Post-flood field investigation of the June 2020 flash flood in the upper Muráň River basin and the catastrophic flash flood scenario

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Abstract: After a dry spring, in June 2020 several intense storms occurred at the headwaters of the small basins of the Muráň and Zdyčava rivers in the territory of the Muránska planina National Park (Slaná River basin, Slovakia). In the first part of the study— according to a hydrological survey made by the authors after the flash flood – the peak discharge was reconstructed at several Muráň River profiles. Next, the flash flood waves were reconstructed by the rainfall-runoff model NLC (non-linear cascade). The results of modelling based on field investigations show that, despite the extreme precipitation event (108 mm per 1 hour at the precipitation gauging station at Predná Hora), the peak flow rates were not exceptional in selected profiles on the Muráň River. The fact that extreme precipitation above 120 mm fell in a relatively very small area at the division of the Muráň and Zdyčava rivers' water contributed to this result. In the second part, a catastrophic 1000-year rainfall event scenario on the Zdyčava River basin has been prepared. In analysing time series and identifying T -year daily rainfall depths, daily data was used from six precipitation stations in the vicinity of Muránska planina. Then, the 1000-year discharge of the Zdyčava at Revúca was simulated by the calibrated NLC model. In such an extreme precipitation scenario, the peak flow rate would reach $105.15 \text{ m}^3 \text{ s}^{-1}$, i.e. with a specific runoff of $1.78 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$. The total runoff in an 18-hour period would be 1.119 million m^3 , representing 21.11% of the rainfall (5.301 million m^3).

Keywords: Flash flood; Small basins; Rainfall-runoff NLC model; Catastrophic precipitation and flood scenario.

1 INTRODUCTION

Hydrologists around the world have been working intensively on flash floods' intensity and frequency analysis in recent years (Gaume and Borga, 2008; Gaume et al., 2009, 2016; Kjeldsen et al., 2014; Marchi et al., 2010). There have been several floods in the Czech Republic, Poland and Ukraine since 1995. For example, in Poland in 18 July 2018 the daily rainfall (103.1 mm) caused flash flood in two small Jamne and Jaszcze Carpathians catchments (Bucala-Hrabia et al., 2020). The maximum unit flow ($4.1\text{--}4.8 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$) placed this flood event among the 10 largest flash floods in the Polish Carpathians (based on the K index). In Slovakia, since the flash flood in the Malá Svinka basin on 20 July 1998 (Svoboda and Pekárová, 1998), several flash floods have been documented (Bačová Mitková et al., 2018; Blaškovičová et al., 2011; Hlavčová et al., 2016; Majerčáková et al., 2004; Pekárová et al., 2012; Šťastný and Majerčáková, 2003).

The estimation of event-based flood events is one of the most important parts of the design process for a large number of engineering projects and studies. A significant problem may arise in small catchments that are poorly gauged or when no recorded data exist (Szolgay et al., 2020). Several published datasets exist that document flash flood and surface runoff events triggered by heavy precipitation (Kaiser et al., 2020). According these authors, the amount of documented events increases steadily towards recent decades. This is probably due to the internet, which has drastically simplified the search for past flash flood events. In addition, there has been a marked increase in public interest in natural hazards over the past decade, not least because of recurring severe events.

It sometimes evokes the opinion that flash floods did not occur (at least as frequently) in the past and that they are the consequence of the recent bad land management. The analysis of recorded descriptions of extreme historical storms and flash floods in Slovakia from professional publications, or the chronicles of towns and villages (please see Appendix 1) indicates, however, that flash floods have been observed over the territory of Slovakia in the past as well.

Historical floods in the Slaná River basin from the end of the 18th Century till the beginning of the 20th Century were studied by Melo and Bernáthová (2013). Their paper provides information about historical floods on the Slaná River and its tributaries, obtained by studying historical documents in archives. According to the authors, great floods in the Slaná River basin occurred in 1780, 1813, 1845, and 1878, which caused much damage for the inhabitants. Approximately from the end of the 19th Century up till 1915 mainly smaller floods are known. They are commented on in the newspaper *Sajó Vidék*. The information about these floods concerns mainly the Slaná and Rimava rivers. In archives they also found information about many floods on smaller rivers such as the Drázus, Balog, Turiec, etc. In the case of the Slaná River and its tributaries, some floods relate to the territory of Hungary, too. Floods in the river basin of the Slaná occurred practically in every season; more frequently in summer and winter, less frequently in autumn.

The origin and formation of the flash flood is a complex scientific topic. Each flash flood is unique because of the rainfall depth-duration and environmental (geology) characteristics, but they are basic for understanding and possible comparison of the flash floods. Another scientific problem is how to assess the maximum possible magnitude of the flash flood due to possible rainfall depth and intensity.

The months of June-August 2020 were marked by the occurrence of several intense storms in the territory of Slovakia, Czechia, Hungary, Poland and Ukraine, which caused flash floods with catastrophic consequences from small torrents. One of the most extreme storms occurred at the water divide of the upper Muráň River and its tributary Zdychava in the area of the Predná Hora resort (upper part of the Slaná River basin, Slovakia). During the afternoon storm on 28 June 2020, a maximum hourly rainfall depth of 108 mm and, the three-hour total of 132 mm were recorded (Halaj et al., 2020a; Halaj et al., 2020b; Siman, 2020). Local extreme rainfall caused a flash flood with large damages.

The main objective of this study is to understand the mechanisms and factors controlling the generation and magnitude of flash flood in the upper Muráň River. The aims are:

1. To describe the hydrological regime of the Muráň River to reconstruct runoff during the flood on 28 June 2020 on the Zdychava and upper Muráň using the rainfall-runoff NLC model (Svoboda, 1987);
2. To process a catastrophic 1000-year precipitation scenario on the Zdychava River basin, and use this scenario to predict a catastrophic 1000-year flood of the Zdychava River with the NLC model.

2 BASIN DESCRIPTION AND METHODS

As mentioned above, during the afternoon storm on 28 June 2020, at the precipitation gauge of SHMI Muránska Huta - Predná Hora above the upper part of the Muráň and Zdychava basins (Figure 1a), a maximum hourly rainfall depth of 108 mm was recorded; the three-hour total was 132 mm. But the Revúca gauge showed a rainfall depth of only 18 mm, and at Telgárt it was 0.3 mm (Figure 1b).

The extreme rainfall occurred in a relatively small area. In the Zdychava basin, a flash flood hit villages located above Revúca and part of Revúca town's suburb Revúčka. The flood destroyed the state roads between the Muráň and Muránska Huta villages and Muránska Zdychava village and Revúca town.

Just four years before this flood, a similar event occurred on July 29, 2016 in the town of Revúca, on the confluence of the Zdychava and Muráň rivers (Bírová et al., 2017). The automatic precipitation station on the northern part of Revúca measured 112 mm of rainfall in three hours. At the rain gauging station located in Revúca city centre, near the Zdychava River, up to 139.8 mm in three hours (141 mm/ 24 hours) were recorded.

Fig. 1a. Location of the area of interest of the Slaná basin within Slovakia and location of the upper Muráň basin and Zdychava basin. The diagram shows the profiles in which the hydrological survey was carried out and the precipitation and water gauges of the SHMI network.

Fig. 1b. Minute rainfall depths on 28 June 2020 from the stations Predná Hora and Revúca and daily rainfall depths in June 2020 in the station Predná Hora (data of SHMI).

2.1 Physical-geographical and hydrological characteristics

In the study area of the upper Muráň and Zdychava, the relief variability is pronounced. The valleys are deep, the slopes steep and high. The mountainous and sub-mountainous character of the territory prevails here. The upper Muráň sub-basin reaches the highest point on Kľak mountain (1409 m a.s.l.) and the lowest point at the outlet of the Muráň River from the sub-basin (475 m a.s.l.). The upper part of the Muráň basin is situated between the geomorphological units of the Spišsko-Gemerský kras Karst and Stolické vrchy Mountains (south-eastern and eastern edge of the sub-basin). The Spišsko-Gemerský Karst is made up of limestones, dolomites and deluvial sediments (see Appendix 2). The Stolické vrchy Mountains are made up mainly of granodiorites. In the valleys of water-courses there are fluvial sediments. Rendzinas have been created on limestone and Cambisols in the rest of the area. The natural environment is well preserved and it is enriched with karst forms of relief (sinkholes, grikes, swallow holes, exurgences, underground cavities).

The study area is situated in part on the territory of the Muráňská Planina National Park. It is largely forested and is mainly covered by oak, hornbeam and beech forests (Petruška, 2010). The average annual temperature is from 5°C in the highest parts to 8°C in the lowest parts of the study area. The average annual rainfall depth varies from 700 to 1250 mm. The average annual maximum daily rainfall depth ranges from 46 to 50 mm. In the month of June, the monthly rainfall depth is between 80 and 140 mm.

The Muráň River (basin area: 386.578 km²; length: 42.91 km) stems from the south-western slope of the mountain situated south-west of the Predná Hora resort at an elevation of 688 m a.s.l. (Figure 1a). The water course from the source flows to the south-west to road No. 531 connecting the municipalities of Muráň and Muráňská Huta; along the road it runs to the bottom of the valley and from the north-east towards the village of Muráň. Before the village it arches along the foothills of Ostrý vrch Hill (730 m a.s.l.) to the south-east.

2.2 Data used

In analysing the hydrological discharge regime in the territory of interest, we used a time series of average daily flows and maximum annual flows from the SHMI water gauging stations at Muráň: Hrdzavý Creek and Revúca: Zdychava, and Felsőezsolca: Slaná (Sajó in Hungarian) for the entire observation period.

Hrdzavý Creek (40.17 km²) flows into the Muráň River at Muráň village. In Revúca town the Muráň River receives from the left the Zdychava River (basin area: 59.324 km²; length: 15.38 km), which springs under the mountain Kyprov (1391 m a.s.l.), then flows approximately to the south-west through the village of Muráňská Zdychava to Revúca town (see Fig. 1a). In the village of Bretka the Muráň River estuaries from the right side to the Slaná River.

According to the Slovak Hydrometeorological Institute (Šipikalová, 2005), the long-term annual runoff of the Muráň basin under Hrdzavý Creek (river basin area 50.271 km²) for the period 1961–2000 was 429 mm, areal precipitation for catchment 891 mm, runoff coefficient 0.48, and specific outflow 13.60 l s⁻¹ km⁻². In Table 1 are shown the basic morphometrical characteristics of the studied subbasins of the Muráň River according to HP ČSSR (1965).

Table 1. Basic morphometric characteristics of subbasins of the Muráň River basin.

River/cross-section	<i>P</i> [km ²]	<i>L</i> [km]	<i>P/L</i> ²	<i>F</i> [%]
Muráň upstream Hrdzavý Creek	10.097	5.3	0.36	30
Hrdzavý Creek – mouth	40.174	8.8	0.52	90
Muráň downstream Hrdzavý C.	50.271	5.3	0.18	70
Hutský Creek – mouth	14.822	6.2	0.38	70
Zdychava - mouth	59.324	16.3	0.22	60

explanatory notes: *P* - catchment area, *L* - length of the valley, *F* – forest.

2.3 Methods

2.3.1 NLC model

To simulate flood waves, a conceptual non-linear NLC (non-linear cascade model) rainfall-runoff model was used (Svoboda, 1987). The NLC model is a rainfall-runoff model with lumped parameters to simulate isolated rainfall-runoff events. Its use is aimed at simulating extreme summer floods in small basins (flash floods). The resulting outflow is formed by the superposition of simulated direct runoff (surface and so-called hypodermic runoff), and groundwater runoff. The first component is simulated by a cascade of linear or non-linear reservoirs in series, the second component by a single linear reservoir. The input into the model represents the precipitation during the simulation period and the index of antecedent precipitation at its beginning. A description of the model can be found e.g. in Pekárová et al. (2012). The schematic model structure is shown in Fig. 2.

Fig. 2. Schematic representation of the NLC model structure. (PA – input precipitation, PE – effective precipitation, ETP – evapotranspiration, Q_s – direct runoff, GI – groundwater input, Q_g – groundwater runoff, Q – total runoff, Q_d – deep percolation, EN and EF are storage parameter and actual water content of the unsaturated zone).

2.3.2 Selection of the theoretical distribution of the daily maximum precipitation series by means of global probability curves

In this study the possibility of the ergodicity hypothesis in the statistical processing of the maximum daily precipitation time series is used according to Dzubák (1969). It is assumed that the time series of the maximum daily precipitation data during the years form stationary random functions and that their statistical characteristics are characterised also by so-called spatial series which are formed by the values of the considered functions at various points of the catchment. The conditions under which the use of this assumption can be made are elucidated (the mutual independence of the time series and the stability of the statistical parameters in the space). If the condition of the spatial invariability of the statistical parameters is not preserved, then new variables are introduced, i.e. the variable $k_i = x_i/x_{pr}$, when only x_{pr} (mean) varies with the area, or $t_i = (k_i - 1)/c_v$, when the c_v (coefficient of variation)-value changes also.

3 RESULTS

3.1 Analysis of the hydrological regime of the Zdychava, Hrdzavý potok and Slaná rivers

In analysing the development of the long-term regime of average annual discharge (Q_a) and maximum annual discharge (Q_{max}), time series from the following water gauging stations were used: Muráň city: Hrdzavý Creek, Revúca city: Zdychava River, and Felsoezsolca city (HU): Slaná River. From the graphs in Figure 3, as well as from autocorrelograms, you can see that there is a more or less regular repetition of multi-year wet and dry periods in the Slaná basin. From the Felsoezsolca closure station at Slaná, it can be concluded that after ca 35–40 years there is a more pronounced wet/dry period.

Empirical and theoretical lines of probability of exceedance have been drawn from the series of maximum annual discharge Q_{max} of Hrdzavý Creek and the Zdychava River, and the design

values of the T -year discharge have been calculated. A three-parametric log-Pearson type III distribution was used. Figure 4 presents the derived theoretical lines for exceeding the maximum annual discharge of Hrdzavý Creek and the Zdychava River for the 40, or 37-year periods 1970–2019 or 1974–2020, respectively. Estimated T -year flow rates for stations Muráň: Hrdzavý Creek and Revúca: Zdychava River are shown in Table 2 with 5% and 95% limits.

From the results there is clearly considerable uncertainty about the determination of the design values of T -year discharge, especially at Hrdzavý Creek. Interestingly, all three extreme floods of Hrdzavý Creek occurred in autumn – due to the regional rains. On the Zdychava River there are higher floods during summer storms. The flood of 28 June 2020 of the Zdychava River in Revúca was only evaluated as a 25-year flood. Several conclusions follow from the discharge analysis:

- In the Q_a and Q_{max} series, multi-annual wet periods alternate with multi-annual drier periods; the Q_a and Q_{max} series are clearly cyclical (long-term cycle ca 36 to 40 years);
- The flood occurs with a higher probability during wet years;
- The flash floods due to summer storms cover small areas. They do not occur at the same time in both Zdychava and Hrdzavý Creek basins;
- The hydrological regime of the Zdychava and Hrdzavý Creek are different due to differences in geology;
- The flood on 28 June 2020 hit a very small area at the water divide of the Muráň and Zdychava rivers, and no extraordinary high discharge was observed at the gauging stations Revúca and Muráň city.

3.1.1 Post event peak flood survey, and reconstruction of the flood wave during the flood of 28 June 2020 using the NLC model

In order to obtain background information for simulating floods in sub-basins, where direct measurements are not available, the authors conducted a post-flood field investigation in the Muráň basin on 28–30 July 2020, focusing on three profiles at the highest part of the river basins. In order to determine the peak flood flow by hydrotechnical calculation, it is necessary to find profiles in which there are clear traces of the height of the water level during the flood and in which there has been no change to the river bed since the occurrence of the flood. These were: 1. Muráň River in the profile Sysľovisko 3.0 km above the mouth of Hrdzavý Creek; 2. Muráň River in profile above Muráň village 1.3 km upstream of the mouth of Hrdzavý Creek (see Figure 5a); and 3. Muráň River below Muráň village in profile 0.5 km downstream from the confluence of Muráň River and Hrdzavý Creek. In these profiles, the river cross section during the peak water level of the flood, and longitudinal inclinations of the anticipated water table, which are supposed to correspond to the river bed inclination in these river reaches, were measured.

Table 2. T -year discharge in $\text{m}^3 \text{s}^{-1}$ in stations Muráň: Hrdzavý Creek and Revúca: Zdychava River.

N -year	Hrdzavý Creek: Muráň 1970–2019			Zdychava: Revúca 1974–2020		
	Q	$Q(5)$	$Q(95)$	Q	$Q(5)$	$Q(95)$
1000	82	211	42	144	275	91
500	45	104	25	106	190	70
200	21	41	13	70	116	49
100	12	20	8	51	79	37
50	6	10	5	37	54	28
20	3	4	2	24	32	19

Fig. 3. Average annual discharge Q_a and maximum annual discharge Q_{max} (left) and autocorrelagrams (right) in the selected stations of the Slaná River basin.

Fig. 4. T -year discharge and 95% lower and upper limits of the confidence intervals of the selected two stations and full period of observations.

Fig. 5. a) Profile No. 2 on the Muráň River above Muráň village, 1.3 km upstream the Hrdzavý Creek mouth July 29, 2020 (Photo: Miklánek, July 2020); b) characteristics of the profile No. 2 during the flood on 28 June; c) road No. 531 Muráň-Muránska Huta; d) Zdychava River downstream Muránska Zdychava village during the June 28, 2020 flood. (Photo: I. Pašiák).

Table 3. Measured and calculated characteristics, in the three surveyed sections.

Cross section	1. Muráň Sysľovisko 3 km upstream Hrdzavý c.	2. Muráň 1.3 km upstream Hrdzavý c.	3. Muráň 0.5 km downstream Hrdzavý c.
Mean rainfall depth [mm]	115	100	71.3
Catchment area [km ²]	3.9	8.97	52.71
River slope	0.037	0.032	0.01
Hydraulic radius [m]	0.307	0.568	0.614
Mean velocity [m s ⁻¹]	2.19	2.455	1.806
Roughness coefficient	0.04	0.05	0.04
Peak discharge [m ³ s ⁻¹]	6.297	10.065	12.101

The flow velocities were calculated using the Chezy formula with Manning roughness coefficient, and continuity formula that was then used to calculate the peak flow (Eqs. 1–3). In determining the average profile speed, we based it on the assumption of steady uniform water movement, in which the slope of the water level is parallel to the slope of the bottom.

$$v = C \cdot (R \cdot i)^{1/2} \quad (1)$$

$$C = 1/n \cdot R^{1/6} \quad (2)$$

$$Q = F \cdot v, \quad (3)$$

where v is average velocity [m/s]; C is Chezy's coefficient [m^{1/2}/s]; R is hydraulic radius [m]; i is hydraulic gradient

[m/m]; n is Manning's roughness coefficient, and F is the water-filled area of the cross section [m²]. The results of the calculations are listed in Table 3.

3.1.2 Calibration of the NLC model

The NLC model was calibrated on the measured discharge from the Revúca: Zdychava gauge (basin area: 58.95 km²).

After a severely dry period in the first five months of 2020, in June several intense rainfalls were recorded at Predná Hora, e.g. on 10 June; 14 June and 26 June 2020. The Muráň and Zdychava basins were saturated with previous rainfall before the extreme storm on 28 June 2020.

For the model, a 15-minute interval was chosen. Input data – 15-minute rainfall depths derived from minute data from the

Predná Hora and Revúca gauges are plotted in Figure 6a - upper graph. Based on rainfall data from neighbouring gauges and radar images, the rainfall depth was estimated for the Muráň River basin to the profile downstream at Muráň village, and for the River Zdychava to Revúca town (see Fig. 1b). The estimated average rainfall depth in the Zdychava basin was 65 mm in 90 minutes. Figure 6a below shows the results of the NLC model's calibration. The input rainfall water volume for the Zdychava basin on 28 June 2020 amounted to 3699 thousand m³ of water. Modelled wave volume in 18 hours (from 11:00 a.m. on 28 June 2020 until 05:00 a.m. on 29 June 2020 CET) was 644 thousand m³ of water; the measured volume was 637 thousand m³ of water. Nash's model efficiency coefficient was 0.901. In 18 hours, only 17.36% of the volume of rainfall water flowed out of the Zdychava profile at the Revúca gauge.

As a result, the fallen precipitation was caught well by the Zdychava basin.

3.1.3 Reconstruction of the flood waves by NLC model

After calibration, the NLC model was used to reconstruct the course of the flood wave in four profiles: 1. Muráň River in the Sysľovisko profile (Figure 6b); 2. Muráň River in the profile above Muráň village; 3. Muráň River below Muráň village; and 4. on Hutský Creek (tributary of the Zdychava River). We assume that there are the same characteristics in the Muráň basin, so we can use the parameters of the Zdychava model's calibration in the Muráň basin as well. The results of the model are presented in Table 4. The peak flow rates and specific runoff calculated by us are not extremely high even under the conditions of small basins. Higher values were estimated only on Hutský Creek.

3.2 Simulation of a catastrophic 1000-year flood on the Zdychava River at Revúca

The calibrated NLC model can also be used to simulate the course of flood waves in extreme precipitation scenarios. The

simulation assumes that a 100-year precipitation event will cause a 100-year flow wave, a 1000-year precipitation event will cause a 1000-year flow wave.

The basin of Zdychava is a small basin – with an area of only 59 km². Two rainfall gauges are situated in the basin: at Revúca and Predná Hora, for which data are available only since 1985. Of these data series, a 100-year precipitation depth could only be estimated with great uncertainty. The determination of 200- or more year values is very inaccurate. Therefore, the method described by Dzubák (1969) was used in the construction of a catastrophic 1000-year precipitation scenario at the Revúca and Predná Hora stations with a short series of observations (approx. 35 years).

For Revúca station (and, by analogy, for the Predná Hora station), P_{max} series were extended in this study with the help of P_{max} series from Telgárt, Ratková and Chopok stations. We assume that P_{max} series in the area have a log-Pearson type III distribution – (LP3 distribution).

3.2.1 T-year daily rainfall depth at precipitation stations in the Zdychava basin

According to Šamaj et al. (1985), the highest daily rainfall depth in Slovakia in the period 1901–1980 was recorded on 12 July 1957 in Salka village (north of Štúrovo town), where 228.5 mm of water fell in 65 minutes (but the daily total was still 3.4 mm higher). In 1873 a daily depth of 267 mm was recorded in Trenčín town.

Table 5 shows the highest daily rainfall depths in the Slovak rainfall gauges around the Muránska planina according to Šamaj et al. (1985) and Zitek (1958). These data were processed on the basis of precipitation measurements in the period 1901–1980. Highest rainfall totals occur mainly in the months of June, July and August. The last column of Table 5 shows the 100-year daily precipitation depths calculated on the basis of a log-Pearson type III distribution. After 1980, daily rainfall of a depth of over 100 mm occurred in the Muránska planina region on 23 August 1985, when the daily rainfall depth at the Muránska Huta – Predná Hora gauge reached 104.7 mm.

Fig. 6. a) Model NLC calibration, observed (Q_{obs}) and modelled (Q_{sim}) discharge at Revúca: Zdychava gauge (down), mean areal precipitation depth over the Zdychava basin (upper); b) Results of flood wave reconstruction at the Muráň basin Sysľovisko, NLC model output. Runoff since 11:00 a.m. till 21 p.m., 15 minutes' time step.

Table 4. NLC-model outputs for three upper Muráň River sub-basins and Hutský Creek basin, input – Area and Rainfall; since 12:00 a.m. till 12 p.m.

Profile	Area [km ²]	Rainfall [mm]	Peak discharge [m ³ s ⁻¹]	Peak specific runoff [m ³ s ⁻¹ km ⁻²]	Rainfall volume [thousand m ³]	Runoff volume [thousand m ³]	Runoff coefficient [-]
1	3.9	115	7.2	1.846	445	88.4	0.198
2	6.7	100	11.0	1.22	886	140.8	0.160
3	52.7	71.3	14.1	0.26	3656	338.6	0.093
Hutský	14.82	115	27.2	1.835	1611	233.1	0.144

Table 5. Maximum daily precipitation P_{max} and 100-year daily rainfall depths P_{100} by Šamaj et al. (1985) and Zitek (1958) in SHMI gauges around the Muránska planina for the period 1901–1980.

Station	Elevation of station in m a.s.l.	Number of years of observation	Date	P_{max} [mm]	P_{100} [mm]
Muráň	394	60	16. 06. 1937	103.7	102.5
Predná Hora	736	51	29. 06. 1958	82.3	87
Tisovec	411	80	29. 06. 1958	81.7	85.2
Ratková	287	79	13. 08. 1929	105	95.5
Revúca	317	80	27. 06. 1927	110.3	97.8
Telgárt	901	39	16. 06. 1937	99.8	94.6

Table 6. T -year daily rainfall depth P [mm], 90% lower $P(5)$ [mm] and upper $P(95)$ [mm] confidence interval limits for P. Hora, Revúca, Chopok, Ratková, and Telgárt weather stations for the period 1984–2019, including the historical maximum according to Table 5.

p	P. Hora			Revúca			Chopok			Ratková			Telgárt		
	P	P(5)	P(95)	P	P(5)	P(95)	P	P(5)	P(95)	P	P(5)	P(95)	P	P(5)	P(95)
0.001	262	398	197	204	302	156	182	232	151	168	217	139	162	201	137
0.002	221	323	171	174	248	137	158	197	134	147	185	124	143	174	123
0.005	176	244	141	141	191	114	131	159	113	123	150	106	121	144	106
0.01	148	196	121	119	156	99	113	134	100	107	128	94	106	123	94
0.02	123	157	104	101	127	86	98	113	87	93	108	83	93	106	84
0.05	96	117	84	80	96	71	80	89	73	76	86	69	77	85	71
0.1	79	92	70	67	77	60	68	74	63	65	72	60	66	72	62
0.2	64	72	58	55	62	51	57	61	53	54	59	51	56	60	53
0.5	46	51	42	41	45	38	43	46	41	41	44	39	43	46	41

Table 7. T -year daily rainfall depth P [mm], 90% lower $P(5)$ [mm] and upper $P(95)$ [mm] limits of the confidence intervals for the station Predná Hora (the series extended according to stations Chopok, Ratková and Telgárt) and Revúca Hora (the series extended according to stations Chopok, Ratková and Telgárt).

p	P. Hora			Revúca		
	P	P(5)	P(95)	P	P(5)	P(95)
0.001	175	196	158	174	198	156
0.002	155	172	141	154	173	140
0.005	131	144	121	131	145	119
0.01	115	125	107	114	126	105
0.02	101	108	95	100	108	93
0.05	83	89	79	82	87	77
0.1	71	75	68	69	73	66
0.2	60	63	58	57	60	55
0.5	45	47	44	41	43	40

To compare the development of T -year 24-hour rainfall depth after 1984, we calculated T -year values using LP3 distribution for the period 1985 (or 1951)–2020 from the gauges at Predná Hora, Revúca, Chopok, Ratková and Telgárt (Table 6) with a 90% confidence interval. We also included historical rainfall events from the period 1901–1980 into the calculation. The year 1937 was extremely rich for precipitation, and precipitation fell mostly during extreme storms, similar to 2020. Unfortunately, we do not have the input series of maximum precipitation data processed by Šamaj et al. (1985) from 1901 to 1980; a shorter series of daily rainfall depths were processed from 1950 or 1960 by Faško (Faško et al., 2006; Parajka et al., 2004).

From the values in Table 6, it can be seen that there is already a great deal of uncertainty about the 100-year daily precipitation depths. Therefore, the estimates of T -year depths for the Predná Hora and Revúca stations were recalculated, and the P_{max} time series were extended by the Dzubák method (1969). The results are presented in Table 7.

By comparing the values in Tables 6 and 7, it can be seen that the uncertainty of the estimate has decreased significantly, as well as a reduction in the estimates of daily rainfall depths with a very long recurrence time at both Predná Hora and Revúca stations (Figure 7).

Fig. 7. Example of the T -year daily rainfall depth and 90% lower and upper confidence interval limits, Predná Hora calculated by two methods.

3.2.2 1000-year precipitation scenario in the Zdychava basin

In constructing the 1000-year precipitation scenario, we relied on the one hand on the historically recorded catastrophic precipitation events in Slovakia, on the other statistical estimates of the probability of their occurrence.

According to Miklánek et al. (2003), on July 20, 1998 between 4 and 5 p.m. in the location of the Mala Svinka basin in the Bachuren Mountains (east Slovakia), rainfall depth in a 40 km² area reached 100 mm. This precipitation event was marked as a 1000-year precipitation event in Slovakia.

The 1000-year catastrophic precipitation scenario (probability of occurrence of event: 0.001) for the Zdychava River basin can be obtained by combining the values in Table 7, such as the product of the probabilities of extreme rainfall occurring at Predná Hora and Revúca. For example, the depth of daily rainfall of 115 mm on Predná Hora ($p = 0.01$) and 69 mm at Revúca station ($p = 0.1$) has a probability of occurring once every 1000-years ($p = 0.001$). Another example shows that daily rainfall of 131 mm on Predná Hora and 57 mm in Revúca also has a probability of occurring once in 1000 years.

The average 1000-year rainfall for the Zdychava basin is then 92 or 94 mm (arithmetic mean). Of course, the duration of such rainfall event on the Zdychava basin is unknown. The analysis was made from 24-hour (1-day) precipitation depths. It can only be assumed that these high totals are caused by intense summer storms.

The reality of this scenario has been confirmed by historical storm events in the Muránska Planina region. A very similar precipitation event to the event in 2020 occurred on the upper Muráň River also on 23 August 1985. The daily rainfall depth at Muránska Huta station reached 104.7 mm, in Telgárt the daily depth was 27.4 mm, in Ratková 0.9 mm and in Revúca 0.2 mm.

Also in 1937, a similar or possibly even larger storm occurred on 16 June in the region. At the Muráň station the precipitation depth reached 103.7 mm, from the Predná Hora station there are no data as the station was out of order, in Telgárt the daily depth was 99.8 mm, in Šumiac 82.1 mm, in Polianka 60.9 mm, in Revúca 50.8 mm, in Ratková the depth was 51 mm, and in Brusno 64.8 mm. The year 1937 was extremely rich in precipitation and storms in central and southern Slovakia.

Based on the above, an extreme 1000-year rainfall depth for the Zdychava basin was estimated at 90 mm in 1.5 hours.

3.2.3 Catastrophic 1000-year discharge of the Zdychava River

Because the NLC model was calibrated in 15-minute stages, various scenarios of 15-minute precipitation totals per basin were determined, e.g.: 10 mm, 15 mm, 20 mm, 20 mm, 15 mm, and 10 mm; or 20, 25, 10, 10, 15, 10. The simulated flows changed insignificantly.

In the first extreme precipitation scenario, the peak flow rate would reach 105.15 m³ s⁻¹, i.e. a specific outflow of 1.78 m³ s⁻¹ km⁻² (Figure 8). The total run-off in 18 hours would be 1.119 million m³, representing 21.11% of the rainfall dropped (5.301 million m³).

Of course, we are aware that this simulation is only one of many options that could occur. We used the parameters of the model (e.g. initial saturation of the river basin by precipitation) that we obtained when calibrating the wave from June 28, 2020.

Fig. 8. The rainfall event of 90 mm depth with duration of 90 minutes – catastrophic scenario for the Zdychava basin to station Revúca (upper); simulation of flows from the catastrophic rainfall, Zdychava River: Revúca, total (points) and base (dashed line) flows – output of the NLC model (lower).

4 DISCUSSION AND CONCLUSION

Several conclusions follow from the average and maximum discharge analysis in the Slaná basin. In the Q_a and Q_{max} series, multi-annual wet periods alternate with multi-annual drier periods, as the Q_a and Q_{max} series are clearly cyclical (long-term cycle ca 36 to 40 years). This cycle corresponds to the cycle of 32–33 years which was described by Varga in the Turisták Lapja newspaper in 1939 in the Slaná basin in the Rožňava region (Melo and Bernáthová, 2013). According to Varga, records of catastrophic floods from Rožňava date back to 1780, 1813, 1845, 1878 and 1897. For example, during the historical flood of 25–26 August 1813, 187 houses were destroyed in Rožňava, leaving no trace of 83 houses.

In wet years, extreme flooding is more likely to occur. Flash floods from summer storms occur in small areas. Interestingly, flash floods in the Zdychava and Hrdzavý Creek do not occur at the same time. The hydrological regimes of the Zdychava and Hrdzavý Creek are diametrically opposed due to different geology.

The culmination flows calculated by us during the June 2020 flood and the specific runoffs in our surveyed small sub-basins are not particularly extreme. Only 17.36% of the rainfall water volume of 3,699 thousand m^3 in the Zdychava basin flowed through the profile in Revúca in 18 hours. As a result, the Zdychava basin caught well the fallen precipitation. Higher values were only estimated in Hutský Creek (Zdychava River sub-basin) at the heart of the storm.

We must recall that in the wet year 1937 there were similar storm events in the Muránska planina region on 16 June 1937. In Slovakia, year 1937 is one of the wettest years for the entire precipitation observation period (since 1901). When assessing climate change, we cannot confine ourselves to the last 30 years of data: it is necessary to evaluate it over as long a period as possible.

Interestingly, a similar situation to 2020 year's flood in the upper Muráň basin occurred on 23 August 1985. A peak discharge of $31.27 \text{ m}^3 \text{ s}^{-1}$ was recorded at Revúca: Zdychava gauge. On this day, the daily rainfall depth at Muránska Huta – Predná Hora gauge reached 104.7 mm. Similarly, in 1985 the catchment was saturated with previous precipitation - on 07 August 1985 the daily rainfall depth was 33.1 mm and on 08 August 1985 the daily rainfall depth was 10.2 mm.

A comparison of the results obtained with historical data on similar flash floods in other small river basins shows that the cause of these catastrophic phenomena is, crucially, causal precipitation and the initial distribution of soil moisture in the river basin, and not the impact of the vegetation cover as has been emphasized recently in many works. The major damage to the new road in the upper Muráň basin was caused by insufficient space to drain the water from such an extreme precipitation event.

The use of methods of mathematical modelling of rainfall-runoff events has proven to be an appropriate tool not only for reconstructing these extraordinary phenomena, but also for creating hypothetical extreme events for the occurrence of such precipitation, which meteorologists consider possible, albeit very unlikely.

When designing effective flood protection measures, we should first of all know the critical peak flows of the floods from which the area must be protected. Mathematical modelling of rainfall runoff is the most appropriate tool for this. We should also have an idea of how the proposed measures will affect run-off. In this work, we used a simple rainfall-runoff model, NLC with lumped parameters, to quickly simulate run-

off from one rainfall event. Of course, it would be advisable to use some complex rainfall-runoff model with distributed parameters (AGNPS, Topmodel, WaSiM, SCS-CN and SCS-UH) through which it is possible to simulate, for example, the impact of change in land use.

We used the Zdychava basin for the simulation, as there are two precipitation stations with long-term precipitation observations in this river basin and it was therefore possible to process a 1000-year precipitation scenario. Water levels and evaluated discharges are also measured there. We have not used climate scenarios in this work. Even without their use, the estimated 1000-year peak flow rate is extremely high.

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REFERENCES

- Báčová Mitková, V., Pekárová, P., Halmová, D., Mikláněk, P., 2018. Reconstruction and post-event analysis of a flash flood in a small ungauged basin: a case study in Slovak territory. *Natural Hazards*, 92, 2, 741–760.
- Bírová, M., Wendlová, V., Randusová, R., Smrtník, P., 2017. Severe flash floods in Slovakia, July 2016. In: XXVII Conference of the Danubian Countries on Hydrological Forecasting and Hydrological Bases of Water Management - Golden Sands: Bulgarian NC for the IHP UNESCO, 409–418. ISBN 978-954-90537-2-2. http://www.shmu.sk/File/Hydrologia/Publikacna_cinnost/2017/2017_Danube_Conference_Birova_akol.pdf
- Blaškovičová, L., Horvát, O., Hlavčová, K., Kohnová, S., Szolgay, J., 2011. Methodology for post-event analysis of flash floods – Svacennický Creek case study. *Contributions to Geophysics and Geodesy*, 41, 3, 235–250. <https://doi.org/10.2478/v10126-011-0009-9P>
- Bucala-Hrabia, A., Kijowska-Strugała, M., Bryndal, T., Cebulski, J., Kiszka, K., Krocak, R., 2020. An integrated approach for investigating geomorphic changes due to flash flooding in two small stream channels (Western Polish Carpathians). *Journal of Hydrology: Regional Studies*, 31, 100731. <https://doi.org/10.1016/j.ejrh.2020.100731>
- Dzubák, M., 1969. The convenience judgement of the choice of distribution of the maximum total precipitation by means of the global cumulative probability curves. (Stanovenie zákona rozdelenia maximálnych denných zrážkových úhrnov pomocou globálnych čiar prekročenia). *Vodohospodársky Časopis (J. Hydrol. Hydromech.)* 18, 3, 209–225. (In Slovak.)
- Elleder, L., Herget, J., Roggenkamp, T., Nießen, A., 2013. Historic floods in the city of Prague – a reconstruction of peak discharges for 1481–1825 based on documentary sources. *Hydrol. Res.*, 44, 2, 202–214.
- Faško, P., Gaál, L., Lapin, M., Pecho, J., Šťastný, P., 2006. Contribution to estimation of the design values of daily precipitation depths. In: Proc. to the 80th birthday of Prof. Milan Dzubák, SHMÚ, Bratislava, pp. 19–26. (In Slovak.)
- Gaume, E., Borga, M., 2008. Post-flood field investigations in upland catchments after major flash floods: proposal of a methodology and illustrations. *J. Flood Risk Management*, 1, 175–189.
- Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaškovičová, L., Blöschl, G., Borga, M., Dumitrescu, A., Daliakopoulos, I., Garcia, J., Irimescu, A.,

- Kohnova, S., Koutroulis, A., Marchi, L., Matreata, S., Medina, V., Preciso, E., Sempere-Torres, D., Stancalie, G., Szolgay, J., Tsanis, I., Velasco, D., Viglione, A., 2009. A collation of data on European flash floods. *Journal of Hydrology*, 367, 70–78.
- Gaume, E., Borga, M., Llassat, M.C., Maouche, S., Lang, M., Diakakis, M., 2016. Mediterranean extreme floods and flash floods. *The Mediterranean Region under Climate Change. A Scientific Update*, IRD Editions, pp. 133–144, Coll. Synthèses, 978-2-7099-2219-7. hal-01465740v2
- Halaj, M., Hrušková, K., Trstenský, T., 2020a. Intensive storms and flash floods in June 2020 in the Hron, Ipel', Slaná and Rimava river basins. SHMÚ, Banská Bystrica, 19 p. (In Slovak.)
- Halaj, M., Hrušková, K., Trstenský, T., 2020b. Extreme storm and flash flood in the Muránska planina. SHMÚ News. <http://www.shmu.sk/sk/?page=2049&id=1068> assessed on August 4, 2020 (In Slovak.)
- Hlavčová, K., Kohnová, S., Borga, M., Horvát, O., Šťastný, P., Pekárová, P., Majerčáková, O., Danáčová, Z., 2016. Post-event analysis and flash flood hydrology in Slovakia. *J. Hydrol. Hydromech.*, 64, 304–315. <https://doi.org/10.1515/johh-2016-0041>
- HP ČSSR, 1965. Hydrological conditions of the Czechoslovak Socialist Republic. Hydrometeorological Institute, Prague, 414 p.
- Kaiser, M., Günnemann, S., Disse, M., 2020. Providing guidance on efficient flash flood documentation: an application based approach. *Journal of Hydrology*, 581. <https://doi.org/10.1016/j.jhydrol.2019.124466>
- Kjeldsen, T.R., Jones, D.A., Morris, D.G., 2014. Using multiple donor sites for enhanced flood estimation in ungauged catchments. *Water Resour. Res.*, 50, 6646–6657. DOI: 10.1002/2013WR015203
- Majerčáková, O., Makel', M., Šťastný, P., Kupčo, M., Rončák, P., 2004. Selected flash floods in the Slovak Republic. GWP report. Slovak Hydrometeorological Institute, Bratislava, 34 p.
- Marchi, L., Borga, M., Preciso, E., Gaume, E., 2010. Characterisation of selected extreme flash floods in Europe and implications for flood risk management. *J. Hydrol.*, 394, 118–133. DOI: 10.1016/j.jhydrol.2010.07.017
- Melo, M., Bernáthová, D., 2013. Historical floods in Slaná River basin since the end of the 18th century till the beginning of the 20th century. *Acta Hydrologica Slovaca*, 14, 2, 291–298. (In Slovak.)
- Miklánek, P., Halmová, D., Pekárová, P., 2003. Extreme runoff simulation in Mala Svinka Basin. In: IHP-VI Technical Documents in Hydrology, No. 66, UNESCO, Paris, pp. 61–67.
- Parajka, J., Kohnová, S., Szolgay, J., 2004. Mapping of N-year maximum daily precipitation depth in the upper Hron basin. *Acta Hydrologica Slovaca*, 5, 2, 258–265. (In Slovak.)
- Pekárová, P., Svoboda, A., Miklánek, P., Škoda, P., Halmová, D., 2012. Estimating flash flood peak discharge in Gidra and Parná basin: case study for the 7–8 June 2011 flood. *J. Hydrol. Hydromech.*, 60, 3, 206–216.
- Petrůška, M., 2010. Analysis of natural risks on the territory of the National Park Muránska planina. Diploma thesis, VŠB-Technical University Ostrava, 84 p. <https://core.ac.uk/download/pdf/8985039.pdf>, assessed on July 15, 2020 (In Slovak.)
- Šamaj, F., Valovič, Š., Brázdil, R., 1985. Daily precipitation depths with extraordinary yield in ČSSR in the period 1901–1980. In: *Zborník prác SHMÚ 24. ALFA*, Bratislava, pp. 9–112. (In Slovak.)
- Siman, C., 2020. Return to the intense storm on Predná Hora from June 28, 2020. (Návrat k intenzívnemu lejaku na Prednej Hore zo dňa 28.6.2020). SHMI. <http://www.shmu.sk/sk/?page=2049&id=1073>
- Szolgay, J., Blöschl, G., Gribovszki, Z., Parajka, J., 2020. Hydrology of the Carpathian Basin: interactions of climatic drivers and hydrological processes on local and regional scales – HydroCarpath Research. *J. Hydrol. Hydromech.*, 68, 2, 128–133. DOI: 10.2478/johh-2020-0017
- Šťastný, P., Majerčáková, O., 2003. Reconstruction of the flood in Štrba on July 2001. In: *Proceedings of 'Hydrology at the Beginning of the 21st Century: Vision and Reality'*, Smolenice, May 5–7, 2003. Institute of Hydrology SAS, Slovak Committee for Hydrology, Slovak IGBP Committee, (In Slovak.)
- Svoboda, A., 1987. Two-component nonlinear rainfall-runoff model NLC. *J. Hydrol. Hydromech.*, 35, 6, 661–663. (In Slovak.)
- Svoboda, A., Pekárová, P., 1998. The catastrophic flood of July 1998 in the Malá Svinka catchment – its simulation. *J. Hydrol. Hydromech.*, 46, 6, 356–365. (In Slovak.)
- Zítek, J. (ed), 1958. Yearbook of atmospheric precipitation on the territory of Slovakia in the water year 1937. Hydrometeorologický ústav, Praha, 36 p. (In Czech.)

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APPENDIX 1

Descriptions of historical extreme storms and flash floods in Slovakia from professional publications, or chronicles of towns and villages

- In the publication of Brezina (2017) on page 71 is an inventory of historical floods in Sobotište since 1630. We read about the flood of 1672: "*A local cloud burst on 10.8. sparked a flood that collapsed 90 houses built from adobe brick in Sobotište, ..., Nearly 100 people died, including dozens of children...*"
- During the flood from the cloud burst on 5 June 1902, the water flooded houses near the square in Sobotište up to a height of 127 cm.
- In the History of Catholic parishes in Myjava and Turá Lúka (2019) a reference can be found to the catastrophic flood of 8 June 1775.
- Oskár Dubovický mentions a huge storm and flood of 25 June 1893 in Stará Bystrica in the chronicle of Stará Bystrica. According to his description, "*the water took banks, fields, benches, bridges and buildings. There were landslides in many places*". In 2009, ca 50 houses were flooded during the flood in Stará Bystrica on 29 June, with rainfall depth reaching 91 mm in 1.5 hours.
- The chronicler Karol Okál' (Okál', 2010) described on his blog the flood on the River Ľubochňanka of 28 May 1925. This flood not only damaged roads and the track, but also damaged all bridges in the Ľubochňanska Valley.
- Peter Vítek (Vítek et al., 2013) in the chronicle of the village of Bešeňová mentions the flash flood of 1929: "*Large hail and subsequent flash flood in 1929*". The commemorative book of the village of Lúky (Chronicle of the village of Lúky, 2018) describes two floods from two extreme storms on 16 and 17 June 1939 on Biela voda. *On June 16, at about 2:00 p.m., a terrible storm slid over our valley, coupled with a cloud burst. The rain lasted about 1 hour. At least 2/3rds of the homes were flooded with water. The wild waves took*

away everything that got in their way. Tremendous timbers, whole trees, roofs of houses and barns, several quintals of heavy rocks, pigs, bee-hives, slabs, farm machinery, it all swam down the water. All the crops around the stream were taken along with the barn. Fruit trees broken. Bridges taken away.... The next day, again at about 2 p.m., the storm came again, but even more terrible. Lightning criss-crossed the sky, and the rumble of thunder did not stop. Then the clouds opened and the water from them did not fall as drops, but continuously poured down, forming a kind of water wall. Although it was between 2 and 3 p.m., we could not see through the rain further than 10 m. It rained for about 1 hour.... Everything that's left of the previous day in the fields and gardens has disappeared now. Hundreds and hundreds of fruit trees were broken, and in places where grain, beets, potatoes, cabbage, flax, hemp, etc., were greened, only piles of sand, stone and mute water remained in the pits. In many places in the area, large areas of earth have slid. Many houses have been damaged.

- Dub's study (1941) describes the aforementioned catastrophic flood on the Vydrňanka (inflow of Biela voda from the Javorníky flysch area, middle Váh catchment) on 17 June 1939, in which "... the rain was so heavy you could not see ten steps away and the valley sides were all covered with water that rolled into the stream.... The effect of the torrent was devastating. The only longitudinal road was completely destroyed, houses damaged, or demolished and taken away by water. The original regulated trough was covered in full length with coarse sediments up to a height of 1–1.5 m, so that the water created a new trough..." Dub determined the culmination flow rate of this flood at $100 \text{ m}^3 \text{ s}^{-1}$, i.e. the specific outflow was $10 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$.
- Further information about the catastrophic flood of 1848 comes from Terchová on the Varínka/Vrátňanka Creek. A niche with a table resembling the height of the flood from Vrátna Valley is carved into the rock above the stream in

Tiesňavy. In the newspaper TERCHOVÁ No. 4/2008 this mark was described by Michal Kapasný. According to his information, Ferenz Blaha had the niche carved for the statue of Our Lady back in 1848. He was a gamekeeper who lived in Vrátna in a gamekeeper's house. In addition to the niche, he also sculpted the flood level mark. His name was also underneath the inscription about the event. In the postwar period, around 1948, this original plate, with more religious text, was rebuilt in its present form. The text on the table recalls that on 11 June 1848 there was a flood in the current settlement of Štefanová. At the time, 14 citizens drowned. The line on the table indicates the level to which the water reached during the flood in 1848. A similar event occurred in the Vrátna Valley in 2014. It is notative that the flood in 2014 did not reach the level of 1848.

REFERENCES

- Brezina, P., 2017. Sobotište on postcards and photographs. Sobotište Municipal Office, pp. 248. (In Slovak.)
- History of Catholic parishes in Myjava and Tura Lúka, 2019. (Dejiny katolíckych farností v Myjave a Turej Lúke). <http://www.rkmyj.szm.com/historia.htm> (In Slovak.)
- Dub, O., 1941. Large water regime on small streams. (Režim veľkých vôd na malých tokoch). Publication of the State Hydrological and Meteorological Institute in Bratislava. (In Slovak.)
- Chronicle of the village of Lúky, 2018. (In Slovak.) <https://www.obecluky.sk/obecna-kronika.html>
- Okál', K., 2010. Floods (Povodne). (In Slovak.) <https://okal.blog.sme.sk/c/231449/Povodne.html>
- Vítek, P., Martinický, M., Janura, T., Laučík, P., Vaněk, O., Hlavienka, J., 2013. Liptovský Ján: From the first written mention to the present. (Liptovský Ján: Od prvej písomnej zmienky po súčasnosť). The village of Liptovský Ján, 254 p.

APPENDIX 2

Geological Map of the territory of the Muránska Planina National Park, Muráň and Zdychava basins, Slovakia.