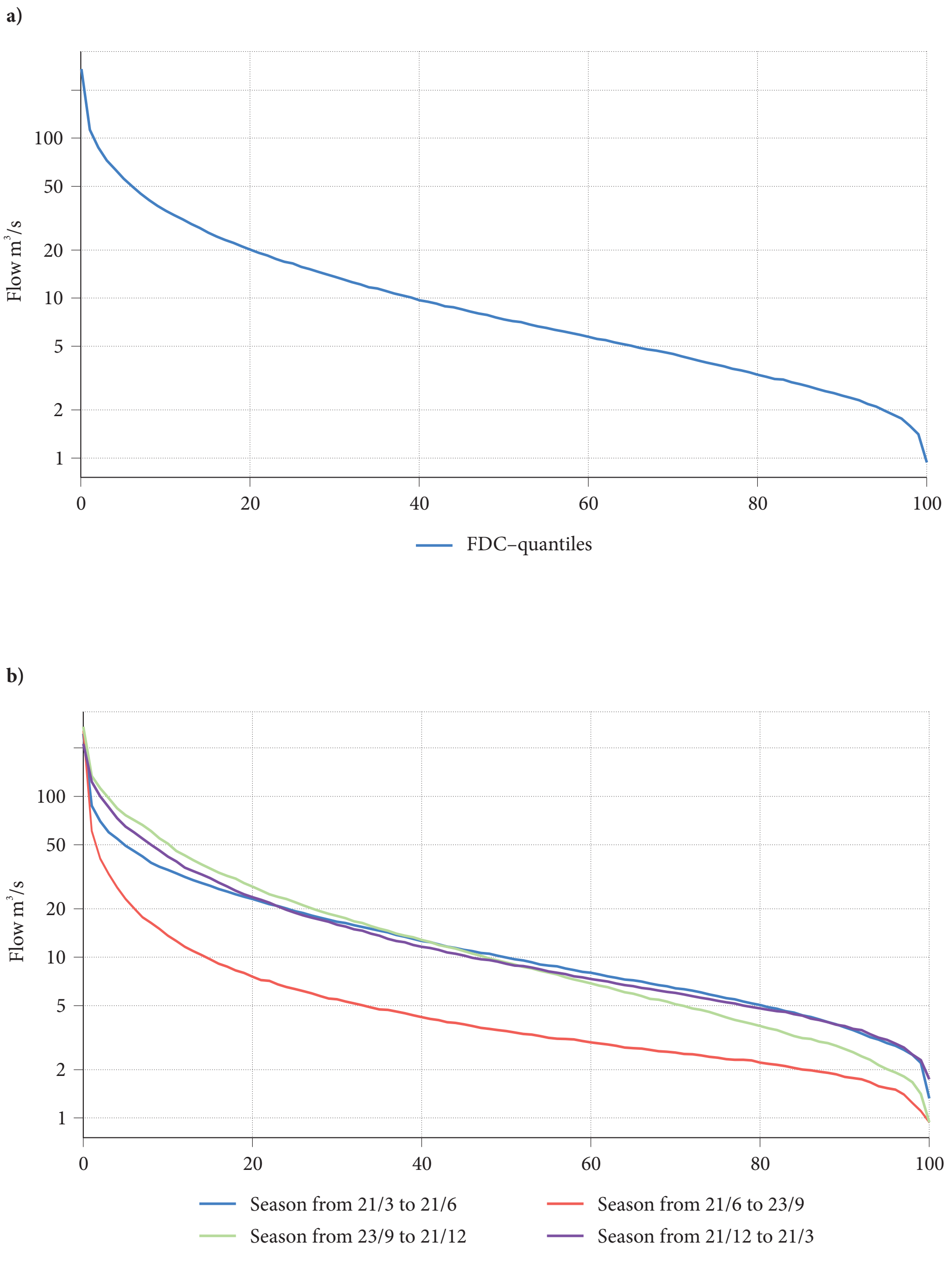

Figure 6: A: Flow duration curve for the whole data set (1951–2014) of the Dornberk gauging station; B: Flow duration curves by individual seasons for the Dornberk gauging station. The black, red, green, and blue lines represent the spring, summer, autumn, and winter seasons, respectively.

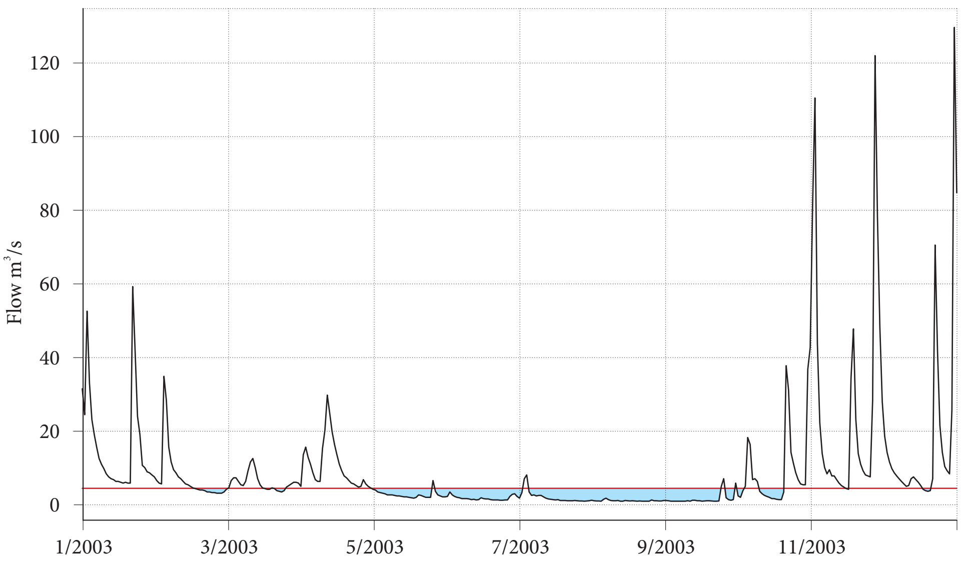

Figure 7: Streamflow deficit for the gauging station Dornberk. The threshold value is marked with the red line and the volume of the streamflow deficit with the blue colour.

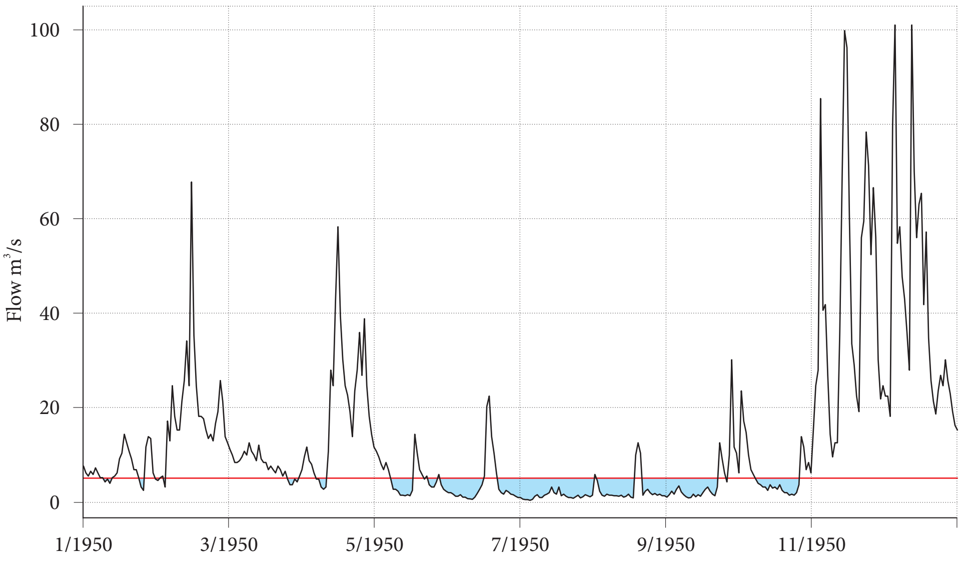

Figure 8: Streamflow deficit for the gauging station Miren. The threshold value is marked with the red line and the volume of the streamflow deficit with the blue colour.

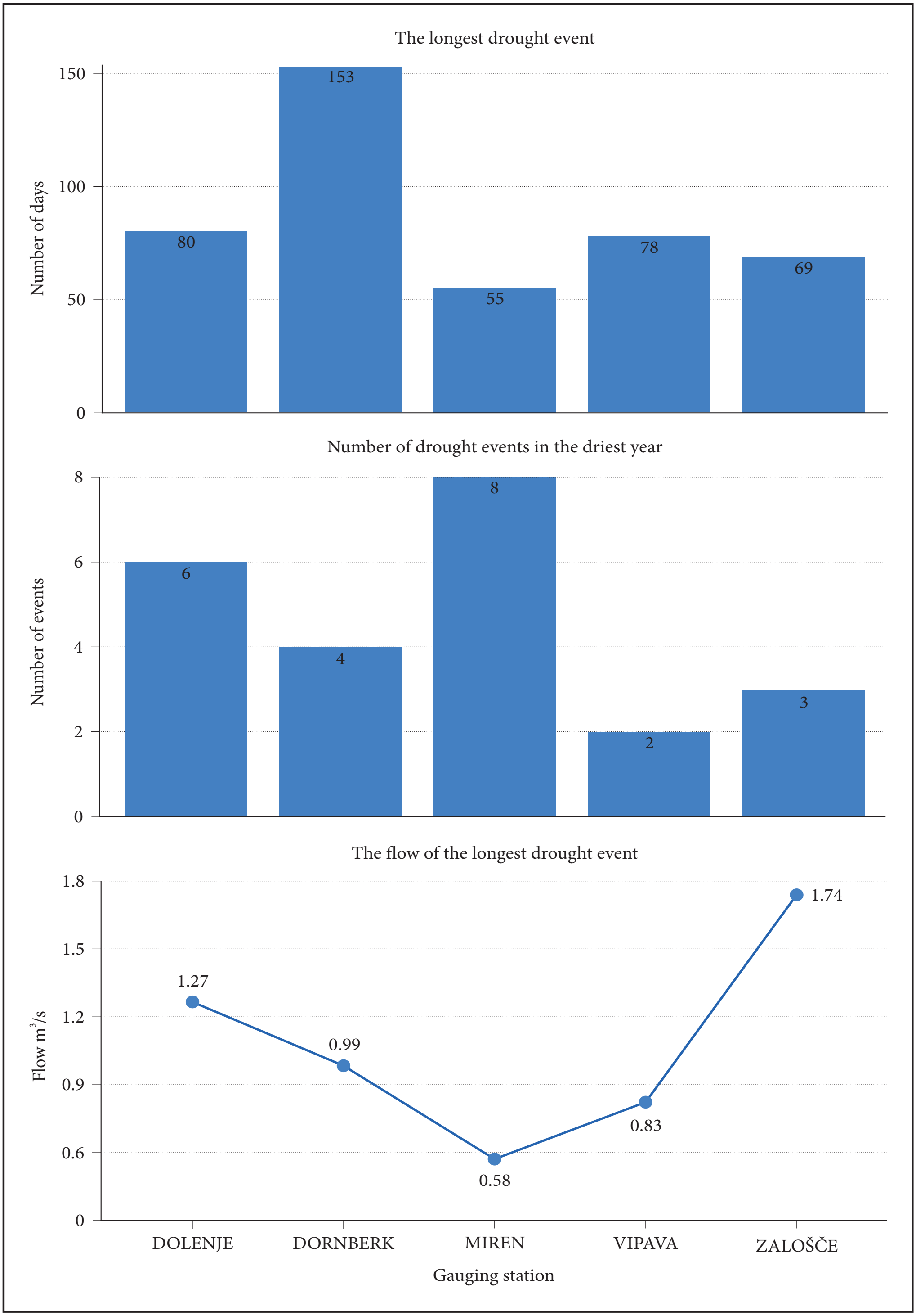

Figure 9: Comparison of the duration and flow of the longest drought events and the number of drought events in the driest year between gauging stations.

drought events in the same year were much shorter, lasting only 7 and 12 days, respectively, and fell in the winter and autumn seasons.

In contrast, the shortest identified drought event was recorded at the Miren gauging station in 1950 (Figure 8, Table 3) and lasted for 55 days. It began in the second half of June (June 24th) and reached a minimum flow of 0.58 m^3/s. This drought event is one of eight drought events that occurred in 1950. The other drought events that year were shorter than 30 days.

Figure 9 shows a comparison of drought events among the individual gauging stations in the Vipava Valley. As described earlier, the longest drought event occurred at the Dornberk gauging station in 2003. The Vipava (78 days in 2004) and Dolenje (80 days in 2012) stations have almost half the length of the longest drought event. The shortest drought event was recorded at the Miren gauging station. The lowest flow measured during drought events was 0.58 m^3/s at the Miren gauging station. At the Miren station, the number of drought events in the driest year 1950 was the highest (8 events). Only two drought events occurred at the Vipava gauging station.

3.4 Recession curve analysis

The recession curve analysis presented in Table 4 shows that the IRS method gives slightly higher values for the recession constants than the MRC method, a fact that was reported by Sapač, Rusjan and Šraj (2019). The Zalošče gauging station has the highest recession constant and the Miren station the lowest. Due to the shortness of the data set (5 years), results of the Zalošče station are difficult to compare with the results of other stations. With high values of recession constants, Zalošče station is followed by the Vipava and Dolenje stations. As mentioned above, stations Vipava and Dolenje had the largest BFI at the same time. Thus, it seems that higher BFI values are associated with higher values of the recession constant, suggesting that surface water and groundwater reserves are well connected. This is consistent with the conclusions of previous studies (e.g. Sapač, Rusjan and Šraj 2019). Furthermore, Jelovčan and Šraj, 2020, analysing groundwater levels in piezometers in the Vipava Valley, reported that piezometers in the lower part of the valley, where the river is in contact with karst, e.g. well-permeable carbonate rocks (limestones), respond less and slower to higher water levels of the Vipava River.

3.5 Seasonality

Seasonality indices for individual gauging stations are presented in Table 5. The calculated values of the seasonality ratio are comparable and range from 0.538 (Miren) to 0.773 (Vipava). Values below 1 indicate that the Vipava River has predominantly low-flow summer regime, which is common in Slovenia, according to Petek, Kobold and Šraj (2014).

The results of the seasonality index show that low flows at all stations occurred in the second half of the year, i.e. in summer. The mean day of occurrence of low flow is at the end of August and it is comparable for the stations Dolenje, Dornberk and Miren. Of the listed stations, only the Vipava station deviates slightly, where the low flow occurs on September 11th. The parameter r is quite large at all stations, indicating that most of the extreme drought events occurred on the calculated mean days, so the variability of the occurrence of low flows throughout the year is low. Petek (2014) also obtained very similar results for both the seasonality ratio and the seasonality index at the Dornberk gauging station.

Table 4: Results of the recession constants in days by the IRS and MRC method (threshold value Q70) for individual gauges in the Vipava Valley.

Seglength	Vipava		Dolenje		Dornberk		Zalošče*		Miren	
	C (IRS)	C (MRC)	C (IRS)	C (MRC)	C (IRS)	C (MRC)	C (IRS)	C (MRC)	C (IRS)	C (MRC)
4	12.59	10.47	11.63	9.22	10.90	9.13	12.61	10.06	10.29	7.97
5	13.14	11.21	12.30	10.05	11.33	9.54	13.91	11.52	10.53	8.72
6	13.60	11.58	13.61	11.15	12.27	10.47	14.94	12.67	11.57	9.50
7	14.72	12.21	14.71	12.31	12.95	10.83	15.32	13.30	13.11	10.80

* Due to the short set of data (5 years) at the Zalošče gauging station, the results cannot be compared directly with the results of other stations.

Table 5: Seasonality ratio and seasonality index for the considered gauging stations.

Gauging station	Seasonality ratio	Seasonality index		
		Θ [rad]	D [/]	r [/]
Vipava	0.773	4.370	254 (11th September)	0.635
Dolenje	0.686	4.109	239 (27th August)	0.875
Dornberk	0.578	4.176	243 (31st August)	0.817
Zalošče*	0.631	4.149	241 (29th August)	0.889
Miren	0.538	4.109	239 (27th August)	0.810

* Due to the short data set (5 years) at the Zalošče gauging station, the results cannot be directly compared with the results of other stations.

4 Discussion

According to Dolinar (2008), the spatial and temporal variability of precipitation in Slovenia is very high. The precipitation regime also changes seasonally. Furthermore, the simulations for the future precipitation in Slovenia predict a significant decrease in summer and its increase in winter by the middle of the 21st century (Slovenian Environment Agency 2019). According to the National water management plan 2016–2021 (Ministrstvo za okolje … 2016) will also have a significant impact on river flows. The same is true for the Vipava Valley, where the autumn season is characterised by an increase in precipitation and other seasons by a decrease (Kajfež Bogataj 2013). Due to the changes in the precipitation regime, low flows and the associated drought and water scarcity can become a major problem in the coming decades (Oblak, Kobold and Šraj 2021). This fact is also supported by the finding that the frequency and intensity of extreme drought events is increasing (Slovenian Environment Agency 2017; Šebenik, Brilly and Šraj 2017). Therefore, a comprehensive analysis of low flows is very important for efficient water management and planning. The analysis of low flows using various indicators, which is presented in this article, is necessary from the point of view of regulation and conservation of water quantities (e.g. Ferk et al. 2020). It is important for sustainable and efficient use of water or, during the minimum available quantities, for anticipating restrictions on the water use in different sectors, for example, agriculture (for irrigation), industry or energy production.

5 Conclusion

In the study, we presented the results of comprehensive analyses of low flows in the Vipava River Valley based on daily discharge data at the Vipava, Dolenje, Dornberk, Zalošče and Miren gauging stations for the available measurement series. Due to the short data set of the Zalošče gauging station, we cannot compare it with the other stations. Therefore, the Zalošče gauging station is included in the study only to achieve greater comprehensiveness of data presentation even though it is not considered in the analyses.

Low-flow statistics analysis shows that maximum low flows occur in spring (April) and autumn (November). Minimum low flows occur in July and August. Relatively low BFI values indicate low soil permeability in the Vipava Valley. The similarity between MAM7 and Q95 values indicates that the study area is characterised by a temperate climate as expected.

The hydrographs for wet years show relatively large fluctuations in flow during the year at all gauging stations, when the flow can increase by more than 10 times relative to the baseflow during precipitation. The hydrographs for dry years show that periods of higher flows occur at the beginning and end of the year, while in the intermediate period, when there is no precipitation, the flow consists mainly of the baseflow.

From the analysis of the flow duration curves we can conclude that the flow is about 2 m^3/s most of the time and can increase 10 times or more during the extreme events. This result is consistent with the shape of the curves, from which we can see that karst underground sources contribute substantially to the surface flow, especially during summer.

The analysis of the streamflow deficit shows that the longest drought event was registered at the Dornberk gauging station in 2003 and lasted 153 days. The highest number of drought events (8 events) in the driest year was recorded at Miren station in 1950.The analysis of recession curves shows that the stations Vipava and Dolenje have high recession constants and Miren station the lowest. We also find that higher BFI values are associated with higher recession constants, indicating a good connection between surface water and groundwater.

The seasonality indices show that low flows occur mainly in summer. The calculated values of seasonality ratios are less than 1 at all gauging stations, indicating that the Vipava River experiences a predominant summer regime of low flows. The mean day of the low flow occurrence is at the end of August.

The study presents in one place the analysis of low flows for all gauging stations on the Vipava River and as such can form the basis for further analysis and research. A comprehensive analysis of low flows at all gauging stations on the Vipava River and their mutual comparison has not yet been carried out. Existing studies and research on low flows on the Vipava River include only single gauging stations and only individual calculations.

Analysis of low flows can be performed for any location, but it is important and necessary especially in areas where the amount of water is limited. In general, the comprehensive analysis of low flows is necessary in terms of sustainable water management and planning.

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