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Post-flood analysis of the flood from the rupture of the stone dam in Rudno nad Hronom on May 17, 2021

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The study is aimed at reconstructing the course of the flood from May 17, 2021 breach of the stone dam in Rudno nad Hronom. Firstly, the volume of water in the reservoir before its breach was determined. The reservoir storage volume was estimated to be 14 807 m^3. Then, we focused on the analysis of the hydrological regime in the wider Rudniansky Brook region. In order to derive the flood wave course from the rainfall, a series of 15-minute discharge from neighbouring water gauges measured by the Slovak Hydrometeorological Institute were analysed. In analysing the long-term trends of precipitation and temperature series we used data from the Banská Štiavnica meteorological station (period 1901–2020). In the second part, based on several field measurements after the flood event, we estimated the peak flows of floods from May 17, 2021 above the reservoir and under the reservoir. One hundred meters above the reservoir culmination reached 7.8 $m^3 s^{-1}$, under the reservoir it was between 80 to 100 $m^3 s^{-1}$. Finally, we reconstructed the course of the flood wave from the precipitation above the reservoir by hydrological analogy and by simple rainfall-runoff hydrological model NLC. The course of the breakthrough wave from the reservoir water just below the dam was determined to be triangular in shape so that the peak reached 90 $m^3 s^{-1}$ and the volume was 15,000 m^3.

KEY WORDS: breakthrough wave, rupture dam, Rudniansky Brook, rainfall-runoff NLC model

Introduction

Dams on streams play an important role in the comprehensive development of the landscape. Reservoirs are built for various purposes, e.g. for agricultural irrigation, fishing, recreation, drinking water supply, flood prevention or energy production. Thousands of reservoirs have been built on watercourses around the world over the last 200 years. For example, in China alone, according to statistics from 2021, 98 000 reservoirs have been built, including 4 700 reservoirs with a capacity of between 10 million and 1 billion cubic metres. Hundreds of reservoirs have been built in the Danube basin since the beginning of the 16th century, especially on the upper Danube (ICPDR, 2013).

In Slovakia, according to Bednárová and Dušička (2011), 281 water reservoirs have been built, which fall under the administration of the Slovak Water Management Company. Of these, 231 are small reservoirs and 50 reservoirs are included in the world register of large dams (ICOLD – International Comittee on Large Dams). A total of 1.89 billion m^3 of water can be stored in them. In densely populated areas, a flood due to a dam rupture can cause a devastating disaster with loss of life and property. The time required to warn people living below the reservoir is very short in the event of a flood caused by a dam rupture (Oguzhan, and Aksoy, 2020; Xu et al., 2012).

May 2021 was extremely cold and very wet in Slovakia. From 12 to 17 May 2021 several frontal waves passed eastwards through Slovakia. The dam rupture was caused by persistent rainfall, which peaked in the afternoon of May 17, 2021. This precipitation caused the water levels of several Slovak rivers to rise (SHMÚ Flood Reports No 4, 6 and 7, 2021). In the Hron river basin, peak flows with a probability of being exceeded once in 20 years were assessed in Kalinčiakovo on the Sikenica, and once in 10 years in Jasenie on the Jaseniansky brook, in Harmanec–Papiereň on the Bystrica and in Žiar nad Hronom and Kamenín on the Hron River. As a result of intense rainfall, the watercourses were dammed in many places and flooded local roads as well as the intravillans and extravillans of several municipalities.

On the Rudniansky brook above the village of Rudno nad Hronom on 17.5.2021 at the time after 15.30 a 6 m high unpaved stone dam was washed away by the flowing water. The reservoir above the dam was already full before the precipitation event. The breakthrough wave that occurred after the dam broke damaged bridges, cars, footbridges, fences, flooded houses, covered gardens with mud and caused great material damage in the village of Rudno nad Hronom. Unfortunately, the breakthrough wave also caused one human casualty. In order to document this event, we conducted several measurements and hydrological analysis of this event in the Rudniansky Brook watershed.

In the first part of the study the volume of water in the reservoir built in 2011 before its breach in 2021 is determined. In the second part, the hydrological conditions of the Rudniansky Brook basin are analyzed, the results of field measurements are described. Finally, in the third part the course of the flood wave is analysed in the profiles upstream and downstream the reservoir.

Material and methods

The Rudniansky Brook is located in central Slovakia in the Hron basin in the western part of the geomorphological unit Štiavnické vrchy, in the subunit Hodrušská hornatina (Fig. 1). It rises below the Lachtriská saddle in the cadastral territory of the Uhliská municipality at an altitude of about 655 m. It flows in a west to north-west direction and after Rudno nad Hronom it flows into the Hron (left-side tributary of the Hron) at an altitude of 200 m. The river network is leaf-shaped. According to the classification of Gravelius, the Rudniansky brook is a stream of the 3rd order. The length of the stream is 8.2 km, the gradient of the stream is 450 m and the average slope of the stream is 5.3%. The catchment area of the Rudnianský Brook is 17.86 km^2, the average elevation of the catchment area is 495 m, and the average slope of the catchment area is 19.4°. According to the vertical structure, the area is characterised as a lower mountainous area.

The subsoil of the basin is made up of volcanic rocks and occasional deluvial sediments. Fluvial sediments are found along the watercourses. The entire catchment area is covered by Cambisols modal (brown forest soils). Potential natural vegetation would be mainly represented by Carpathian oak-hornbeam forests, foothill beech forests and maple-lime forests at lower elevations. At present, 90 % of the catchment area is covered by forests. Almost half of the forests are made up of beeches, followed by oaks and hornbeams. Maples, ash, spruces, larches, and firs are less abundant (LGIS, 2021).

Description of the historical ponds (tajchy) near Rudno nad Hronom

More than 50 water reservoirs – taichs – were built in the Štiavnické vrchy mountains in the 16th– 9th centuries in order to obtain energy for pumping groundwater from mining tunnels, but also to obtain water supplies for the mining industry (Weis et al., 2017). This unique water management system, together with the town of Banská Štiavnica, was inscribed by UNESCO on the list of cultural heritage of humanity in 1993. Two taichs have been built in the Rudniansky Brook basin above the village of Rudno nad Hronom: the Old/Upper Taich (325 to 345 m a.s.l.) and the New/Lower Taich (276 to 293 m a.s.l.) (Hrdý and Weis, 2020; Pekárová et al., 2021a). These were valley reservoirs that were built by damming the valley with an earthen dam. The Old taich existed until the 19th century. In 1926, the dam of the New Taich near the left bank of the safety spillway partially broke and the water from the breakthrough caused a catastrophic flood in the village of Rudno. In the 1970's, the dam was breached to the bottom of the reservoir for safety reasons and for the passage of forestry equipment. Several solid stone dams were built in the village to trap sediment. These were regularly cleaned (Fig. 2a).

In December 2011, a permeable unpaved stone dam was completed in the place of the original dam of the ruptured New Tajch just above the village of Rudno nad Hronom (Fig. 2 a–b). This was intended to catch extreme flood waves. The crown elevation of the dam was 280 m. The catchment area above the reservoir is 12 km^2. According to the available information, the new retention area of the dry polder was ca. 29 680 m^3 in front of a stone dam 10 m wide, 6 m high, and 22 m long with a DN 800 bottom outlet 32 m long (Hríb, 2012). The stone dam broke and washed away on 17.5.2021 at the time after 15.30 hrs. by the flow of water from the continuous rain. The breakthrough wave that occurred after the break of the dam in the village Rudno nad Hronom caused great material damage (Fig. 2c, d).

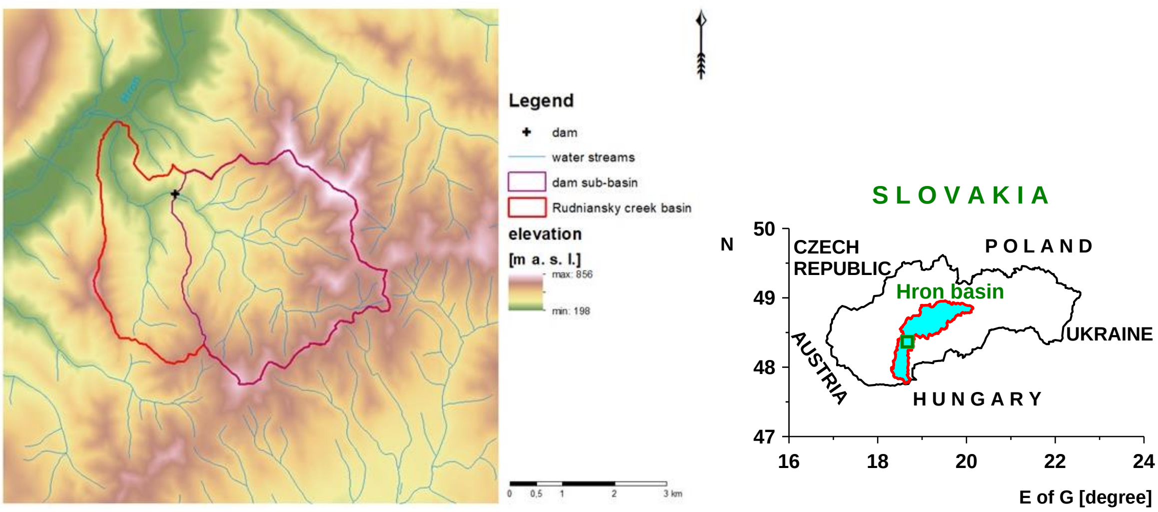


Fig. 1. Position of the Rudniansky Brook basin in the Hron basin (right) and the small reservoirs in the Rudniansky Brook basin (left) upstream the village Rudno nad Hronom.

Fig. 2. a) Two concrete stone dams downstream the reservoir near Rudno nad Hronom. b) Unpaved permeable 6 m high stone dam built in 2011 in the place of the former 17 m high dam of the New tajch, picture taken from the side of the reservoir (Photo Hríb, 2012). c–d) Flood damages in the village Rudno nad Hronom. The water level height of the flood on 17. 5. 2021 at 18.15 hrs. is visible on the house wall (Photo https://www.youtube.com/watch?v=5SWMHLeao1s).

Data used

There is neither a rain gauge station nor a water gauge station on the Rudniansky Brook to record water levels. Therefore, average monthly rainfall totals from the Banská Štiavnica rainfall gauging station from 1901 to 2020 were used to evaluate the long-term trend of annual rainfall totals. The maximum daily rainfall was evaluated from a series of daily rainfall totals for the period 1961–2020 and compared with the values according to Šamaj et al. (1985). The long-term trend of annual mean flows was analysed at the station Plášťovce Krupinica, where flow measurements since 1931 have been evaluated.

As the May 17, 2021 rainfall event also affected the adjacent valleys of Rudniansky Brook with similar intensity, we assume that the course of the flood waves was similar. In order to derive the flood wave course from the rainfall, a series of 15-minute/hourly discharge Q from neighbouring stations measured by the Slovak Hydrometeorological Institute (SHMI) were analysed.

1. Plášťovce: Krupinica (area: 302.79 km^2, measured since 1931).
2. Kalinčiakovo: Sikenica (area: 217.84 km^2, measured since 1970);
3. Žarnovica: Kľak (area: 131.95 km^2, measured since 1958);
4. Pečenice: Jabloňovka (area: 51.36 km^2, measured since 1986);
5. Bzenica: Vyhniansky potok (area: 37.75 km^2, measured since 2008).

In the analysis of the maximum annual flows, the series of peak flows Q_{max} evaluated for the hydrological year (from November 1 to October 31 of the following year) were used.

Methods and NLC model

To simulate flood waves, a conceptual non-linear NLC (non-linear cascade model) rainfall-runoff model was used (Pekárová et al, 2021b). 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. The schematic model structure is shown in Fig. 3.

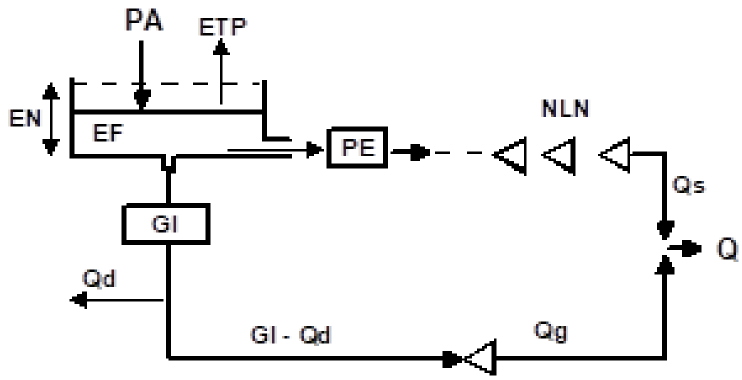


Fig. 3. Schematic representation of the NLC model structure. (PA – input precipitation, PE – effective precipitation, ETP – evapotranspiration, Qs – direct runoff, GI – groundwater input, Qg – groundwater runoff, Q – total runoff, Qd – deep percolation, EN and EF are storage parameter and actual water content of the unsaturated zone).

Results

In order to obtain the necessary hydrological data on the course and height of the catastrophic flash flood wave of May 17, 2021, the staff of the Slovak Hydrometeorological Institute (SHMI) and the Institute of Hydrology of the Slovak Academy of Sciences (IH SAS) carried out a number of independent expeditionary measurements in the Rudniansky Brook catchment (Fig. 4). According to photographs and information from local residents, the reservoir was filled to the crown of the dam before the breach, with water flowing over the crest in two erosion gullies. During the first measurements, the peak flood flow from the rainfall above the reservoir was reconstructed by hydrometry and the peak flow of the breakthrough wave below the reservoir was estimated. Traces of the flood in the basin upstream the reservoir were documented. During further measurements, the sediment elevation in the reservoir was measured.

Determination of the volume of water in the reservoir

In the flood wave volume calculations, it was necessary to find the volume of water that flowed out of the reservoir after the dam broke (Pekárová et al, 2021a). It was not possible to work with the 2011 reservoir volume figure (ca. 30 000 m^3), as the bottom of the reservoir has been covered with sediment for more than 10 years (Fig. 5). The thickest sediment deposits we measured in the field were about 1–1.7 m high.
The volume of the reservoir was calculated using the Digital Model of Relief (DMR) via the ZBGIS Map Client application. The DMR was imaged by airborne laser scanning between November 16, 2018 and March 27, 2019. At least 5 points per m^2 were scanned with a height accuracy of 0.06 m. The water reservoir in Rudno nad Hronom was empty at the time of scanning. The DMR section was processed in ArcGIS 10 software. Contours with an interval of 0.5 m were derived from the DMR section using the Contour tool. The DMR section was clipped with a contour with an elevation of 280 m (Fig. 6). We obtained the DMR of the empty water reservoir. With the Surface Volume tool, the reservoir storage volume in 2019 was calculated to be 14 807 m^3, which is about half of the volume given by the project author more than 10 years ago.

Runoff variability at the station Plášťovce on the Krupinica River

Variability analysis of precipitation, air temperature and runoff

The analysis of the results of the long-term evolution of annual precipitation totals at the Banská Štiavnica station is presented in Figure 7. From 1901 until 1980 the long-term trend was decreasing, since 1994 the annual precipitation totals have increased. In the decade 2001–2010, the highest variability of annual precipitation totals ($c_v = 0.26$) was calculated; both the lowest (2003–491 mm) and the highest (2010–1296 mm) annual precipitation totals for the whole period since 1901 were measured in this decade.
At this station, the highest 24-hour rainfall in the period 1961–2020 was 70.8 mm on 29 October 1990. But in the past, a rainfall of 82.5 mm was measured on 5 May 1908 (Šamaj et al., 1985). The *100*-year 24-hour rainfall is 88 mm in the period 1961–2018, the same *100*-year rainfall was calculated by Šamaj et al. (1985) for the period 1901–1980.
Similarly, as in the case of precipitation, the runoff of the Krupinica River at Plášťovce station has been decreasing from 1931 to 1993. The decade 1931–1940 was the wettest, the decade 2011–2020 the driest (Fig. 7). Despite the increase in annual precipitation in the last two decades, Krupinica flows have been declining. This is mainly due to higher air temperatures, but also to the increasing amount of wood in forests and the resulting higher evaporation. Average daily discharges are highest in March-April and lowest in August–September.

a)–b) Surface runoff after the breakthrough wave on May 17, 2021 at 18.15 hrs.
(Photo from https://www.youtube.com/watch?v=d2bixIHpRbs)

c) Surface runoff on May18, 2021 at 16.20 hrs. *d) Clogged pipe from the bottom drain on June 8, 2021.*
(Photo Mészáros, Pekárová)

Fig. 4. Runoff from the rainfall wave downstream the reservoir after the breakthrough wave.

Fig. 5. Thickness of 10 years sediments at the reservoir bottom at Rudno nad Hronom. (Photo Pekárová, 8. 6. 2021).

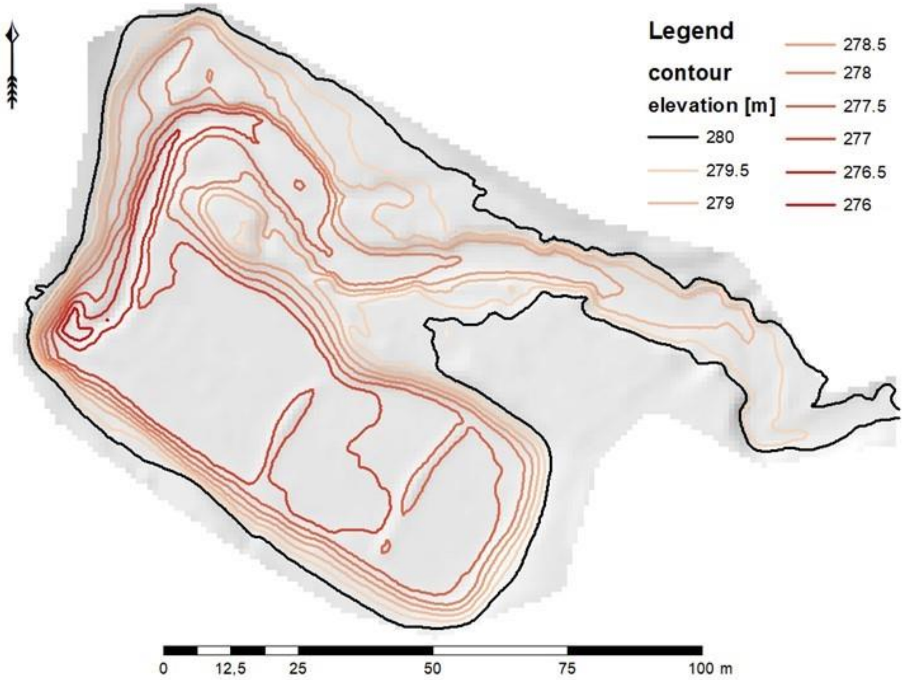


Fig. 6. *Water reservoir in 2019.*

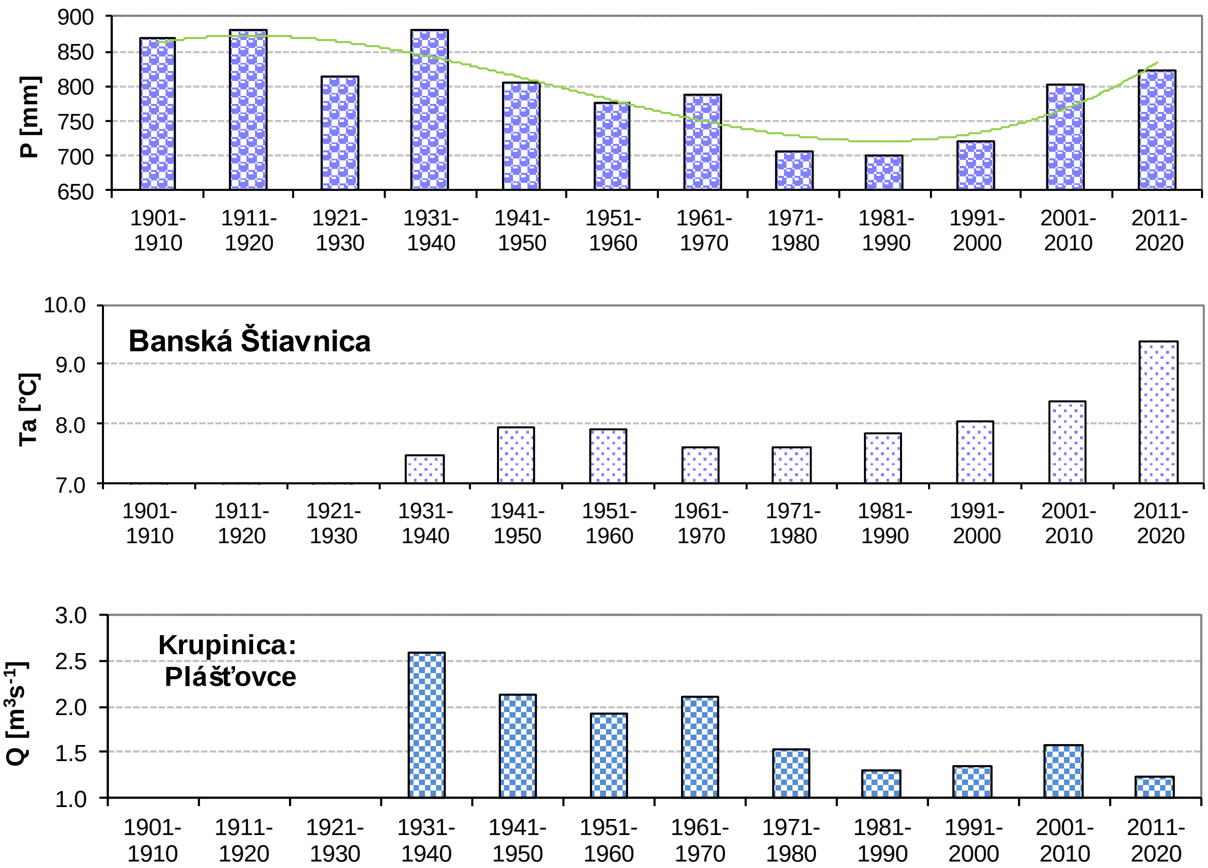


Fig. 7. *Development of the 10-year average air temperature and precipitation depth, the meteorological station Banská Štiavnica (1901–2020), and 10-year average discharge at Plášťovce on the Krupinica River.*

Analysis of the maximum annual discharge of the streams in the Rudniansky Brook surroundings

According to the SHMI data, the peak flow of the flood wave on May 17, 2021 at 5.15 p.m. CEST reached 38.5 $m^3 s^{-1}$ at Kľak in Žarnovica. In Bzenica on the Vyhniansky Brook, the flood wave from rain peaked at the same time at a discharge of 7.452 $m^3 s^{-1}$. The *T*-year return period of the flood at Kľak was only at the level of 2 years.

For the Rudniansky brook we could use the *T*-year values of the specific runoff from the Vyhniansky brook. The q_{max} series from Vyhniansky brook, however, is only observed since 2008. Therefore, we analyzed the distribution functions of *T*-year specific runoff (q_{max}) from stations in the wider area.

The LP3 distribution was used to estimate the *T*-year specific runoff (Fig. 8). The smaller catchment area leads to the higher gamma skewness parameter (the line turns upwards more). The estimated values of *T*-year specific runoff for the two streams are shown in Table 1. As the catchment area of Rudniansky Brook above the reservoir is only 12 km^2, and Vyhniansky Brook 37.75 km^2, the distribution function will have a much higher skewness parameter and the *T*-year specific discharges with small return period on Rudniansky Brook are likely to be much higher (95% upper limit of *100*-year discharge may reach 40 $m^3 s^{-1}$. The uncertainty in determining this value by statistical methods is very high. According to the SHMI, the *100*-year discharge in this profile (12 km^2) is estimated at 30 $m^3 s^{-1}$.

Analysis of the flood event on 17. 5. 2021 at Rudno nad Hronom

Description of the meteorological situation in May 2021

The months of April and May 2021 in the Hron basin were cold and rainy. On 16 May 2021, a cold front associated with a large-scale pressure low centred over the British Isles moved eastwards across the basin. On 17 May, a frontal wave associated with a shallow pressure low influenced weather in the Rudniansky Brook watershed. This caused numerous persistent precipitation events in the catchment areas of the Hron, Ipeľ and Slaná rivers. From 1 to 16 May at 11 p.m., the rainfall total reached 50.1 mm at the Banská Štiavnica station.

On 16 May it rained 9.1 mm at station Banská Štiavnica. Such rainfall could have fallen over the entire catchment area of the Rudniansky brook up to the reservoir, i.e. 109 000 m^3 of water fell on the catchment area. On 17 May, from 1.00 a.m. until the dam in Rudno nad Hronom broke, the rainfall depth at station Banská Štiavnica was 41 mm. The daily rainfall from 1.00 a.m. to 12 p.m. was 46.4 mm.

Estimation of the peak discharge of the rain flood wave upstream the reservoir

The profile 100 m above the reservoir (48.4191300N, 18.7049519E) was selected to determine the peak discharge by hydrotechnical calculation (Fig. 9). In this profile (Fig. 10a), the flow area at the estimated

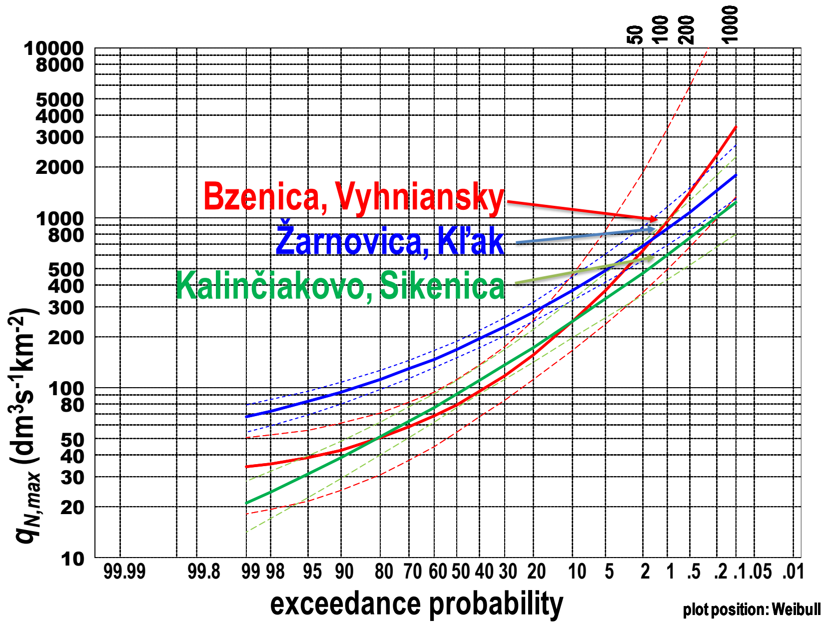


Fig. 8. T-year specific discharge q in l $s^{-1}km^{-2}$ and 95% lower and upper limits of confidence interval. Bzenica Vyhniansky Brook, Žarnovica Kľak and Kalinčiakovo Sikenica, log-Pearson distribution type III.

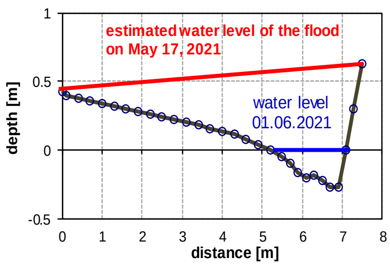
Fig. 9. Traces of the flood (Photo Mészáros, 1.6. 2021).

(Photo Podolinská, 25. 5. 2021

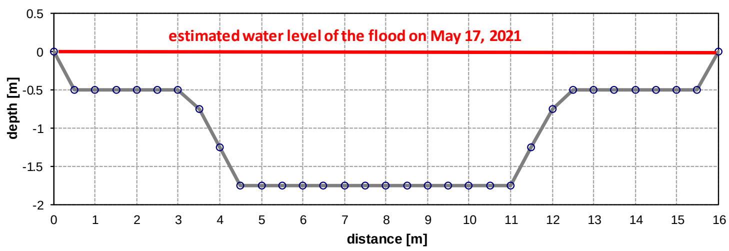
Photo Podolinská, 25. 5. 2021)

(Photo Miklánek, 1. 6. 2021

Photo Pekárová, 8. 6. 2021)



a) Rudniansky brook



b) Rudniansky brook

Fig. 10. a) Cross-section of the Rudniansky Brook based on field measurements, 100 m upstream the reservoir. (Roughness coefficient = 0.028; stream slope 0.023). b) Cross-section of the Rudniansky Brook about 70 m downstream the reservoir dam.

Table 1. ***T*-year specific discharge of the Kľak and Vyhniansky Brook in l s^{-1} km^{-2}**

T	p	Kľak			Vyhniansky Brook		
		q	*q(5)*	*q(95)*	***q***	*q(5)*	*q(95)*
1000	0.001	**2055**	3180	1478	**3251**	20549	1270
500	0.002	**1624**	2419	1201	**2248**	11849	959
200	0.005	**1181**	1670	907	**1370**	5671	656
100	0.01	**921**	1252	728	**935**	3221	489
50	0.02	**712**	931	580	**633**	1814	360

maximum flood water level of May 17, 2021, the longitudinal slope of the predicted water level, which corresponded to the slope of the stream channel in that profile, was measured.
The flow velocity was calculated using the Chezy formula with Manning roughness coefficient, and continuity formula that was then used to calculate the peak flow.

$$v = C.(R.i)^{1/2} \qquad (1)$$

$$C = 1/n \,.\, R^{1/6} \qquad (2)$$

$$Q = F.v, \qquad (3)$$

where
v is average velocity [m s^{-1}];
C is Chezy's coefficient [$m^{1/2}$ s^{-1}];
R is hydraulic radius [m];
i is hydraulic gradient [m m^{-1}];
n is Manning's roughness coefficient,
F is the water-filled area of cross section [m^2].

The peak discharge of the May 17, 2021 rainfall flood event in the profile 100 m above the reservoir was estimated to be 7.8 m^3 s^{-1}, i.e. 650.2 l s^{-1} km^{-2}. Similar to the neighbouring streams, the flood wave from the rain peaked around 17.00 hrs. CEST. In determining the average profile speed, we were based on the assumption of steady uniform water movement, in which the slope of the water level is parallel to the slope of the bottom.

Estimation of the breakthrough flood wave peak discharge

The profile of the old solid concrete and stone dam below the destroyed spillway was selected to determine the peak discharge from the breakthrough wave below the dam (Fig. 10b). The peak flow was estimated based on the surveyed cross-sectional area and the estimated water velocity to be 90 m^3 s^{-1}.

Reconstruction of the combined rainfall and breakthrough flood wave in Rudno nad Hronom in the profile downstream the reservoir

The temporal development of the rain flood wave upstream the reservoir was derived by two approaches (Fig. 11):

1. hydrological analogy according to temporal development of the rain flood wave in the station Pečenice: Jabloňovka Q_{HA};
2. rainfall-runoff model NLC, Q_{sim}.

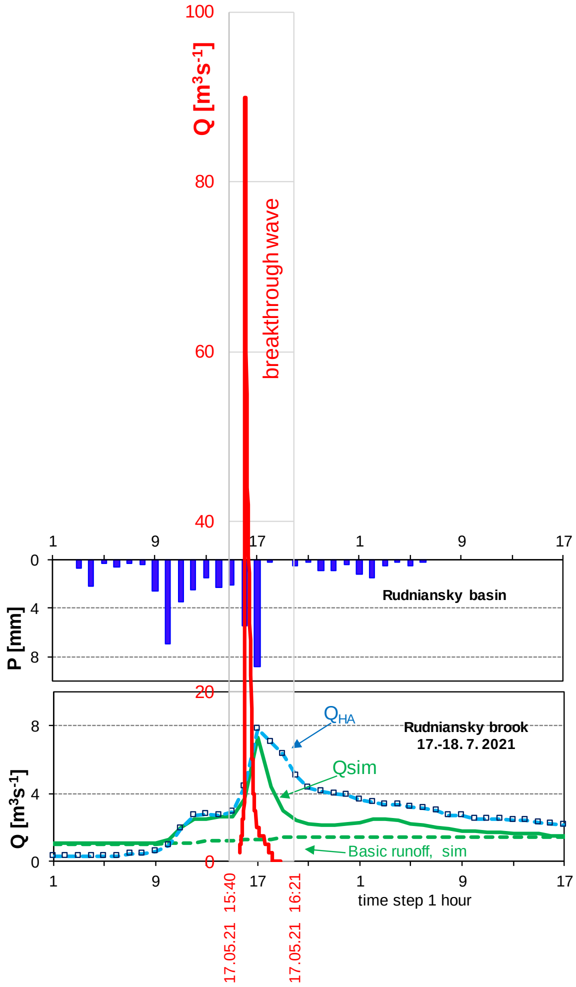


Fig. 11. Scheme of the reconstructed rain flood wave Q_{HA} – by hydrologic analogy (blue) and simulated Q_{sim} – by NLC model (green) downstream the reservoir on 17. 5. 2021. The breakthrough wave (red). The breakthrough wave and the rain flood wave have different scales on both x and y axes.

The course of the breakthrough wave from the reservoir water just below the dam was determined to be triangular in shape so that the peak reached 90 m^3s^{-1} and the volume was 15,000 m^3. The breakthrough wave has an extremely high flow rate on the one hand and a very short duration on the other. Its course is schematically indicated in red in Figure 11.

On 17 May, the daily rainfall from 1.00 to 24.00 hrs on the Rudniansky Brook catchment up to the dam above the village was estimated at 43.2 mm. It means that 481,000 m^3 of water fell on the saturated catchment before the breach of the dam in Rudno nad Hronom. The rainfall for May 17-18, 2021 on the catchment was 47.3 mm, i.e. 568,800 m^3 of water. For two days, 447,480 m^3 of water (78.8%) flowed out based on the hydrological analogy, or 334,520 m^3 of water (60.6%) according to the NLC model.

Discussion and conclusion

The results of the study clearly show that the damage to property in the village of Rudno nad Hronom was caused by the breakthrough wave from the ruptured dam above the village. The breakthrough wave reached a flow rate of 80–100 $m^3 s^{-1}$, while the wave from the rain over the reservoir reached a peak flow rate of about 8 $m^3 s^{-1}$. In the village the discharge would have been maximally two times higher.

The average annual rate of dam failures in the world since 1900 (excluding those caused by war) is 0.02%. The most common causes of dam failure include:

- Non-standard construction materials/techniques;
- Error in the design of the safety spillway;
- Geological instability caused by poor geological investigation;
- Landslide of soil into the reservoir;
- Poor maintenance especially of outlet culverts;
- Extreme inflow into the reservoir;
- Human, computer or design error;
- Internal erosion in earthen dams;
- Earthquakes.

The most important reasons for failure of earthen dams are overtopping problems, outlet blockage problems, and problems associated with improper foundation of the dam. This was also the case with the dam on Rudniansky Brook.

Acknowledgement

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Dedicated to the memory of our young PhD. student, colleague and friend RNDr. Jakub Mészáros (29. 01. 1991 Levice – 04. 09. 2021 Budapešť).

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