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ANALYSIS OF LOW-FLOW CONDITIONS IN A HETEROGENEOUS KARST CATCHMENT AS A BASIS FOR FUTURE PLANNING OF WATER RESOURCE MANAGEMENT

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ABSTRACT

Understanding and prediction of low-flow conditions are fundamental for efficient water resources planning and management as well as for identification of water-related environmental problems. This is problematic especially in view of water use in economic sectors (e.g., tourism) where water-use peaks usually coincide with low-flow conditions in the summer time. In our study, we evaluated various low-flow characteristics at 11 water stations in the non-homogenous Ljubljanica river catchment in Slovenia. Approximately 90% of the catchment is covered by karst with a diverse subsurface, consisting of numerous karst caves. The streams in the remaining part of the catchment have mainly torrential characteristics.

Based on daily discharge data we calculated and analysed values of 5 low-flow indices. In addition, by analysing hydrograph recession curves, recession constants were determined to assess the catchment's responsiveness to the absence of precipitation. By using various calculation criteria we analysed the influence of individual criteria on the values of low-flow recession constants. Recession curves are widely used in different fields of hydrology, for example in hydrological models, baseflow studies, for low-flow forecasting, and in assessing groundwater storages which are crucial in view of assessing water availability for planning water resources management.

Moreover, in the study we also investigated the possible impact of projected climate change (scenario RCP4.5) on low-flow conditions in two sub-catchments of the Ljubljanica river catchment. For the evaluation we used the lumped conceptual hydrological model implemented in the R package airGR. For periods 2011-2040, 2041-2070, and 2071-2100 low-flow conditions were evaluated based on flow duration curves compared with the 1981-2010 period. The lowest discharges at all water stations in the Ljubljanica river catchment occur mostly during the summer months. Our results for the future show that we can expect a decrease of the lowest low-flows in the first two 30-year periods, while in the last one low-flows could increase by approx. 15%. However, the uncertainty/variability of the results is very high and as such should be taken into account when interpreting and using the results.

This study demonstrates that evaluation of several low-flow characteristics is needed for a comprehensive and holistic overview of low-flow dynamics. In non-homogeneous catchments with a high karstic influence, the hydrogeological conditions of rivers should also be taken into account in order to adequately interpret the results of low-flow analyses. This proved to be important even in case of neighbouring water stations.

Keywords: low-flow analysis, low-flow indices, Ljubljanica River catchment, climate change, heterogeneous karst catchment

INTRODUCTION

For efficient water resources management and planning, understanding and prediction of low-flow conditions is needed. This is fundamental for identification of water-related environmental problems too, since in many cases, the low-flow season coincides with the high-demand season for water use (e.g. in tourism). According to the World Meteorological Organization (WMO, 1974), "low-flow is flow of water in a stream during prolonged dry weather". As the definition was not quite clear, therefore, Smakthin (2001) added an important complement to the definition that low flows are seasonal phenomena and an integral part of all streams.

In the literature, one can find many different methods and indices, by which low-flow characteristics can be described. For example, for estimating the contribution of stored water in the catchment to the surface stream water, baseflow index (Gustard et al., 1992), different mean annual minima, and hydrograph recession analyses are widely used. Flow-duration curves contain information on how much of the time over a certain period individual flow is exceeded. In the review paper of Tallaksen (1995), baseflow recession analysis is discussed in detail. Laaha and Blöschl (2006) did a regionalization of low flows in Austria based on different seasonality indices. A comprehensive overview about low-flow hydrology, including different indices and methods, can be found in Smakthin (2001) and WMO (2008). Based on the Manual of Low Flow Estimation and Prediction (WMO, 2008) package *lfstat* (Koffler et al., 2016) included in R (R Core Team, 2018) software was also prepared. The package was used also in our study for calculation of low-flow indices.

In this paper, we present some of the calculated low-flow indices in the Ljubljanica river catchment. More specifically, BFI, Q50, Q90, ratio Q90/Q50, and recession constants. A more detailed discussion is devoted to recession constants, which are often used in hydrological modeling and consequently in planning measures for efficient water resources management. Moreover, we included in this paper the results of investigating the influence of projected climate scenario RCP 4.5 (one of the most optimistic scenarios about greenhouse gas emissions) on low flows in the future at two stations in the considered Ljubljanica river catchment.

STUDY AREA AND DATA

In our study, we evaluated various low-flow characteristics at 11 water stations in the non-homogenous Ljubljanica river catchment in Slovenia (Fig. 1). Approximately 90% of the catchment is covered by karst with a diverse subsurface, consisting of numerous karst caves. The streams in the remaining part of the catchment have mainly torrential characteristics and are located in the north-western part of the catchment. Hydrogeological properties of the catchment are in detail discussed in Kogovšek (2001, 2004).

The catchment's altitude varies between 300 and 1800 m a.s.l. Consequently, annual rainfall is between 1400 mm and more than 2000 mm. The lowest (1400-1600 mm) is at Ljubljana Marshes) while more than 2000 mm can be expected in the Snežnik karst plateau in the southern part of the catchment.

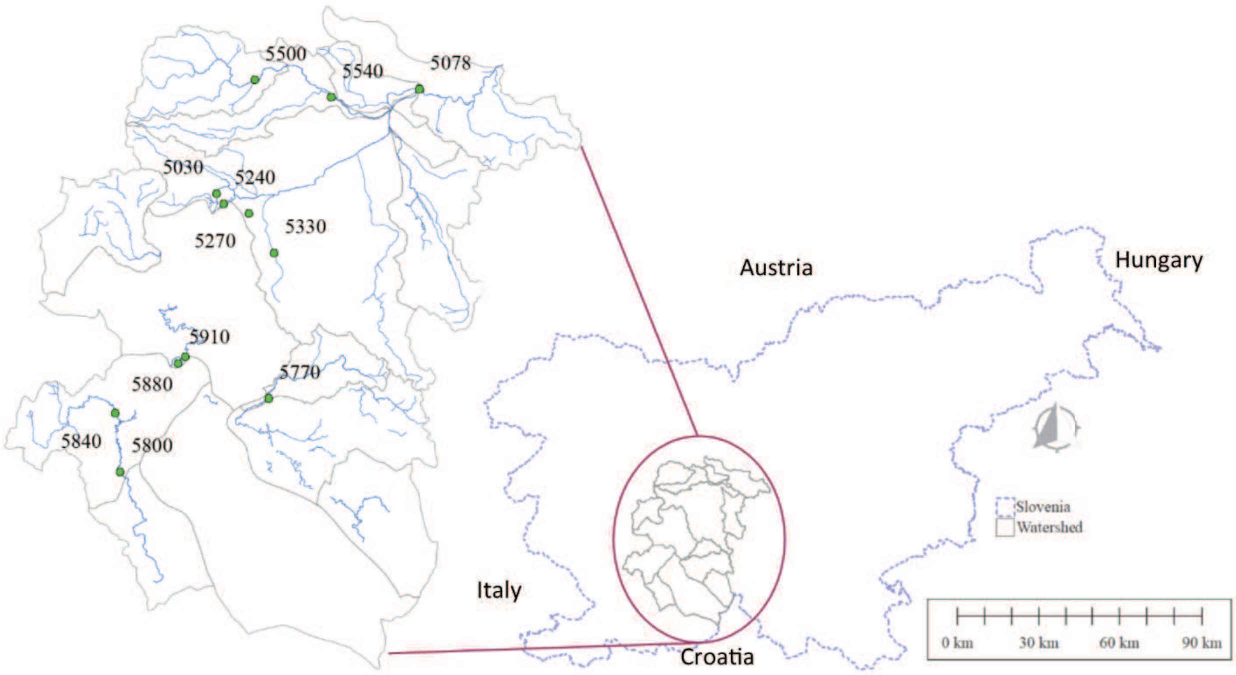

Fig. 1. Study area with locations (green dots) of water stations under consideration in the Ljubljanica river catchment

Analyses of low-flow indices were made based on the daily discharge data series (ARSO, 2018) at 11 water stations in the Ljubljanica river catchment (Fig. 1). In the catchment, there were more water stations operating at the time, however, we included in the analyses only those, where the length of the available data was more than 25 years, and where there were no major gaps in data (i.e. for more than 5 consecutive years).

METHODS

In this paper, we present 5 low-flow indices, which were evaluated in our study: baseflow index, Q50 and Q90, which are flows exceeded 50% and 90% of the time, respectively, ratio Q90/Q50, and recession constant.

With baseflow index (BFI), which is defined as the ratio between the baseflow volume and the total flow volume and is one of the most frequently used indices, the proportion of the total flow that comes from stored sources of the catchment (e.g., groundwater, lakes) can be expressed (Gustard et al., 1992; Smakhtin, 2001). When the duration of low-flows is of interest, flow duration curves (FDC) contain information on how much time over a certain period the individual flow/discharge is exceeded. In low-flow analyses, Q95, Q90, and Q70 are the most frequently used. However, ratios Q90/Q50 are sometimes more informative and contain similar information as BFI (Caissie and Robichaud, 2009).

The recession constant was evaluated by using the *lfstat* package. In the past many methods for its evaluation were developed. We used MRC (master recession curve) and IRS (individual regression segment) methods and different calculation criteria to assess the influence of calculation criteria on the results of recession constants. When calculating the recession constant, either by the MRC or IRS method, one has to define the following calculation criteria: length of the segment (days), and the period for which the discharge threshold is calculated, from which onwards the recession curves are taken into account. We made 24 calculations of recession constants for each of the stations: using 4, 5, 6 and 7 days as the segment lengths, calculating threshold Q70 for the whole data set, by months and by seasons, and for 2 different methods (Fig. 2). The seasons were defined as follows: the time from 1 April to 30 November was defined as summer, and the time from 1 December to 31 March was defined as winter. The influence of the selected computational criteria on the values of recession constants was investigated by using the paired *t*-test. In the *t*-test the mean values of two dependent samples were compared. This is reasonable, since we have calculations with the same input data, but with one criterion changed (e.g., the influence of the calculation method). A two-sided test with level of significance $\alpha=0.05$ was used. When analyzing the influence of method selection (i.e. MRC or IRS) one test was made (1 combination), while when analyzing the influence of the segment length we made 6 tests (6 combinations), and to analyze the influence of the time period for which the threshold for recession analysis Q70 was calculated, we did 3 tests (3 combinations). Since the Ljubljanica river catchment is highly non-homogenous, one can expect that this will be reflected also in the recession constants. Therefore, the results of different stations are not comparable, and tests were made for each of the 10 stations separately. The Mali Otok station was excluded from the analysis because the sample of the calculated recession constants was too small for an objective interpretation of *t*-test's results. A description of the tested criteria and the methodology for investigating their influence on the results of recession constants can be found in Sapač et al. (2019b).

All the indices mentioned above, including the methodologies, are in detail described in Smakthin (2001), WMO (2008), and Koffler et al. (2016).

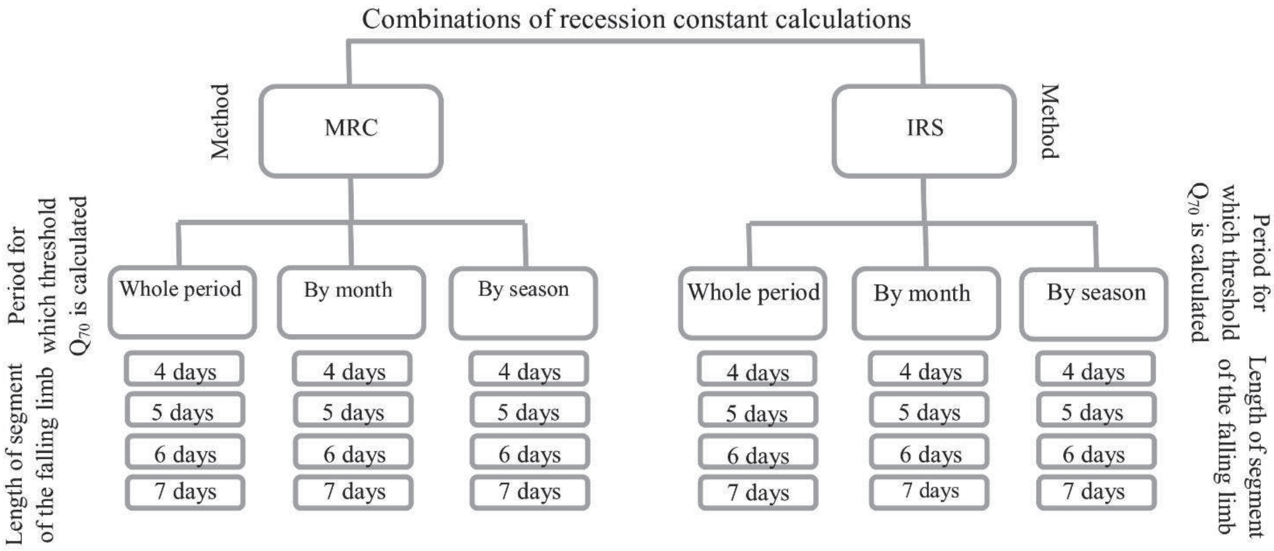

Fig. 2. Scheme of combinations of recession constant calculation for 1 station. For 1 station 24 different recession constants were obtained (adopted by Sapač et al., 2019*b*).

In addition to the current picture of low flows, we were also interested in the future flow situation in relation to the projected climate scenarios. We took into account scenario RCP 4.5, which is one of the most optimistic climatic scenarios.

The catchments of the Ljubljanica river upstream to the Vrhnika water station and the Nanoščica river (Mali Otok water station) have been further investigated in view of the effects of climate change on low flows in the future. Lumped conceptual model GR6J (Pushpalatha et al., 2011) was used at Nanoščica river, while at the Ljubljanica river the CemaNeigeGR6J model (Valéry et al., 2014a; Valéry et al., 2014b) was used for the investigation. CemaNeigeGR6J in comparison with the GR6J model includes also a snow module and two additional parameters. In both models the input data are rainfall and evapotranspiration. However, in the CemaNeige model additional required data are the air temperature and the catchment hypsometric curve. To run the models we used the airGR package (Coron et al., 2017; Coron et al., 2018) in the R software (R Core Team, 2018).

For the selected RCP 4.5 scenario we analyzed 5 combinations of global climate models (GCM) and regional climate models (RCM) which were after some bias corrections to model data used for investigating the influences of the projected climate scenario on precipitation, air temperature, and evapotranspiration in Slovenia (ARSO, 2017; Bertalanič et al., 2018). The projected situation suggests a decrease of summer precipitation and therefore longer and more frequent droughts. On the other hand, in autumn one can expect an increase of precipitation and therefore more frequent flood events. To confirm these assumptions, we performed hydrological modeling. More details about the models, data, and methodology used can be found in Sapač et al. (2019a).

The results of the influence of the projected climate change on flows at two stations in the Ljubljanica river catchment will be presented by flow duration curves. To more clearly present how the flows are expected to change in the future, we will plot flow-duration curves for the next three 30-year periods (2011-2040, 2041-2070, 2071-2100) as a percentage of the reference flow duration curve (1981-2010). Therefore, for each Q in the flow duration curve, one can see if it is expected to be higher or lower than in the reference period.

RESULTS AND DISCUSSION

Table 1 presentes the results of all low-flow indices included in this study. Based on BFI values one can notice that the highest contribution of water from delayed sources (e.g. groundwater) to the surface water is in case of Malni and Bistra, where BFI is 0.85 and 0.91, respectively. This is confirmed also by the Q90/Q50 ratio. The highest the ratio the greater the contribution from the groundwater and other sources of stored water in the catchment. At both stations, Malni and Bistra, the Q90/Q50 ratio is 0.43. On the other hand, the smallest contribution from delayed sources to the surface water is observed at Mali Otok, according to BFI 0.22, and ratio Q90/Q50 0.07. A relatively high ratio Q90/Q50 is observed also on torrential rivers Gradaščica and Šujica, 0.43 and 0.40, respectively.

In the last column of

Table 1, the average values of recession constants, calculated using 24 calculation criteria, are reported. The results of recession constants confirm the results of the BFI and Q90/Q50 ratio. The hydrograph recession limb is falling the slowest at the Malenščica (Malni) and Bistra (Bistra) rivers with average recession constants of 26 and 27 days, whereas the fastest declining of the falling limb is observed at the Mali Otok and Cerknica water stations with average recession constants of 3.8 and 4.7 days, respectively. At other stations under consideration, average recession constants are between 9.7 and 15.8 days.

Table 1. Low-flow indices for water stations in the Ljubljanica river catchment. The recession constant is reported as the average value of the results obtained by using various calculation criteria

River and water station name	Water station code	BFI	Q50 [m^3/s]	Q90 [m^3/s]	Q90/Q50	Recession constant (average) [days]
Ljubljanica, Vrhnika	5030	0.55	14.3	3.24	0.23	10.2
Ljubljanica, Moste	5080	0.56	37.4	11.20	0.30	12.1
Ljubljanica, Verd	5240	0.67	5.34	1.48	0.28	12.7
Bistra, Bistra	5270	0.85	7.54	3.21	0.43	27.0
Borovniščica, Borovnica	5330	0.47	0.59	0.19	0.32	10.7
Gradaščica, Dvor	5500	0.5	1.37	0.59	0.43	15.8
Šujica, Razori	5540	0.47	0.82	0.33	0.40	9.7
Cerkniščica, Cerknica	5770	0.41	0.61	0.16	0.26	4.7
Nanoščica, Mali Otok	5840	0.22	0.44	0.03	0.07	3.8
Unica, Hasberg	5880	0.63	13.6	2.87	0.21	12.3
Malenščica, Malni	5910	0.91	6.97	3.03	0.43	26.0

Unica and Malenščica rivers are geographically relatively close. However, low-flow indices show that their hydrogeological properties, which influence the amount of water in the stream, are significantly different. Therefore, to adequately interpret the results of low-flow analyses, the hydrogeological conditions of rivers should also be taken into account.

In Table 2 all the 24 recession constants calculated for each individual water station are presented. The minimum values for each station are highlighted in green color, while maximum values are marked with yellow color. the minimum values were at 8 out of 11 stations calculated while using the MRC method, a segment length of 4 days and where Q70 as a threshold for the recession analysis was calculated for the entire period of data. At the Dvor water station it was similar. However, Q70 was calculated separately for each season (1 April-30 November, 1 December-31 March). At water stations Malni and Bistra, which were based on low-flow indices recognized as stations with the largest contribution of groundwater, the minimum value was obtained with the MRC method, Q70 calculated for the entire period of data, and with the segment length of 5 days.

Regarding the maximum values of the recession constants, one can notice that the combination of criteria is not as uniform as for minimum values. However, the segment length is 6 or 7 days (with the exception of Malni station), in all cases (with the exception of Mali Otok) calculated with the IRS method. The period of Q70 calculations varies from one station to another.

Since we obtained 24 recession constants for each station (with the exception of Mali Otok, where some values could not be obtained), we wanted to know if there are any statistically significant differences between the values. Three calculation criteria were investigated: the method of calculation, the segment length of the falling limb, and the period for which Q70 as a threshold for recession analysis is calculated. By using a dependent two-tailed *t*-test (α=0.05) it was found that at all 10 stations there is a statistically significant difference between the values calculated by the MRC and IRS methods. More specifically, the recession constants calculated by the IRS method are on average by 3.1 day higher than those calculated by the MRC method.

Table 2. Recession constants calculated for all 24 combination of criteria for 11 stations in the Ljubljanica river catchment. Combination of criteria in the first column is interpreted as follows: the first part represents the method (MRC or IRS), the second part represents the segment length in days (4, 5, 6, and 7), and the third part is the period for which the Q70 threshold is calculated (E = entire period of data, M = monthly, S = seasonally).

Combination of criteria	Water station										
	5030	5078	5240	5270	5330	5500	5540	5770	5840	5880	5910
	Vrhnika	Moste	Verd	Bistra	Borovnica	Dvor	Razori	Cerknica	Mali Otok	Hasberg	Malni
MRC_4_E	7.1	8.7	8.7	20.6	6.5	10.2	5.6	2.2	2.3	10.5	19.4
MRC_4_M	9.3	11.1	11.0	25.9	7.9	11.0	6.9	3.2	4.0	11.0	28.1
MRC_4_S	8.9	10.3	10.2	22.6	7.6	8.5	8.1	2.4	3.5	11.2	21.4
IRS_4_E	10.0	12.1	12.5	29.0	10.7	14.5	8.5	4.6	3.4	12.6	24.3
IRS_4_M	9.3	13.2	14.2	30.2	10.2	16.1	9.3	5.4	NA*	12.8	36.7
IRS_4_S	10.7	12.8	13.9	29.9	11.5	15.5	9.8	4.8	3.6	12.8	27.5
MRC_5_E	7.7	9.6	9.1	20.2	8.0	11.8	8.3	3.5	2.5	10.9	19.0
MRC_5_M	9.6	11.6	12.0	27.7	9.1	12.4	7.4	5.3	4.5	11.3	28.3
MRC_5_S	9.7	11.1	10.7	23.6	9.3	9.1	8.9	3.6	3.8	11.6	21.9
IRS_5_E	9.9	13.1	12.8	28.2	13.1	16.8	10.9	5.6	3.4	12.6	22.7
IRS_5_M	11.7	13.0	15.2	31.1	11.7	18.8	10.4	6.7	4.5	13.0	35.8
IRS_5_S	11.1	13.3	14.4	29.6	12.9	19.3	10.1	5.5	4.1	13.2	27.4
MRC_6_E	8.8	10.4	10.9	21.3	8.0	14.4	9.3	3.9	2.9	11.2	19.5
MRC_6_M	10.1	11.8	13.0	28.4	9.2	16.0	6.6	4.8	4.7	11.8	29.1
MRC_6_S	10.2	11.9	12.0	24.9	10.2	9.2	9.7	3.5	4.9	12.1	22.4
IRS_6_E	10.4	13.8	13.4	28.5	14.0	18.2	12.4	6.5	3.5	12.8	22.6
IRS_6_M	12.0	13.4	15.2	31.2	11.5	19.8	11.0	6.4	4.6	13.6	35.7
IRS_6_S	11.6	14.1	14.2	30.3	13.6	21.6	11.6	5.7	4.2	13.6	27.4
MRC_7_E	9.6	10.7	11.3	21.1	12.6	16.6	11.4	3.7	3.0	11.8	20.6
MRC_7_M	9.9	12.3	13.3	29.5	8.9	19.3	9.8	3.7	4.2	12.0	28.5
MRC_7_S	10.9	11.4	12.9	25.4	10.5	18.3	9.2	3.3	3.6	12.2	22.7
IRS_7_E	11.0	13.9	13.8	27.4	15.7	20.3	12.9	7.2	NA*	13.3	23.5
IRS_7_M	12.3	13.6	15.1	32.2	10.5	21.3	12.2	6.1	4.1	13.7	33.6
IRS_7_S	11.9	13.9	15.0	29.6	13.6	21.3	11.6	5.4	NA*	13.7	26.8
σ_x [days]	1.3	1.5	1.9	3.6	2.3	4.1	1.9	1.4	0.7	1.0	5.2
σ_x [%]	13	12	15	13	22	26	19	29	18	8	20

* the calculation of the recession constant value was not successful

Minimum value | Maximum value

Results of the influence of the segment length on the value of the recession constant are not as uniform as in the case of the calculation method. Where in the *t*-test the recession constants calculated with the segment length of 4 days were used, the differences are statistically significant at

7 or 8 of a total 10 stations. This suggests that the segment length 4 days has the highest impact on the value of the recession constant. However, one should note that this does not mean that results are not appropriate or correct.

When we look at the same results from a station's point of view, we see that at station Malni there is no statistically significant difference between the pairs of the recession constant in any combination, while in the case of the Bistra station it is only one combination where a statistically significant difference was noticed (5 and 6 days). We could conclude that at stations with a greater contribution of the groundwater and other sources to the streamflow, the segment length of the falling limb has a smaller influence on the recession constant value. To exclude characteristics of the catchment, which are reflected in the value of the recession constant, we additionally investigated the influence of the segment length on the value of the recession constant. Firstly, for each of the 24 combinations, the average value of 10 stations was calculated. Secondly, we calculated the differences between the average values of 12 pairs which differed only in the type of the method. We obtained 4×3 values which vary according to the segment length (4, 5, 6, and 7 days). Finally, we calculated 4 average values, based on which the smallest difference was found in the case of the segment length of 7 days (the average of differences 2.6 days).

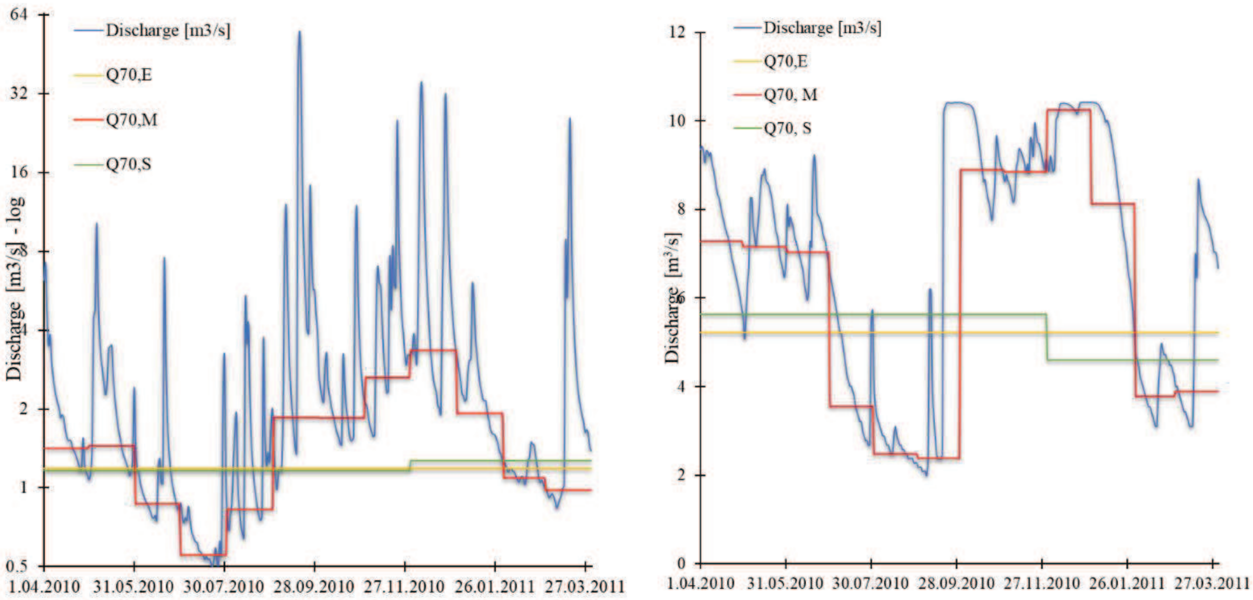

Fig. 3. Discharge at Dvor (left) and Malni (right) water stations between 1 April 2010 and 31 March 2011 with Q70 calculated for the entire period of data (yellow line), monthly (red line), and seasonally (green line). Please note that the plot for Dvor (left) is in the logarithmic scale

When analyzing the influence of the tested period to calculate the threshold for the start of the recession analysis (in our case Q70), we performed three *t*-tests for each station (i.e. monthly vs. seasonal, monthly vs. entire period, and seasonal vs. entire period). It was found that the Razori station is the only one where the impact of the selection of the period on the result of the recession constant is not statistically significant. The opposite (i.e. test showing statistically significant differences for all three combinations of criteria) was found at stations Verd, Bistra, Hasberg, and Malni. This suggests that the selection of the period for calculating Q70 as a threshold influences the result of the recession constant. At Vrhnika and Moste, a statistically significant difference was found for the following combinations: the entire period of data vs. monthly, and the entire period of data vs. seasonal. The opposite was found for stations Borovnica and Cerknica. At Dvor station on the torrential Gradaščica river, a statistically significant difference was found when testing pairs with Q70 calculated with the entire period of data and monthly calculated Q70.

Additionally, the influence of the selected period for calculating Q70 was investigated also by the graphical representation of a 1-year hydrograph of two randomly selected stations. Stations with different hydrogeological characteristics were selected, i.e. Malni (5910) and Dvor (5500), and the hydrographs between 1 April 2010 and 31 March 2011 were plotted (Fig. 3). One should note that the results of the *t*-test are not directly comparable with the 1-year hydrograph. However, the graphical representation helped us interpret why there are some differences or similarities between the stations and what influences the results. On the plots (Fig. 3) hydrographs for Dvor (left) and Malni (right) are presented with a blue line, while Q70 is presented by yellow, red, and green lines, calculated for the entire period of data (1 year), monthly, and seasonally, respectively. While Q70 values, calculated for the entire period and seasonally, do not differ much, there is a greater variability within the monthly calculated Q70. Since Q70 represents the beginning of the recession curve from where on it is included in the recession analysis, in the case of Malni in some months (autumn, spring) we actually did not analyze low flows. On the annual basis, monthly-calculated Q70 in the autumn months represents high flows. This is not the case for the Dvor water station. The reason could be attributed to the torrential characteristic of the Gradaščica river. At this river, the high range between low and high flows is typical. Moreover, due to the quick response of the Gradaščica catchment, the hydrograph decreases and increases rapidly (Fig. 3, left). For these selected periods and water stations, we recalculated the recession constants by using all combinations of criteria. We found that at the Malni station, the average value of recession constants where Q70 was calculated monthly is much higher than in the case where Q70 was calculated seasonally and for the entire period of data. For Dvor, the differences between the obtained recession constants are not significant. More about the methodology and results can be found in Sapač et al. (2019*b*).

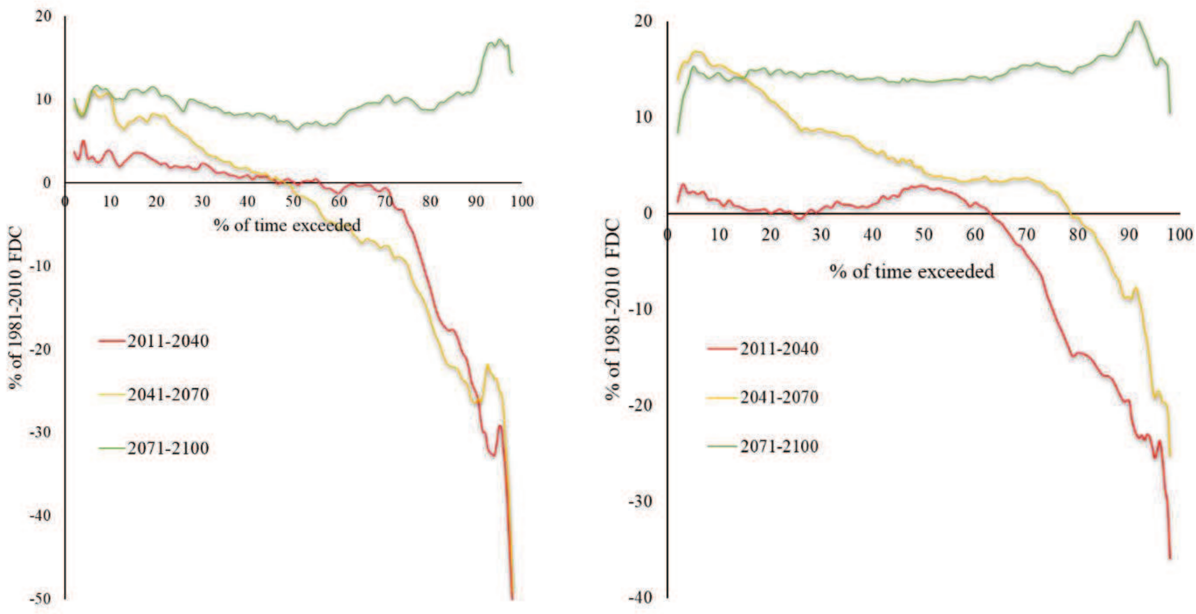

Fig. 4. Flow duration curves (Q2–Q98) for three future periods as percentage of the reference flow duration curve (1981-2010) for two investigated stations: the Nanoščica river (left), and the Ljubljanica river at Vrhnika (right)

In the third part of this study we investigated how low-flows under the projected climate scenario RCP 4.5 will change in the future. For stations at the Nanoščica (Mali Otok) and Ljubljanica (Vrhnika) rivers we obtained 5 data sets with daily discharges (5 simulations). Later on, the discharge data sets were sorted from the highest to the smallest. For each time step, the median value was calculated. Based on the data set of median values, flow duration curves were constructed. Fig. 4 shows flow duration curves for three future periods (2011-2040, 2041-2070, 2071-2100) as a percentage of the reference flow direction curve (1981-2010) (Sapač et al., 2019a). Regarding the low flows, one can notice that in the first two periods (2011-2040 and 2041-2070) flows that are exceeded by more than 60% of the time are expected to be lower in comparison with the reference period. In case of the smaller sub-catchment of the Nanoščica river, the decline of Q90 is expected to be by approx. 25% lower in the periods 2011-2040 and 2041-2070. However, in the third period 2071-2100 the whole flow duration curve is above zero, which means that all flows including high flows are expected to increase. A similar situation can be expected also in the larger sub-catchment of the Ljubljanica river (Vrhnika station), where in the first two periods there are expectations of lowering the low-flows, whereas in the period 2071-2100 all flows (Q2-Q98) are expected to be higher by 10 to 20% compared with the reference period. However, the uncertainty/variability of the results is very high and as such should be taken into account when interpreting and using the results.

CONCLUSIONS

This paper is divided into three major sections: (1) calculation and analysis of low-flow indices in the non-homogenous Ljubljanica river catchment with daily discharge data, (2) a detailed analysis of recession constant results and investigation how calculation criteria influence the value of the recession constant, and (3) investigation of the moderately optimistic scenario RCP 4.5 on the low flows at two stations in the Ljubljanica river catchment.

In the first part we calculated 5 low-flow indices for 11 water stations in the Ljubljanica river catchment. Indices show that the largest contribution from the groundwater (and other sources of stored water in the catchment) to the stream is at Malni and Bistra stations. On the other hand, the smallest contribution was found for the Mali Otok water station.

As part of this study we investigated the influence of the calculation criteria on the values of recession constants. We were not looking for the answer as to which combination gives the best results, but rather which criteria under consideration influence the recession constant the most. Analysis has shown that when investigating the influence of the method on the recession constant, at all stations statistically a significant difference was found. The IRS method gives on average by 3.1 days higher results than the MRC method. On the other hand, the influence of other two criteria is not so uniform and the differences between the results vary from one station to another. However, at rivers with a high BFI, the influence of the segment length on the recession constant is smaller (Sapač et al., 2019b).

Although some methods for the recession analysis were considered subjective in the past, Lamb and Beven (1997) think that subjectivity is not necessarily a weakness. Experts who know a catchment very well are able to judge the quality and relevance of the data, which are later used for the recession analysis. The same is true for the assessment of the analysis results. This is suggested also with the findings in our study. For example, the threshold for the recession analysis should be in our case selected for each water station individually. Moreover, the periods with the highest evapotranspiration usually coincide with the periods of low flows – and it is precisely for these periods that we want to determine catchment characteristics and connection with the water storage in the catchment (Tallaksen, 1991; Demuth and Schreiber, 1994).

The third part of this study was to investigate how the projected climate change will influence the low flows in the future, more specifically in three 30-year periods 2011-2040, 2041-2070, and 2071-2100. Construction of the relative flow duration curves (flow duration curves as the percentage of the reference flow duration curve for the period 1981-2010) suggests that in the first two 30-year periods we can expect even lower low flows. However, in the third period 2071-2100 one could expect that low flows will be higher than in the reference period by approx. 15% (Sapač et al., 2019a). However, the uncertainty/variability of the results is very high and as such should be taken into account when interpreting and using the results.

The study demonstrates that evaluation of several low-flow characteristics is needed for a comprehensive and holistic overview of low-flow dynamics. In non-homogeneous catchments with a high karstic influence, the hydrogeological conditions of rivers should also be taken into account in order to adequately interpret the results of low-flow analyses. This proved to be important even in the case of neighboring water stations.

REFERENCES

ARSO. Assessment of Climate Change in Slovenia Until the End of the 21st Century; Slovenian Environment Agency: Ljubljana, Slovenia, 2017. (In Slovenian). URL: http://meteo.arso.gov.si/uploads/probase/www/climate/text/sl/publications/povzetek-podnebnih-sprememb-temp-pad.pdf (accessed on 17 April 2019).

ARSO. Arhiv hidroloških podatkov. arhiv površinskih voda. 2018. URL http://vode.arso.gov.si/hidarhiv/pov_arhiv_tab.php (accessed on 6 May 2018).

Bertalanič R., Dolinar M., Draksler A., Honzak L., Kobold M., Kozjek K., Lokošek N., Medved A., Vertačnik G., Vlahovič, Ž., et al. Assessment of Climate Change in Slovenia Until the End of the 21st Century. Synthesis Report, Part 1. Slovenian Environment Agency: Ljubljana, Slovenia, 2018; 156p, (In Slovenian). URL: http://www.meteo.si/uploads/probase/www/climate/text/sl/publications/OPS21_Porocilo.pdf (accessed on 17 April 2019).

Caissie D., Robichaud S. Towards a better understanding of the natural flow regimes and streamflow characteristics of rivers of the Maritime Provinces. *Can. Tech. Rep. Fish. Aquat. Sci.* 2009. 2843, viii+53.

Coron L., Perrin C., Michel C. airGR: Suite of GR Hydrological Models for Precipitation-Runoff Modelling. R Package Version 1.0.9.64. 2017. URL: https://webgr.irstea.fr/en/airGR/ (accessed on 17 April 2019).

Coron L., Thirel G., Delaigue O., Perrin C., Andreassian V. The suite of lumped gr hydrological models in an R package. *Environ. Model. Softw.* 2017. 94, 166–171.

Demuth S., Schreiber P. Studying storage behaviour using an operational recession method. In: Seuna P., Gustard A., Arnell N. W., Cole G. A. (Eds.). FRIEND: Flow Regimes from International Experimental Network Data. Proceedings of Second FRIEND Conference, Braunschweig, Germany, October 1993. 1994. IAHS Publ. No. 221: 51−59.

Gustard A., Bullock A., Dixon J.M. Low flow estimation in the United Kingdom, 1992. Report No. 108. Institute of Hydrology, Wallingford, UK.

Koffler A.D., Gauster T., Laaha G., Gauster M.T., Package ‘ lfstat’. 2016. p. 63.

Kogovšek J., Physico-chemical properties of waters in the Malenščica recharge area (Slovenia). *Acta Carsologica*. 2004. Vol. 33. P. 143–158.

Kogovšek J. Monitoring the Malenščica water pulse by several parameters in November 1997. *Acta Carsologica*. Vol. 2001. 30, P. 39–53.

Laaha G., Blöschl G. Seasonality indices for regionalizing low flows. *Hydrol. Process.* 2006. Vol. 20. P. 3851–3878. https://doi.org/10.1002/hyp.6161

Lamb R., Beven K. Using interactive recession curve analysis to specify a general catchment storage model. *Hydrology and Earth System Sciences*. 1997. Vol. 1. P. 101–113. https://doi.org/10.5194/hess-1-101-1997

Pushpalatha R., Perrin C., Le Moine N. Mathevet T., Andreassian V. A downward structural sensitivity analysis of hydrological models to improve low-flow simulation. *J. Hydrol*. 2011. Vol. 411. P. 66–76.

R Core Team. R: A language and environment for statistical computing. *R Foundation for statistical computing*. 2018. Vienna, Austria.

Sapač K., Medved A., Rusjan S., Bezak N. Investigation of Low- and High-Flow Characteristics of Karst Catchments under Climate Change. *Water*. 2019a. Vol. 11(5). 925. https://doi.org/https://doi.org/10.3390/w11050925

Sapač K., Rusjan S., Šraj M. Influence of calculation criteria on the values of low-flow recession constants in a non-homogenous catchment in Slovenia. *Acta Hydrotechnica.* 2019b. Vol. 32. P. 1–19. https://doi.org/https://doi.org/10.15292/acta.hydro.2019.01

Smakhtin V.U. Low flow hydrology: A review. *J. Hydrol.* 2001. Vol. 240. P. 147–186. https://doi.org/10.1016/S0022-1694(00)00340-1

Tallaksen L.M. *Recession rate and variability with special emphasis upon the influence of evapotranspiration.* Dr. Scient. Thesis. Univ. Oslo, Rapp. Hydrol. 25. 1991.

Tallaksen L.M. A review of baseflow recession analysis. *J. Hydrol.* 1995. Vol. 165. P. 349–370. https://doi.org/10.1016/0022-1694(94)02540-R

Valery A., Andreassian V., Perrin C. As simple as possible but not simpler: What is useful in a temperature-based snow-accounting routine? Part 1—Comparison of six snow accounting routines on 380 catchments. *J. Hydrol.* 2014a. Vol. 517. P. 1166–1175.

Valery A., Andreassian V., Perrin C. As simple as possible but not simpler: What is useful in a temperature-based snow-accounting routine? Part 2—Sensitivity analysis of the cemaneige snow accounting routine on 380 catchments. *J. Hydrol.* 2014b. Vol. 517. P. 1176–1187.

WMO. *International glossary of hydrology*. Paris, UNESCO and Geneva, WMO. 1974. P. 393.

WMO. Manual on Low-flow Estimation and Prediction. *Operational Hydrology Report.* WMO, Geneva, Switzerland. 2008. P. 136. https://doi.org/WMO-No. 1029.