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FLOW DURATION CURVES (FDC) FOR SELECTED MOUNTAIN CATCHMENTS IN SLOVAKIA

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Abstract. The article presents the characteristics of the Flow Duration Frequency (FDC) curve statistics of the Hornád River and its tributaries for a period of 60 years (1961-2020) and compares the flow duration curves divided into decades (1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2010 and 2011-2020). High flows corresponding to the flow of 10% (Q10) and 25% (Q25), medium flows corresponding to the flow of 50% (Q50) and low flows corresponding to the flow of 70% (Q75) and 90% (Q90) were analyzed. The study covered 7 catchments located in the Hornád river catchment (eastern Slovakia). The greatest variability of flows in individual decades in relation to the multi-year period 1961-2020 was recorded in all threshold ranges at the station in Prešov Sekčov. The highest values were recorded in the range of low flows (Q90), for which the coefficient of variation was 0.38 (Q90) and 0.27 (Q75). A high coefficient of variation Cv was also recorded for the Košické Olšany station in terms of low flows for Q75 and Q90, which were 0.21 and 0.19, respectively. At the remaining stations, the variability of Cv ranged from 0.08 to 0.15 for Q75 and Q90. The variability of high flows (Q10 and Q25) ranged from 0.11 to 0.17 for all catchments except for the Prešov Sekčov station, for which the values were 0.21 and 0.27, and Stratená 0.19 and 0.18, respectively.

Keywords: Discharge, flow duration curves, basin Hornád

1. INTRODUCTION

River flow is an important element characterizing the size of water resources. Useful tools such as the Flow Duration Curve (FDC) are used to characterize the hydrological regime of rivers and flow variability (Booker and Snelder 2012). The Flow Duration Curve is used to determine the flow of a certain percentage (quantile) in river basins. The FDC is compiled by sorting the observed river flow time series in ascending order and comparing it with the corresponding duration (Banasik and Hejduk, 2013; Westerberg et al., 2011; Sadegh et al., 2016). The FDC is a graphical representation of the frequency distribution of the full flow regime of a river and is one of the most widely used techniques in hydrology (Croker et al., 2003, Ye et al.,

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2018; Ridolfi et al., 2020). The FDC is widely used due to the characterization of extreme flows such as high and low flows (Burgun and Aksoy, 2018; Ma et al., 2023). Among other things, the FDC is of great importance in the design and planning of the use of water resources in water construction. The use and flow characteristics of rivers in the catchment is the key to developing the most appropriate water infrastructure (Wijesekera, 2020). In the literature, you can find the use of the FDC for large rivers in terms of planning electricity production, water consumption, habitat suitability and low flow reinforcement, and many others (Vogel and Fennessey 1994; Rosburg et al., 2017). In recent years, studies using the FDC for small rivers with small catchment areas and for rivers where systematic hydrological observations are not carried out (Viola et al., 2010; Nobert et al., 2011). The reason for this are the observed climate changes, which significantly affect the hydrological regime of rivers and the size of water resources (Kubiak-Wójcicka, 2020). Bearing in mind that small mountain catchments are very sensitive to local physiographic properties such as land use, geological structure, topography, research on such areas is extremely valuable and necessary. This study fills the research gap in terms of analyzes conducted in shorter periods of time, taking into account the smallest elementary catchment areas covered by hydrological measurements. The aim of this study was to construct, analyze and interpret flow duration curves and their statistics in order to understand low and high flow dynamics for 7 catchments located in Slovakia.

2. MATERIALS AND METHODS

2.1. Study area

The research area covered the Hornád river basin, which is located in Slovakia. Within the Hornád River catchment, 7 sub-basins have been designated, which are diverse in terms of area (Fig. 1). The Hornád River receives 2 largest tributaries: the right tributary Hnilec and the left tributary Torysa. The smallest catchment is closed by the Stratená station with an area of approx. 64.67 km^2, while the largest area is closed by the Ždaňa station with an area of 4249 km^2 (Table 1).

Table 1. Discharge characteristics in the years 1961-2020

No.	River	Hydrological station	Catchment area km^2	Flow (m^3·s^{-1})		
				maximum	average	minimum
1.	Hnilec	Stratená	64.67475	19.3	1.077	0.08
2.	Hnilec	Švedlár	352.0132	110.0	3.509	0.230
3.	Hnilec	Jaklovce	604.018	178.0	5.942	0.621
4.	Hornád	Kysak	2337.005	454.188	17.491	2.71
5.	Sekčov	Prešov Sekčov	350.910	97.762	1.894	0.08
6.	Torysa	Košické olšany	1296.257	292.392	7.598	0.54
7.	Hornád	Ždaňa	4249.141	772.254	28.859	3.94

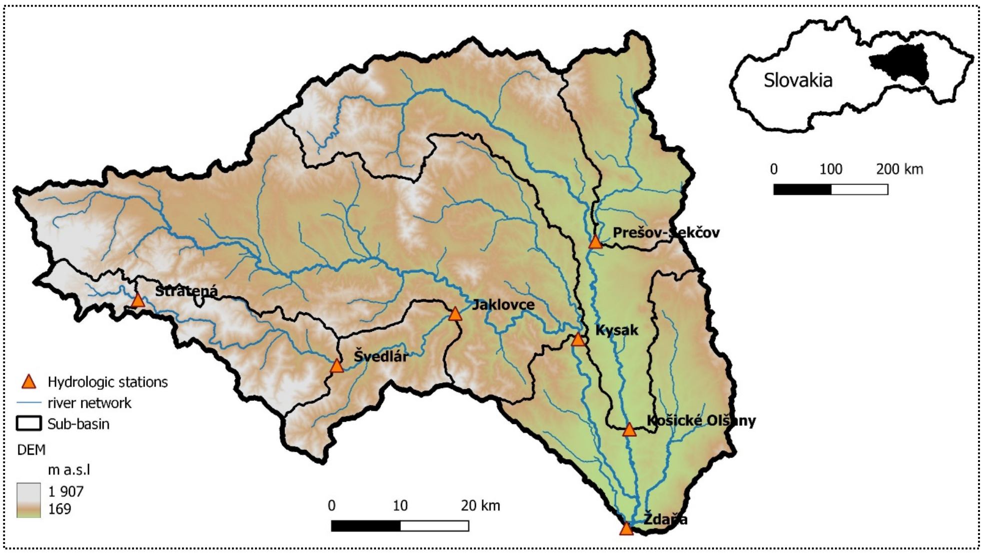


Fig. 1. ***Hornád River catchment***

2.2. Data and methods

This study uses data on daily flow rates over a 60-year observation period for 7 hydrological stations located in the Hornád River catchment. The data was provided by the Slovak Hydrometeorological Institute and covered the research period 1961-2020. Different threshold values are adopted in the literature to define periods of low and high flows. For periods of low flows, threshold values of 70%, 75%, 90%, 95%, 99% and 99.5% are usually adopted. On the other hand, for periods with high flows, threshold values of 1%, 5%, 10%, 20% and 25% are usually adopted. The choice of the appropriate threshold largely depends on the region and importance (Kubiak-Wójcicka et al. 2021, Tomaszewski and Kubiak-Wójcicka, 2021). For the purposes of this study, the threshold ranges of 10% and 25% (denoted Q10 and Q25), medium 50% (Q50) and low 75% and 90% (Q75 and Q95) were adopted for the determination of periods with high flows. The research period 1961-2020 was divided into 10-year periods (decades), for which FDC was prepared for each station. The use of 10-year periods is an appropriate sample size to use for this study (Hope and Barta, 2012). The obtained decadal curves were compared with the curve prepared for the multiannual period 1961-2020 and the variability of flows at individual threshold values was determined.

3. RESULTS
3.1. Comparison of water resources between individual catchments

In order to compare water resources between individual catchments, the flow rate was converted to a unit outflow. The most water-rich catchment is Hnilec in the Stratená profile, whose average unit runoff in the years 1961-2020 was 16.65 $dm^{3}\cdot s^{-}$

$^{1}\cdot km^{-2}$, while the lowest water content was recorded in the catchment of the Sekčov river in the Prešov Sekčov (5.398 $dm^{3}\cdot s^{-1}\cdot km^{-2}$) (Table 2). The highest unit outflow values were recorded for the Hnilec tributary in the Švedlár (312,488 $dm^{3}\cdot s^{-1}\cdot km^{-2}$) and Stratená (298,416 $dm^{3}\cdot s^{-1}\cdot km^{-2}$). The lowest runoff values were recorded in the catchment area of the Sekčov River in the Prešov Sekčov (0.227 $dm^{3}\cdot s^{-1}\cdot km^{-2}$) and the Torysa River in the Košické Olšany (0.416 $dm^{3}\cdot s^{-1}\cdot km^{-2}$).

Table 2. Maximum, average and minimum unit runoff in individual sub-catchments in the years 1961-2020

No.	River	Hydrological station	Unit outflow ($dm^{3}\cdot s^{-1}\cdot km^{-2}$)		
			maximum	average	minimum
1.	Hnilec	Stratená	298.416	16.653	1.236
2.	Hnilec	Švedlár	312.488	9.969	0.653
3.	Hnilec	Jaklovce	294.693	9.837	1.028
4.	Hornád	Kysak	194.346	7.484	1.159
5.	Sekčov	Prešov Sekčov	278.595	5.398	0.227
6.	Torysa	Košické Olšany	225.566	5.862	0.416
7.	Hornád	Ždaňa	181.743	6.791	0.927

The threshold range of 10%, 25%, 50%, 75% and 90% was adopted for determining periods with high and low value flows. High flows ranged from 10% to 25%, medium 50% and low outflows were characterized by threshold values from 75% to 90% of the percentile. Table 3 presents the unit runoff values for all catchments, considering the individual threshold values. The highest water content in terms of unit outflows at the level of the 90th percentile was recorded in the Stratená (4.849 $dm^{3}\cdot s^{-1}\cdot km^{-2}$), while the lowest in the Prešov Sekčov (1.110 $dm^{3}\cdot s^{-1}\cdot km^{-2}$) and Košické Olšany (1.417 $dm^{3}\cdot s^{-1}\cdot km^{-2}$). The situation is similar in the case of water abundance at the 10th percentile. The highest values were recorded at the Stratená station, and the lowest at the Prešov Sekčov and Košické Olšany stations.

Table 3. Unit outflow in dm^3/skm^2 from the catchment 1961-2020

Percent-age of time the flow is exceeded	Stratená	Prešov Sekčov	Švedlár	Jaklovce	Košické Olšany	Kysak	Ždaňa
10	34.069	10.609	21.281	20.871	11.917	15.112	13.906
25	19.196	5.430	11.581	11.259	6.324	8.270	7.649
50	11.138	2.904	6.129	6.132	3.471	4.585	4.236
75	6.950	1.669	3.534	3.720	2.006	3.182	2.753
90	4.849	1.110	2.388	2.529	1.417	2.610	2.183

3.2. FDC frequency from 1961 to 2020

Flow FDC presents the cumulative distribution of flows in the years 1961-2020. It is the relationship between any discharge value and the percentage of time the discharge is equal to or exceeded. It is usually calculated based on available series of daily flow values. The table presents the threshold values of flows for high, medium and low flows in the entire analyzed period of 1961-2020. According to the obtained results, the values of flows corresponding to Q50 are lower than the values of average long-term flows for a given multi-year period. The Q50 flow is from 52% to 67% of the long-term average flow. The lowest value was obtained for Prešov Sekčov (52%) and Jaklovce (56%), and the highest for Stratená (67%). This means that the higher the percentage value, the Q50 flow is closer to the long-term average flow. Thus, for the Prešov Sekčov and Jaklovce stations, the values are the lowest, which may mean that the average flows over the analyzed multi-year period show high variability during the year. An important piece of information is the Q90:Q50 ratio, which indicates the percentage share of groundwater in the supply of rivers. The ratio of Q90 to Q50 ranged from 39% to 57%. The highest share of groundwater in the flow was recorded at the Kysak (57%) and Ždaňa (51%) stations, and the lowest at the Švedlár and Prešov Sekčov profiles (39%).

Table 4. Daily flow in m^3/s from the catchment 1961-2020

Percent-age of time the flow is exceeded	**Stratená**	**Prešov Sekčov**	**Švedlár**	**Jaklovce**	**Košické Olšany**	**Kysak**	**Ždaňa**
10	2.203	3.722	7.491	12.606	15.447	35.318	59.092
25	1.241	1.905	4.076	6.801	8.198	19.328	32.503
50	0.72	0.999	2.157	3.704	4.499	10.717	18.002
75	0.449	0.585	1.244	2.247	2.6	7.437	11.700
90	0.314	0.389	0.84	1.528	1.837	6.099	9.276
Q90:Q50	0.44	0.39	0.39	0.41	0.41	0.57	0.51

When analyzing the flow duration curve, pay attention to the slope of the curve at the top and bottom of the graph. The slope of the curve at the upper end indicates high flows, which may be the result of short-term, moderate rainfall and the decreasing permeability of the catchment. The steep slope at the lower end of the FDC indicates a low natural storage capacity (Kotei et al., 2016).

3.3. FDC over decades

In Fig. 3-9 presents flow duration curves for decades, i.e. 1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2010 and 2011-2020 for individual catchments. The most even distribution of FDC curves in individual decades is characteristic of the Švedlár and Jaklovce stations. The steep slope in the high flow zone of the FDC indicates that high flows are highly variable and for the size of the catchment.

The most outlier course of the curve was recorded in the years 1961-1970 at the Kysak and Ždaňa stations, which may be the result of activities related to the construction of the Ružín I and II reservoir system.

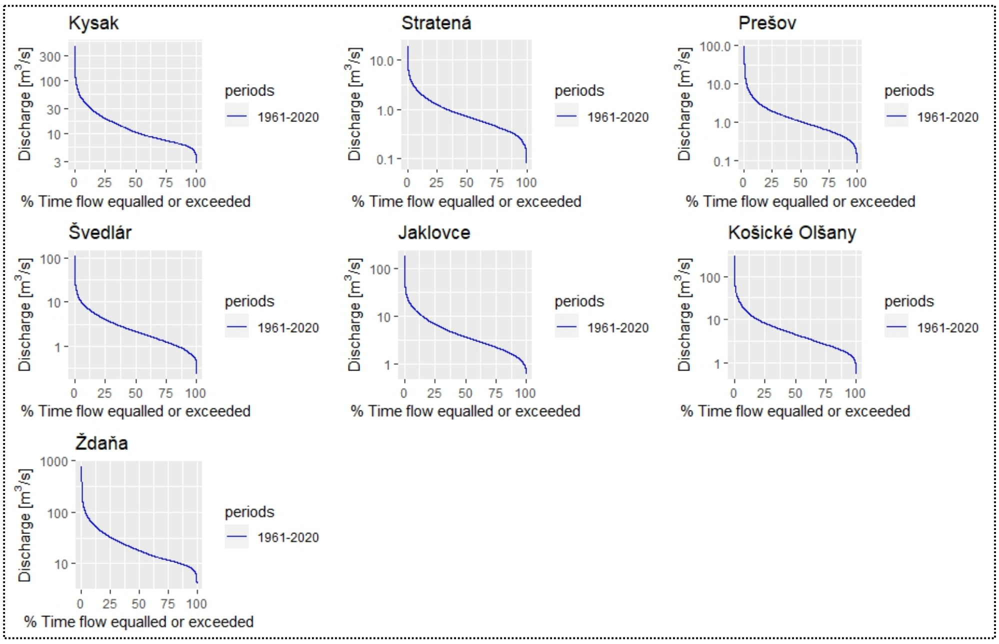


Fig. 2. ***Graph with FDC presentation for the average period of 1961-2020***

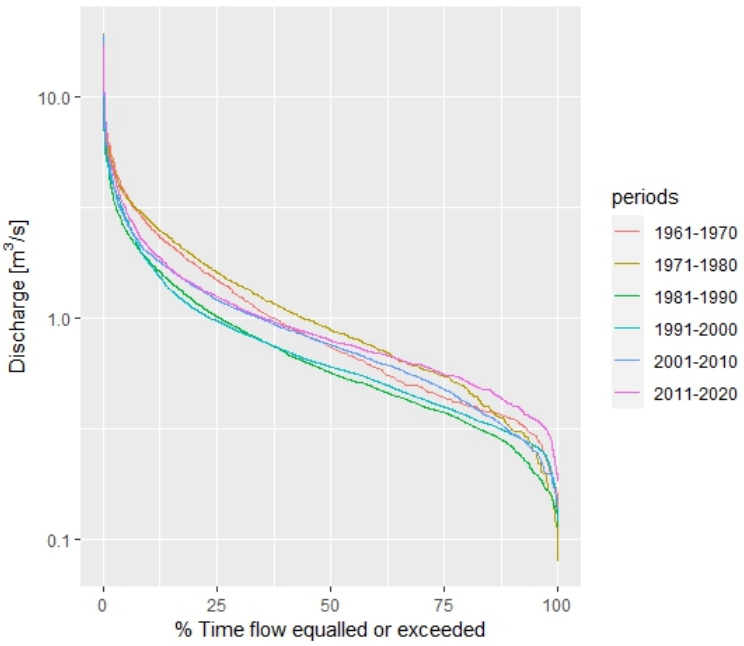


Fig. 3. ***Flow duration curves of daily discharges for Stratená in decades 1961-2020***

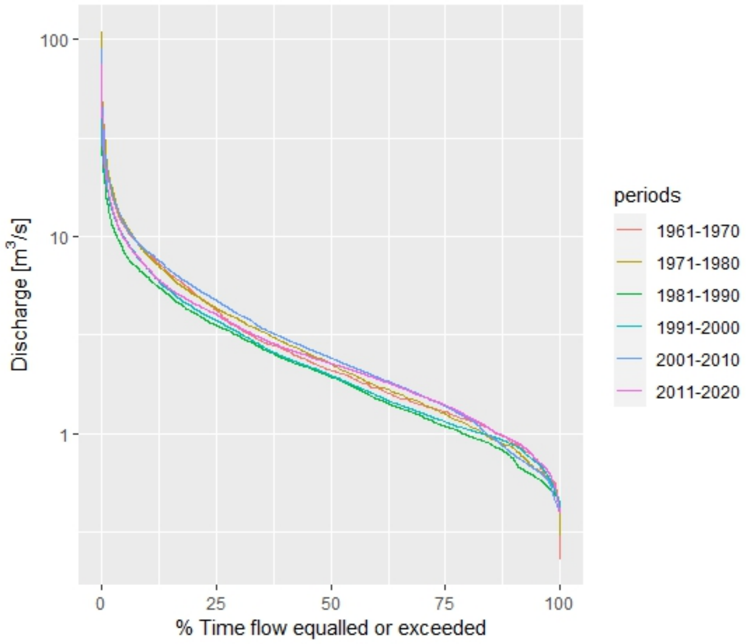


Fig. 4. ***Flow duration curves of daily discharges for Švedlár in decades 1961-2020***

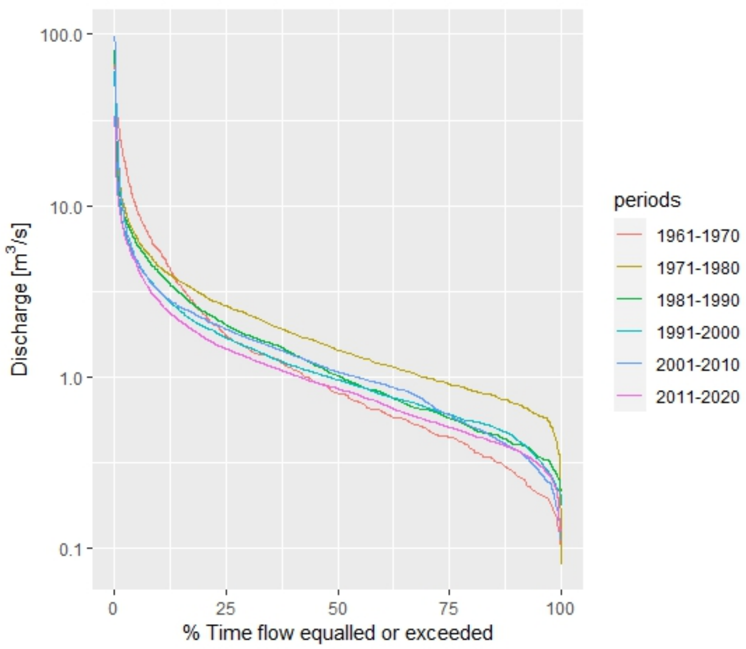


Fig. 5. ***Flow duration curves of daily discharges for Prešov Sekčov in decades 1961-2020***

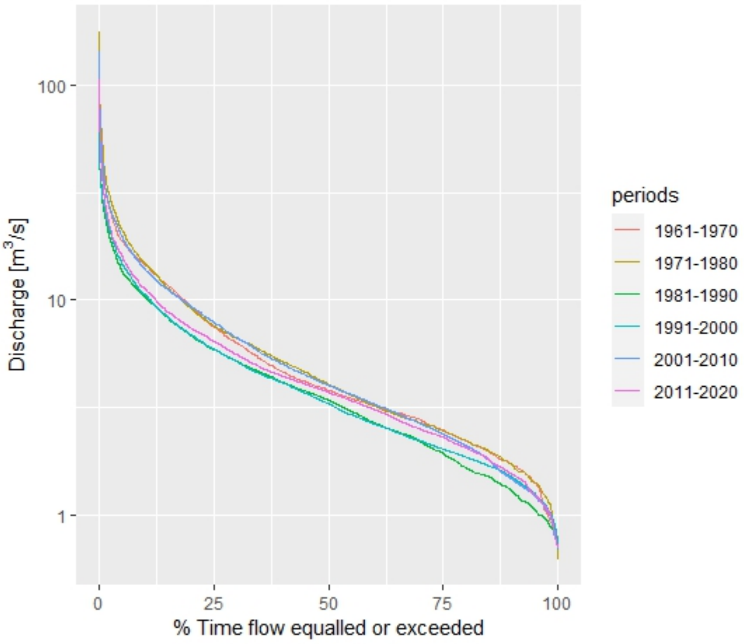


Fig. 6. ***Flow duration curves of daily discharges for Jaklovce in decades 1961-2020***

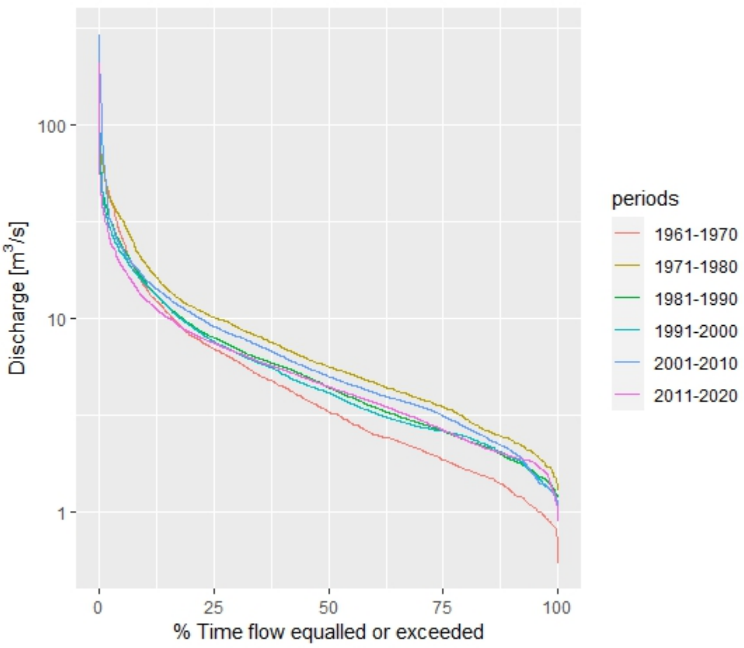


Fig. 7. ***Flow duration curves of daily discharges for Košické Olšany***

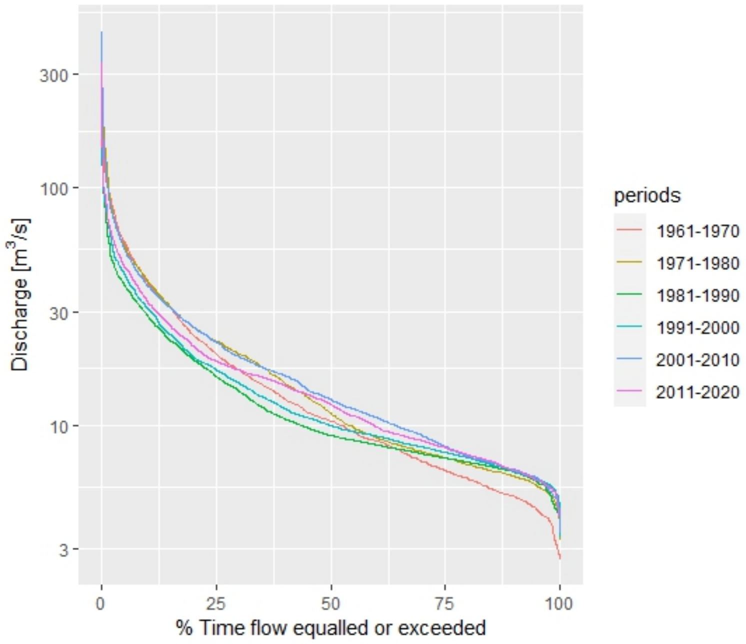


Fig. 8. ***Flow duration curves of daily discharges for Kysak***

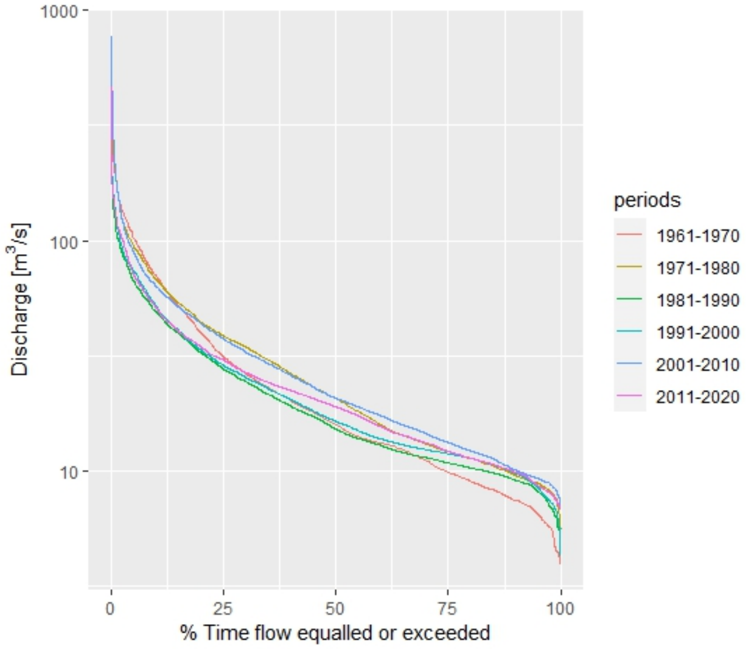


Fig. 9. ***Flow duration curves of daily discharges for Ždaňa***

The reservoirs were built in the years 1963-1970, while its energy part was put into full operation only in 1973 (Kubiak-Wójcicka et al., 2023). The most diversified course of the curves was recorded at the Prešov Sekčov station.

Noteworthy is the flow with the probability of occurrence of 90%, which is characterized by low flows (tables 5-10).

Table 5. Daily flow in m^3/s from the catchment 1961-1970

Percent-age of time the flow is exceeded	Stratená	Prešov Sekčov	Švedlár	Jaklovce	Košické Olsany	Kysak	Ždaňa
10	2.633	5.444	8.391	14.636	14.606	39.928	70.835
25	1.494	1.731	4.238	7.522	6.957	19.977	31.283
50	0.744	0.800	2.095	3.803	3.280	10.427	15.975
75	0.437	0.441	1.294	2.483	1.846	6.397	9.854
90	0.350	0.264	0.893	1.727	1.250	5.001	7.455
Q90:Q50	0.47	0.33	0.43	0.45	0.38	0.48	0.47

Table 6. Daily flow in m^3/s from the catchment 1971-1980

Percent-age of time the flow is exceeded	Stratená	Prešov Sekčov	Švedlár	Jaklovce	Košické Olšany	Kysak	Ždaňa
10	2.792	4.370	8.072	14.842	19.401	40.555	67.960
25	1.610	2.593	4.333	7.604	10.100	22.605	38.612
50	0.888	1.426	2.262	4.060	5.606	11.187	20.627
75	0.547	0.903	1.259	2.470	3.476	7.293	12.127
90	0.312	0.700	0.837	1.709	2.331	6.074	9.582
Q90:Q50	0.35	0.49	0.37	0.42	0.42	0.54	0.46

Table 7. Daily flow in m3/s from the catchment 1981-1990

Percent-age of time the flow is exceeded	Stratená	Prešov Sekčov	Švedlár	Jaklovce	Košické Olšany	Kysak	Ždaňa
10	1.811	4.043	6.248	10.368	15.587	28.973	49.133
25	1.018	2.001	3.557	5.892	7.947	16.017	27.867
50	0.565	1.012	1.948	3.420	4.386	9.027	15.250
75	0.375	0.570	1.089	1.927	2.603	7.244	10.854
90	0.259	0.399	0.732	1.283	1.849	6.332	9.122
Q90:Q50	0.46	0.39	0.36	0.38	0.42	0.70	0.60

With a 90% probability, the flow equal or exceeded at the Prešov Sekčov station increased from 0.264 m^3/s in the decade 1961-1970 to 0.700 m3/s in the decade 1971-

1980 and the long-term average 1961-2020 of 0.389 m^3/s. Noteworthy is the lower value of flows with 90% probability of flow, amounting to 0.374 m^3/s in the years 2001-2010 and 0.370 m^3/s in the years 2011-2020.

Table 8. Daily flow in m^3/s from the catchment 1991-2000

Percent-age of time the flow is exceeded	Stratená	Prešov Sekčov	Švedlár	Jaklovce	Košické Olsany	Kysak	Ždaňa
10	1.781	3.145	6.924	10.612	15.185	31.108	52.091
25	0.970	1.687	3.762	5.909	7.589	17.063	28.705
50	0.602	0.958	1.973	3.297	4.122	9.900	16.473
75	0.397	0.602	1.148	2.025	2.598	7.652	11.907
90	0.296	0.431	0.870	1.498	1.901	6.336	9.785
Q90:Q50	0.49	0.45	0.44	0.45	0.46	0.64	0.59

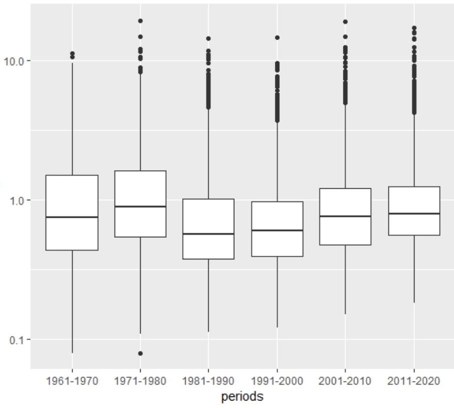
Table 9. Daily flow in m^3/s from the catchment 2001-2010

Percent-age of time the flow is exceeded	Stratená	Prešov Sekčov	Švedlár	Jaklovce	Košické Olšany	Kysak	Ždaňa
10	1.961	3.147	8.413	14.000	15.970	38.835	63.374
25	1.211	1.893	4.770	7.912	9.069	22.262	37.800
50	0.757	1.066	2.420	4.002	4.982	12.800	20.665
75	0.475	0.599	1.380	2.375	3.119	8.096	13.310
90	0.300	0.374	0.777	1.466	2.044	6.477	10.090
Q90:Q50	0.40	0.35	0.32	0.37	0.41	0.51	0.49

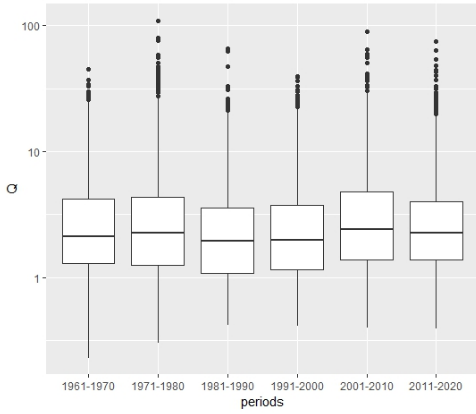
Table 10. Daily flow in m^3/s from the catchment 2011-2020

Percent-age of time the flow is exceeded	Stratená	Prešov Sekčov	Švedlár	Jaklovce	Košické Olšany	Kysak	Ždaňa
10	2.089	2.784	6.920	11.284	12.563	33.074	51.634
25	1.245	1.453	4.027	6.421	7.439	18.590	30.491
50	0.794	0.847	2.267	3.724	4.412	12.171	19.030
75	0.555	0.504	1.394	2.299	2.636	7.992	12.200
90	0.400	0.370	0.913	1.550	1.922	6.441	9.906
Q90:Q50	0.50	0.44	0.40	0.42	0.44	0.53	0.52

At other hydrological stations, an increase in the limit values of Q90 flows has been observed in the last two decades, i.e. 2001-2010 and 2011-2020, compared to the multi-year period 1961-2020. Flows with a probability of occurrence of 10% are characterized by high flows, which at the Stratená and Prešov Sekčov stations show a decrease in the limit values of flows over the last 2 decades in relation to the Q90 values from the multi-year period 1961-2020. At other checkpoints, an increase in border flows in the years 2001-2010 and a decrease in the years 2011-2020 is visible. The figure 10 show the distribution of flow curves in different decades.



Stratená



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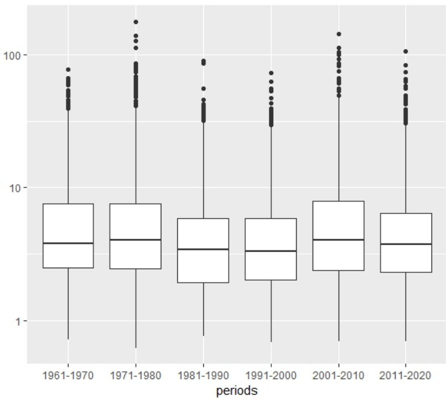

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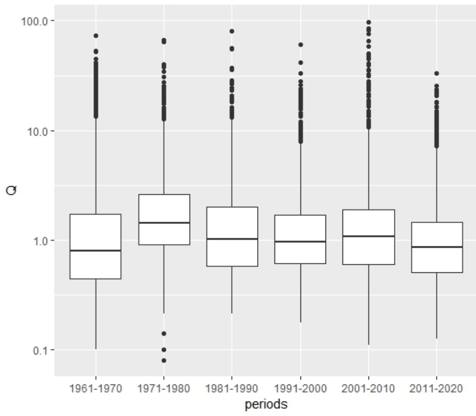

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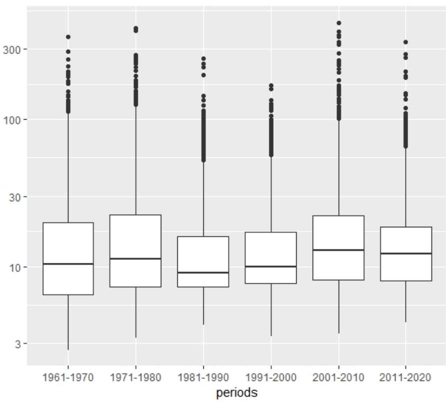

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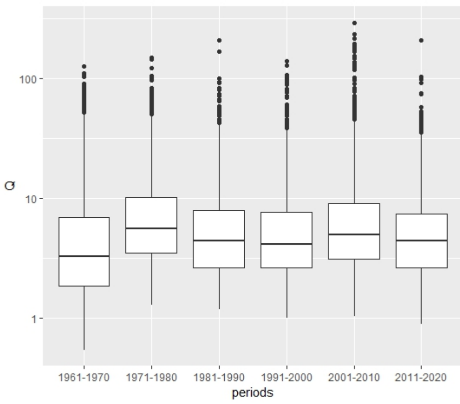
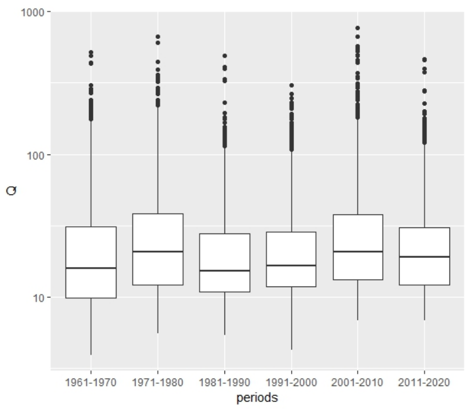


Košické Olšany



Ždaňa

Fig. 10. ***Flow duration curves of daily discharges in different years***

3.4. Variation of flows over decades based on FDC

In order to determine the volatility of flows, the variability index (Cv) was used. The index of flow variability Cv was calculated as the standard deviation of all daily flow values in decades divided by the average flow for the years 1961-2020.

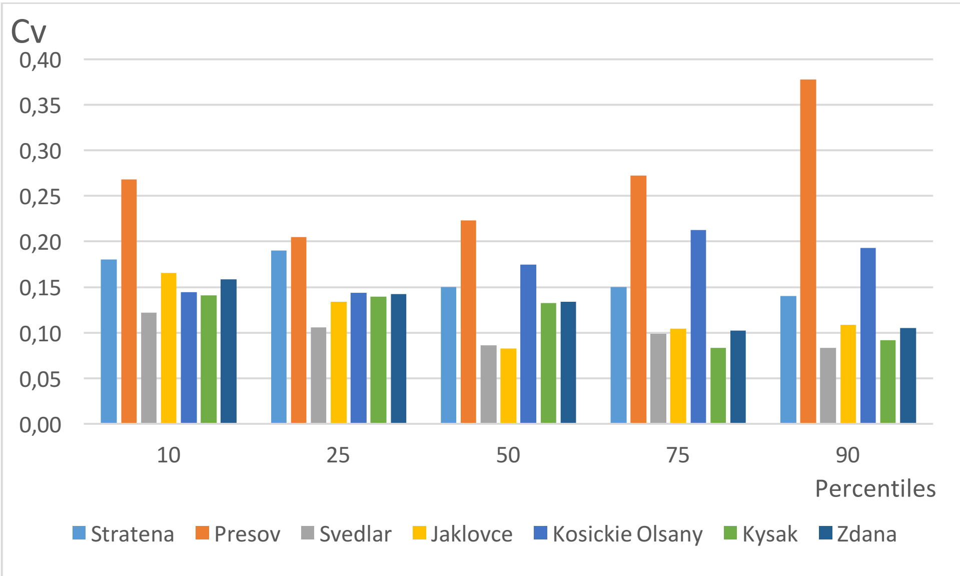


Fig. 11. ***Coefficient of variation of multi-year average flows Cv in decadal periods***

As can be seen from the presented chart, the greatest variability of flows in individual decades in relation to the multi-year period 1961-2020 was recorded in all threshold ranges at the station in Prešov. The highest values were recorded in the range of low flows (Q90), for which the coefficient of variation was 0.38 (Q90) and 0.27 (Q75). A high coefficient of variation Cv was also recorded for the Košické

Olšany station in terms of low flows for Q75 and Q90, which were 0.21 and 0.19, respectively. These are outposts that close lowland catchment areas. At the remaining stations, the variability of Cv ranged from 0.08 to 0.15 for Q75 and Q90. The variability of high flows (Q10 and Q25) ranged from 0.11 to 0.17 for all catchments except for the Prešov Sekčov station, for which the values were 0.21 and 0.27, and Stratená 0.19 and 0.18, respectively. Upward trend of the coefficient of variation in all percentiles at the Stratená and Prešov Sekčov stations, while declining values at the other stations, which show that the threshold values are lower in the percentiles for medium and low flows. This means that the threshold values for low flows have been getting lower and lower over the last decades compared to the average values for the years 1961-2020. This condition is caused not only by the amount of rainfall, but also by the amount of water from rivers used for economic purposes. High variability of the flow coefficient in decadal periods is noticeable for small catchments (Stratená, Prešov Sekčov) in the zone of low flows. The reason for this may be changing meteorological conditions, to which catchments with small areas react extremely quickly (Kubiak-Wójcicka et al. 2023). According to Verma et al. (2017), FDCs developed for 10-year periods reflect the extremely low values of flows occurring in years of drought and provide realistic results of low flows. In addition, FDCs developed over short periods can determine the impact of changes in use on stream flow (Shao et al., 2009).

4. CONCLUSIONS

The aim of this study was to develop flow time curves (FDC) for 7 selected mountain catchments in Slovakia in the multi-year period 1961-2020 and to compare them with curves prepared for 10-year (decade) periods. The adopted 10-year periods showed variability in terms of low and high flows. The greatest variability was recorded at the Prešov Sekčov and Košické Olšany stations for low flows and at the Prešov Sekčov and Stratená stations for high flows. This means that in the case of the catchment in the Prešov Sekčov section, the greatest changes in the flow regime occur, which may result from changes in the use of the catchment or the volume of water abstraction for economic purposes. The obtained information is essential for water managers, especially in the period of drought, when water intake from these watercourses should be limited for economic purposes. Additional studies required based on the preparation of additional percentiles of 0.5%, 1.0% and 5.0% and 95%, 99% and 99.5%, which will allow to determine the appropriate scenarios of actions and in the event of extreme events. Changes in lowland rivers are greater than in mountain ones. In future studies, attention should be paid to changes in high and low flows in conjunction with changes in land use.

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