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Characteristics of runoff events in the Upper Váh River catchment in the warm period of year

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Hourly discharge data were used to evaluate selected characteristics of summer (June to September) runoff events in the streams of the Upper Váh River catchment in years 2014, 2015, 2017 and 2018. Total summer runoff in individual years was very well correlated with the mean altitude of the subcatchments while the average discharge was similarly well correlated with subcatchments areas. Approximately one half of the events for which the peak discharge in Váh at Liptovský Mikuláš (catchment outlet) exceeded the threshold of 20 $m^3 s^{-1}$ came mainly from only part of the catchment. The largest events were dominantly contributed by the streams coming from its northern part formed by the Western Tatra Mountains and the westernmost part of the High Tatra Mountains. The average travel time of the peaks in the Váh River between Liptovský Hrádok and Liptovský Mikuláš was longer and the celerities of the waves were smaller than those between the Belá River (the largest tributary of the Upper Váh River) at Liptovský Hrádok and the Váh River at Liptovský Mikuláš. It was not uncommon that the peaks, especially in Belá at Liptovský Hrádok and in Váh at Liptovský Mikuláš occurred simultaneously. The results indicate that heavy rains in the Western and High Tatra Mountains are especially important for the occurrence of the highest flows at catchment outlet. The most extreme discharge increase during the events regularly occurred in the small Dovalovec Creek (catchment area 22 km^2).

KEY WORDS: runoff events evolution in a river basin, peak discharge travel time, wave celerity

Introduction

Analysis of runoff events characteristics such as time to peak (TTP, i.e. the time elapsed from event beginning to its peak), peak discharge, travel time or celerity of the discharge peaks and waves in a river network can be helpful in understanding contribution of individual subcatchments to river discharge evolution or in flood forecasting. Despite the usefulness of such an information and availability of the data (hourly discharge), there are not many analyses made for the upper (headwater) parts of the Slovak rivers. The existing studies were mostly devoted to the Danube and Morava rivers (e.g. Pekárová et al., 2004; Danáčová and Szolgay, 2005; Szolgay et al., 2006). Contributions of the subcatchments to discharge evolution in a river network can vary during specific conditions. For example, Holko et al. (2013) showed changing contributions of the subcatchments in the Upper Váh River catchment during the snowmelt period of the year 2012 that occurred after a snow-rich winter. In the beginning of the snowmelt period (approximately until the mid-April), the discharge variability in Váh at Liptovský Mikuláš resembled to that in the Biely Váh River at Východná. Later, it was dominated by the contributions from the Western Tatra Mountains (with similar variability found in the tributaries from the Low Tatra Mountains). Similar analysis for the rainfall-induced runoff events was not conducted in the Upper Váh River catchment. However, Sleziak et al. (2023a) estimated runoff contributing areas during six selected rainfall-runoff events from the warm periods of years 2014, 2015, 2017 and 2018 in the Jalovecký Creek catchment, a catchment that is representative of the runoff regime in the headwater catchments of the Western Tatra Mountains. This follow-up article presents the results of the analysis of selected characteristics of runoff events from the warm period of the year (June to September) in the Upper Váh River catchment. The objectives were to evaluate if and how often was discharge variability at Liptovský Mikuláš affected mainly by the tributaries from only part of the catchment (the Western and High Tatra Mountains or the Low Tatra Mountains, respectively), how quickly did the waves travel in the river network and how did the events' characteristics correlate among the streams.

Material and methods

We used hourly discharges in the Upper Váh River catchment measured at 16 gauges in June–September of years 2014, 2015, 2017 and 2018 (Fig. 1, Table 1).

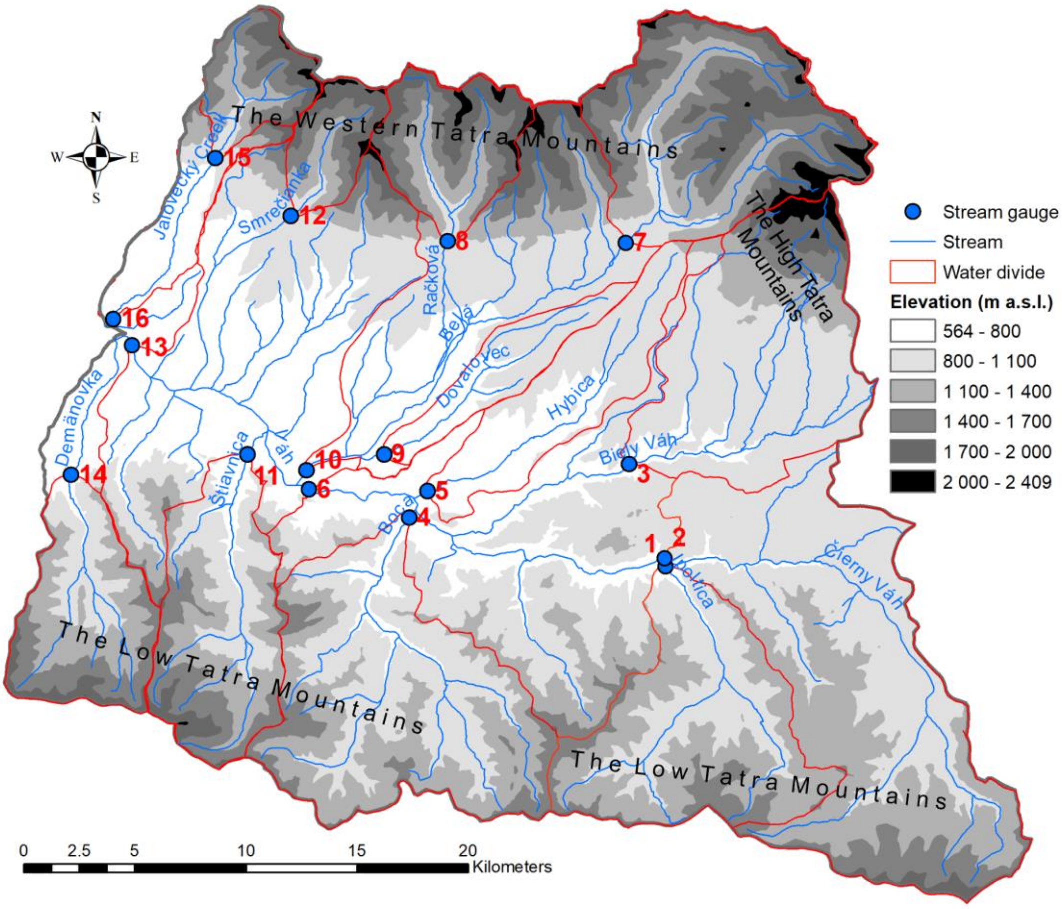

Fig. 1. Study area; the red numbers showing the closing profiles of the subcatchments correspond to the numbers in the first column of Table 1.

Table 1. Study catchments and their characteristics

No.	Stream – gauging station	Catchment area [km²]	mean altitude [m a.s.l.]	mean slope [°]	runoff* [mm]	discharge** [m³s⁻¹]
1	Ipoltica – Čierny Váh	87	1163	22.6	180.2	1.488
2	Čierny Váh – Čierny Váh	243	1127	19	137.5	3.171
3	Biely Váh – Východná	106	1065	9.6	156.5	1.574
4	Boca – Kráľova Lehota	117	1107	23.2	141.9	1.576
5	Hybica – Kráľova Lehota	45	825	6.3	91.2	0.389
6	Váh – Liptovský Hrádok	639	1047	17.2	137.7	8.351
7	Belá – Podbanské	93	1544	26.4	472.1	4.167
8	Račková – Račkova dolina	36	1579	29.2	492.5	1.683
9	Dovalovec – Dovalovo	22	812	4.5	53.6	0.112
10	Belá – Liptovský Hrádok	244	1290	19	312.2	7.229
11	Štiavnica – Liptovský Ján	62	1214	24.9	213.3	1.255
12	Smrečianka – Žiarska dolina valley	18	1540	29	441.2	0.754
13	Váh – Liptovský Mikuláš	1107	1090	17.4	191.6	20.125
14	Demänovka – Demänová	50	1269	23.9	220.8	1.114
15	Jalovecký Creek – Jalovecká dolina valley	22	1500	30	358.5	0.748
16	Jalovecký Creek – Ondrašová	45	1166	19.1	196.6	0.839

*average runoff in June–September 2014, 2015, 2017, 2018; ** average hourly discharge in the same period*

The relationships between seasonal runoff (total runoff from June to September), seasonal discharge (average discharge in period June to September) and subcatchments mean altitudes, slopes and areas were evaluated. The cross-correlations of hourly discharges helped to identify the best correlated sites. Preliminary data examination indicated that discharges below approximately 20 $m^3 s^{-1}$ in the Váh River at Liptovský Mikuláš characterized the occurrence of stable runoff conditions in the entire catchment (Fig. 2). Therefore,

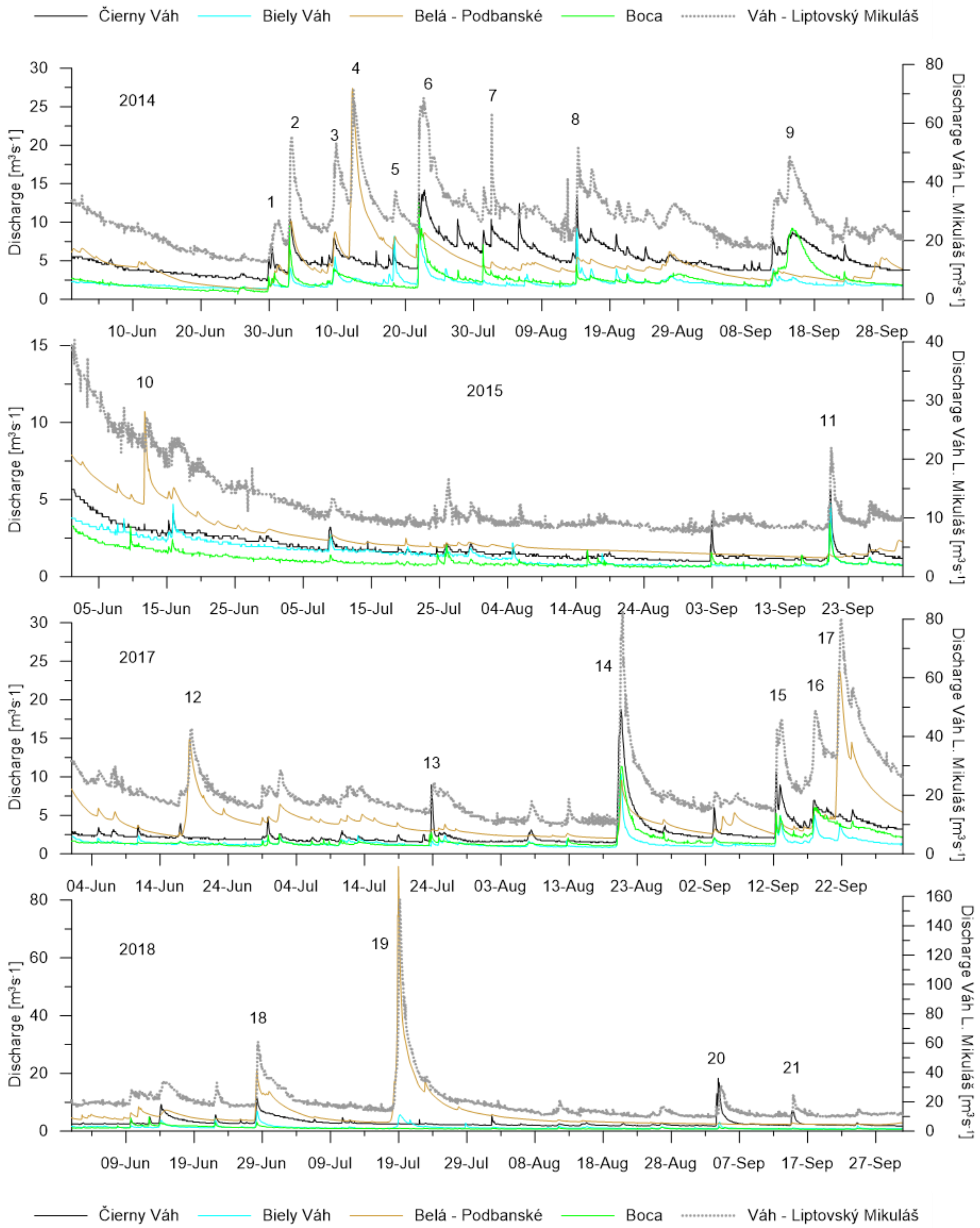

Fig. 2. Variability of hourly discharges in selected streams of the Upper Váh River catchment in period June-September; the numbers indicate events for which the selected characteristics for all the streams were determined; the scale for the Váh River at Liptovský Mikuláš is different than for other streams.

the runoff events at all sites during the periods when the discharge peaks in Váh at Liptovský Mikuláš exceeded 20 $m^3 s^{-1}$ were selected for a more detailed analysis. Characteristics of these events were determined. They included time and discharge at the beginning (Q_o) and peak (Q_{max}) of the events, magnitude of discharge increase expressed by the Q_{max}/Q_o ratio, time to peak (TTP, between Q_o and Q_{max}), and travel time (in hours) of the discharge peaks between the paired gauges on the Váh and Belá Rivers and on the Jalovecký Creek. Celerity of the waves was calculated for the Váh River between Liptovský Hrádok and Liptovský Mikuláš, for the Belá River between Podbanské and Liptovský Hrádok and for the Jalovecký Creek between the Jalovecká dolina valley and Ondrašová (Liptovský Mikuláš) using the reach-scale method (Meyer et al., 2018). The reach length obtained from Google Earth was divided by the travel time and the relationship between the discharge (the mean value of the peak discharges at the two gauges) and celerity was investigated. Finally, the cross-correlations of events characteristics (Q_o, Q_{max}, TTP and Q_{max}/Q_o ratio) for all the streams and gauges were examined.

Results and discussion

Seasonal (June–September) catchment runoff depth (Table 1) was very well correlated with catchment mean altitude that is a surrogate for catchment precipitation in the mountainous study area. Coefficients of determination R^2 in individual years varied between 0.80 and 0.92. Correlations of seasonal runoff depth with catchment mean slope were worse (R^2 0.44–0.60). Catchment mean seasonal discharge correlated very well with catchment area (R^2 0.85–0.97).

The variability of hourly discharges along the Upper Váh River and some of its tributaries representing the Western (High) and the Low Tatra Mountains is shown in Fig. 2. Unlike for the snowmelt events analysed by Holko et al., 2013, the seasonality in the dominant contributions from certain parts of the entire catchment was not observed. However, the majority of the largest events recorded in Váh at Liptovský Mikuláš (with the peak discharges above 40 $m^3 s^{-1}$) was caused by the dominant contributions from the northern part of the catchment, i.e. from the Western and High Tatra Mountains (events 4, 12, 17, 19 in Fig. 2). The discharges in the streams coming from the southern part of the basin (the Low Tatra Mountains) did not increase during those events. Ten out of 21 selected events in Váh at Liptovský Mikuláš (Fig. 2) were contributed by all the streams (hereafter denoted as the E events; the average peak discharge of these 10 events was 55.7 $m^3 s^{-1}$). Five events (the average peak discharge 30.0 $m^3 s^{-1}$) were dominantly contributed by the streams coming from the Low Tatra Mountains (hereafter the S events). Finally, six events (the average peak discharge 69.0 $m^3 s^{-1}$) were dominantly contributed by the streams coming from the northern part of the catchment (hereafter the N events), i. e. from the Western (High) Tatra Mountains. These results indicate that during the warm period of the year, heavy rainfalls in the Western and the westernmost part of the High Tatra Mountains are related to the potentially highest flood risk in the Upper Váh River catchment. The average TTP in Váh at Liptovský Mikuláš was the shortest (11.6 hours) for the S events (15.3 hours for both N and E events). However, the discharge increase during these events was comparatively smaller; the average Q_{max}/Q_o ratio was 2.24 while for the N and E events it was 3.41 and 3.1, respectively.

Average travel times of the peaks between Váh at Liptovský Hrádok and Váh at Liptovský Mikuláš for the E and S events were below 3 hours and below 2 hours, respectively. The average (statistical) travel time for the peaks between Belá at Liptovský Hrádok and Váh at Liptovský Mikuláš for the N events was below one hour, but in 5 out of 6 cases the peak discharges occurred at the two sites in the same hour.

Additional data about the distribution of travel times are presented in Fig. 3. They show that peak discharges occasionally occurred at the downstream gauges earlier than at the upstream ones. Correlations of the peak discharges along the Váh River (i.e. between Váh in Liptovský Mikuláš and other gauges on the Váh River) were not good. On the other hand, the correlation between Q_{max} in Váh at Liptovský Mikuláš and in Belá at Liptovský Hrádok was high (coefficient of correlation 0.89) that further confirms the importance of the contributions from the Western (High) Tatra Mountains for the discharge in Váh at Liptovský Mikuláš. The Q_{max} correlations in the Belá River and in the Jalovecký Creek which, unlike the Váh River downstream from Liptovský Hrádok, do not have significant tributaries between the upper and lower gauges, were very high.

Boxplots of the celerities for the Váh and Belá rivers and for the Jalovecký Creek catchment are shown in Fig. 4. The discharge-celerity relationships were poor and due to a small number of data they are not presented. The mean travel time of the peaks between the upstream and downstream gauges (considering only the positive values) was about 3 hours for each stream.

The cross-correlations among the runoff events characteristics for all the streams revealed the highest number of good relationships (i.e. with correlation coefficients 0.86 and higher) for Váh at Liptovský Mikuláš (mainly for Q_{max}) and for the streams from the headwater parts of the Western Tatra Mountains (Račková, Smrečianka and Jalovecký Creek) for Q_{max} and Q_{max}/Q_o. The TTP had only rarely a good relationship with other characteristics and other streams. A few exceptions included Belá at Liptovský Hrádok and Váh at Liptovský Mikuláš (Fig. 5), Ipoltica and Čierny Váh and the two gauges on the Jalovecký Creek. Catchment wetness state at the beginning of the event expressed by the Q_o did not correlate well with the duration of discharge increase expressed by the TTP.

Duration and magnitude of the discharge increase during an event (TTP and and Q_{max}/Q_o) may be of special importance for the evaluation of flood hazards on individual streams. Boxplots of these two characteristics are presented in Fig. 6. The results indicate that TTP

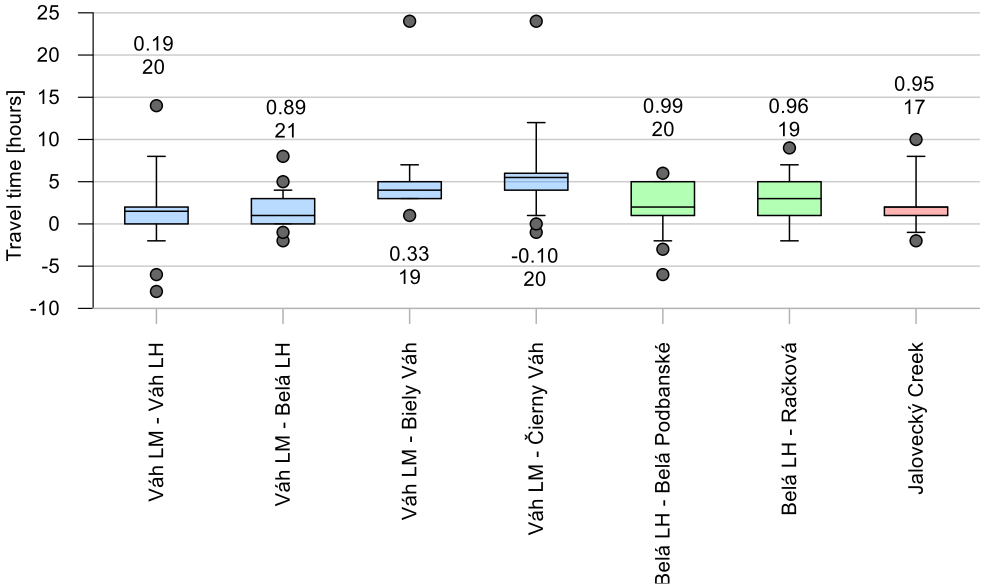

Fig. 3. Travel times of peak discharges in the Váh and Belá rivers and in the Jalovecký Creek (between the Jalovecká dolina valley and Ondrašová); the whiskers in boxplots represent percentiles 10 and 90; the grey dots are the outliers; the numbers show correlation coefficients between peak discharges (Q_{max}) at particular paired gauges and number of events represented by the boxplots.

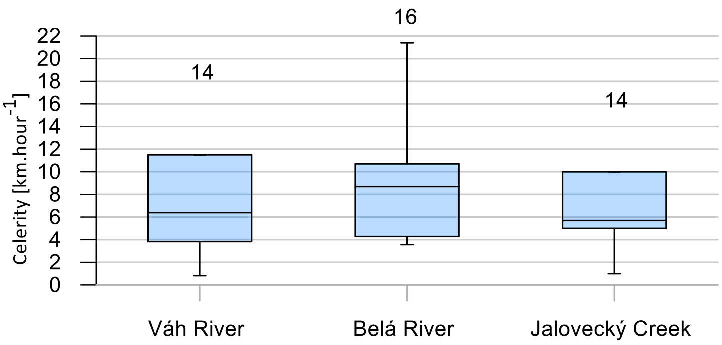

Fig. 4. Celerities of the waves calculated for the Váh River between Liptovský Hrádok and Liptovský Mikuláš (reach length 11.5 km), for the Belá River between Podbanské and Liptovský Hrádok (reach length 21.4 km) and for the Jalovecký Creek between the Jalovecká dolina valley and Ondrašová (reach length 10.0 km); the whiskers show minima and maxima, the line in the boxes indicate arithmetic mean; the number of events is shown above each boxplot.

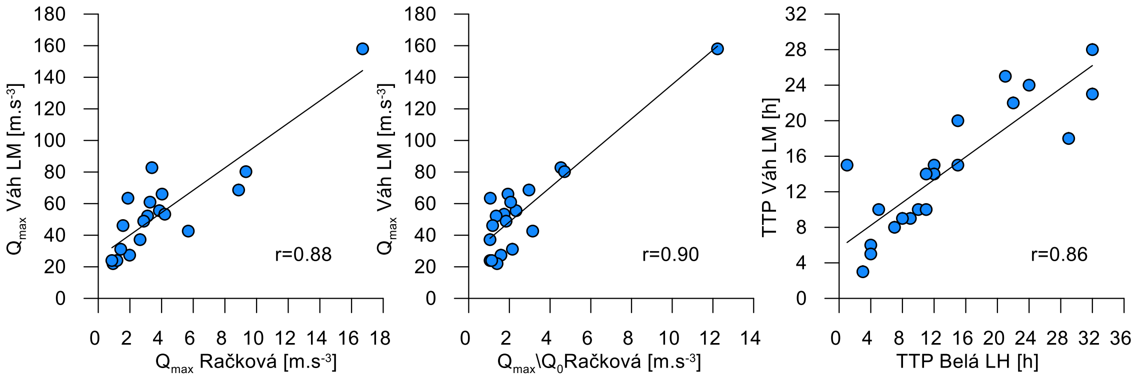

Fig. 5. An example of good relationships (correlation coefficient 0.86 and higher) among runoff events characteristics in the study streams; TTP is time to peak.

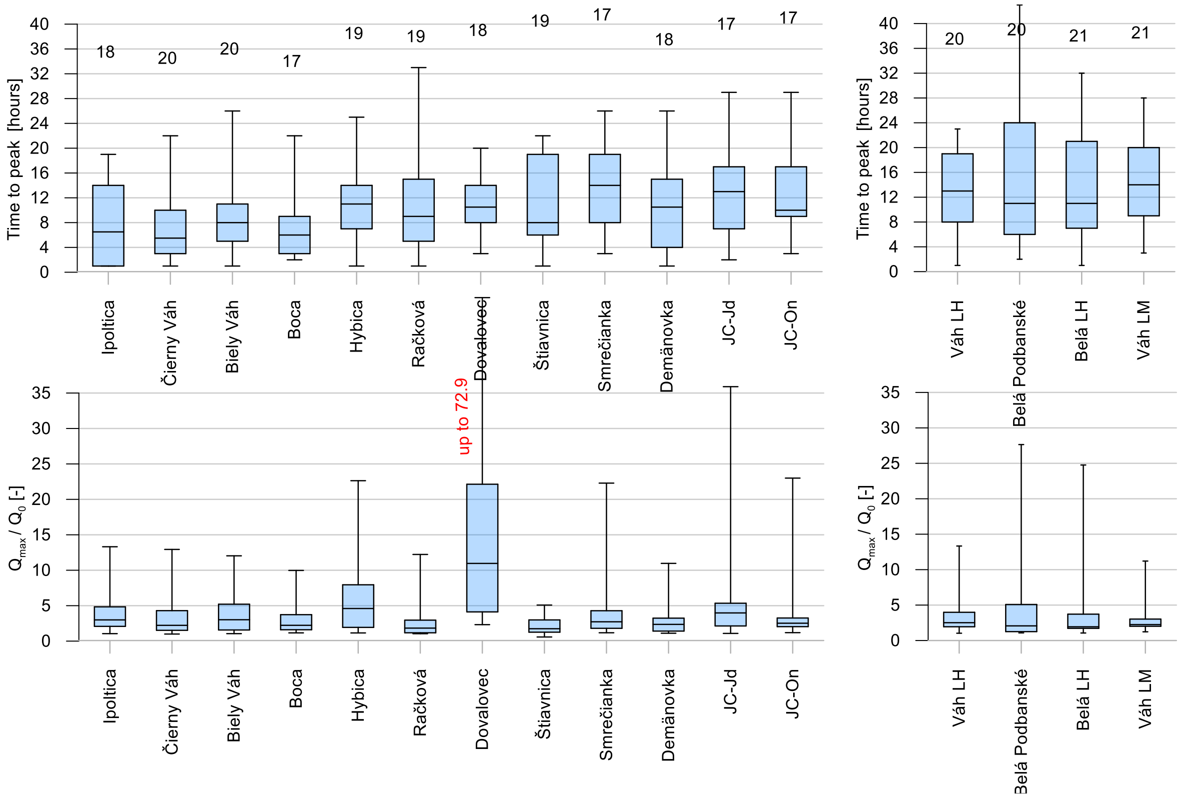

Fig. 6. Time to peak and magnitude of discharge increase (the Q_{max}/Q_0 ratio) during the events at all the streams; the right panels show the "main" rivers, the left panels show the tributaries; the whiskers show minima and maxima, the lines in the boxes indicate medians (the means were typically slightly greater); the number of events (out of 21) registered in a particular stream is shown above the boxplots in the upper panels; JC-Jd and JC-On stand for the Jalovecký Creek at the Jalovecká dolina valley and at Ondrašová, respectively; LH and LM stand for Liptovský Hrádok and Liptovský Mikuláš, respectively.

in the streams coming from the northern part of the catchment tended to be slightly higher than in the streams from the southern part of the catchment. A very large increase of discharge during an event was found for the Dovalovec Creek.

The largest peak discharge at Váh in Liptovský Mikuláš in the study period occurred in July 2018. Sleziak et al. (2023a) estimated that the length of potentially hydrologically connected paths in the headwater (mountain) part of the Jalovecký Creek catchment during the event exceeded 5000 m. The peak discharges (Q_{max}) and the magnitudes of discharge increase (Q_{max}/Q_o) during that event were the highest in the study period not only in Váh at Liptovský Mikuláš, but also in all streams coming from the northern part of the Upper Váh River catchment (Belá, Račková, Smrečianka, Jalovecký Creek).

Conclusion

Despite the short study period, the results confirmed that hourly discharge data provide useful information on the runoff evolution in a river network. The selection of events in this study was determined by the focus on the large events at the outlet of the Upper Váh River catchment in Liptovský Mikuláš. It implies that not all the events that occurred in individual streams were analysed. However, this selection of events should not affect the finding about the variability in dominant contributions of streams from different parts of the catchment to the discharge at catchment outlet. Runoff regime in the main course of the Váh River is apparently affected by the operation of several smaller power plants along the river. However, their existence should not affect the conclusion about the importance of the northern part of the catchment for the occurrence of the highest flows at catchment outlet (Váh in Liptovský Mikuláš). This finding also highlights the importance of rainfall data measurement at higher elevations, especially in the Western Tatra Mountains, for discharge forecasting. Such measurements are at present not conducted within the national observational network and indirect precipitation estimates significantly underestimate measured precipitation at higher elevations (Sleziak et al., 2023b; Hrušková and Hlaváčiková, 2023).

The analysis of hourly data can provide a useful knowledge in other river basins as well. However, possible use of the information about travel times of peak discharges and runoff waves (celerity) should take into account the limitation given by the temporal resolution of the data. With hourly data, it was not uncommon that the peaks at the upstream and downstream gauges occurred in the same hour (the celerity can then not be calculated). Therefore, finer temporal resolution at some gauges may be needed to obtain more accurate characteristics of events evolution in a river network.

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