Disaster Flood Scenario: Case Study of the Uh River at Lekárovce (Slovakia)

Pavla Pekárová 1, Ján Pekár 2, Dana Halmová 1, Pavol Miklánek 1
Veronika Bačová Mitková 1

1 Slovak Academy of Sciences, Institute of Hydrology, Dúbravská cesta 9, 841 04 Bratislava, Slovakia
2 Comenius University in Bratislava, Faculty of Mathematics, Physics, and Informatics, Department of Applied Mathematics and Statistics, Mlynská dolina, 842 48 Bratislava, Slovakia

pekarova@uh.savba.sk

Abstract. The occurrence of extreme floods in several river basins of the countries of Central and Eastern Europe over the last thirty years has drawn the attention of the public (as well as the competent authorities) to the problems of flood protection. Although the development and operational use of non-structural measures (such as flood forecasting and warning systems), represents one of the effective flood protection measures, the structural means (flood protection, levees, flood control reservoirs) are of great importance, too. Especially in the upper parts of the river basin, where the time between the detection of the causes of the flood (heavy rainfall) and its consequence (flood) is short and does not affect the effective protective activity (e.g. evacuation). Over the last 30 years, flood protections have been built along the Uh River (Slovakia, Ukraine) to protect the environment from floods. These dams adversely affected the storage capacity of water in the basin. This resulted in flood flows increase on the lower sections of the Uh River in Slovakia. These facts need to be demonstrated by the need to evaluate the proposed design values for those sections. The study presents an analysis of the long-term flood regime of the river Uh in the section Uzhhorod (Ukraine) - Lekárovce (Slovakia). The first part analyses the trend changes in the time series of maximum annual discharge $Q_{max}$ in the stations Lekárovce and Uzhhorod on the basis of the observed $Q_{max}$ data in these profiles (period 1931–2019). These $Q_{max}$ series were subsequently used to estimate the maximum T-year discharge at the Lekárovce station for the changed conditions of the Uzhhorod - Lekárovce section. Using these derived data and the observed form of the summer flood hydrograph from July 1980, a 100-year flood scenario was developed for the Uh River in Lekárovce. The achieved results indicate a further increase in flood risk in Lekárovce.

1. Introduction

The changing climate and reservoir storage have a far-reaching influence on the nonstationarity in flood peaks worldwide [1]. In the Bodrog catchment (figure 1), in both its parts (Slovakia, Ukraine), as to the structural flood protection measures, considerable differences between these two parts exist. In Slovakia, the lowland river sections are protected by levees (bunds) with elevation mostly lower or equal to 100-year water level. On rivers Ondava, Laborec and Cirocha reservoirs are constructed (Domaša, Žemplínska Šírava, Starina) with storages for substantial reduction of the flood peaks.
In addition to these, two smaller storages exist in form of polders (dry reservoirs) in the lowland part, which can be utilized in case of extreme emergency. On the other hand, neither such storages nor reservoirs exist in the Ukrainian part of the catchment on the Uh and Latorica rivers. Such system does not provide a safe protection against the extreme flood events. Already in 1984 Dzubák [2] pointed out, that by damming of the riverbed on the Ukrainian and on the Slovak territory, the Uh River flood threat increases. This has been documented during several historical events, when on several spots the protection bund had to be breached intentionally in order to eliminate flood hazards downstream in the villages.

The aim of this study is the identification of the long-term trends of the maximum annual discharge series, estimation of the $T$-years design discharges and estimation of the 100-year flood scenario for the Uh River at Lekárovce gauge under today conditions. The study consists from two parts. The first part deals with statistical analysis of the hydrological regime of the Uh River basin. The trend changes in the time series of maximum annual discharge $Q_{max}$ in the stations Lekárovce and Uzhhorod was identified. In the second part, results are presented of the determination of the $T$-years summer design discharges and estimation of the 100-year flood scenario, for the Uh at Lekárovce water gauge.

2. Description of the Uh River basin

The Uh River basin is one of the five large river catchments forming the Bodrog River basin (Topla, Ondava, Laborec, Uh and Latorica rivers). The whole catchment area at the Bodrog outlet from Slovakia to Hungary is 11 423.4 km$^2$, out of which 7 035 km$^2$ (about 60 %) belongs to Slovakia, mainly in the catchments of Ondava and Laborec. The Uh River springs in Ukraine under the Uh Pass (figure 2). The catchment area of the Uh River is 2 790.9 km$^2$ at the confluence with Laborec River. The length of the river is 132.4 km, of which 19.6 km are in Slovakia. The main part of the basin is in Ukraine. Upper parts of the rivers are of a pronounced mountainous character (slopes of the river channels 15–20 m/km), their lower parts belong to the lowland with slopes 2–0.3 m/km, or even less [3], [4]. The hydrological conditions of the Eastern Slovakia were studied e.g. by [5], and [6]. Conditions of the flood wave creation in the Uh River basin are highly unfavourable. A flood comes very fast as well as changes of water levels (over 7 meters in the course of 3 hours). The main Uh tributaries in Ukraine (Turya and...
Lyuta) have similar travel time as the Uh River, and the coincidence of the flood waves of individual tributaries occurs very often.

Figure 2. Scheme of the Uh River basin; water gauges at Uzhhorod (UKR) and Lekárovce (SK) – right. Left – water gauge at Lekárovce on the Uh River (photo Pekárová, 2011).

3. Data used
The Uh water level observations at Lekárovce started in 1930. During the World War II between 1939 and 1945 Lekárovce belonged to Hungary, and the observations 1941–1950 are missing. The mean annual discharges during the period 1941–1950 we completed using hydrological analogy from the mean annual discharges of following stations: Laborec - Michalovce, Ondava - Horovce, and Bodrog - Streda nad Bodrogom, based on the period 1931–1960. The extreme discharges of this period (derived according to Uzhhorod station) were published by Dzubák [2].

Following data were used for the analysis of the change of the hydrological regime of the Uh River at the water gauges Uzhhorod and Lekárovce:
1. mean daily discharge ($Q_d$), Uzhhorod (1947–2012), and Lekárovce (1950–2012) stations;
2. average annual discharge ($Q_a$) (figure 3a), and maximum annual discharge ($Q_{max}$) (figure 3b) from Uzhhorod (calendar year) and Lekárovce (hydrological year 1 Nov–31 Oct) stations.

Figure 3a. Average annual discharge $Q_a$ of the Uh River at Uzhhorod (1947–2012) and Lekárovce, (1931–2019).
4. Results
4.1. Statistical analysis of the hydrological regime of the Uh River basin

4.1.1. Description of the major floods of the Uh River

According to historical records, among the most famous floods in the whole Bodrog basin belong the August floods in 1813, 1893, and 1913 [7]. Šítor et al. [4] refers that the highest evaluated Uh flood is the one from the end of October 1926. At that flood, the peak discharge in Uzhhorod was $1,580 \text{ m}^3\text{s}^{-1}$, and the estimated one in Lekárovce was $1,200 \text{ m}^3\text{s}^{-1}$. The next flood over $1,000 \text{ m}^3\text{s}^{-1}$ came only after 32 years, in February 1968 (figure 3). The decade 1974–1983 was rich with floods over $1,000 \text{ m}^3\text{s}^{-1}$; they occurred in winter spring period 1974, 1979, 1992, and in July 1980 (figure 4a).

The highest recorded Uh flood in Lekárovce was the one of 17 November 1992 (figure 4b). It was a typical heavy rainfall flood. The precipitation amount over the Uh basin was app. 100 mm within 24 hours. This caused the highest so far observed water level at Lekárovce gauge 1090 cm. At such water level in Lekárovce in today conditions, already the discharge of $960 \text{ m}^3\text{s}^{-1}$ overtopped the protective embankment (bund). This indicates an insufficient riverbed capacity. Peak flow at Uzhhorod reached $1,280 \text{ m}^3\text{s}^{-1}$. The peak at Lekárovce reached $870 \text{ m}^3\text{s}^{-1}$. The flood wave volume passing through the Lekárovce cross section reached 114 mil. m$^3$, water volume that overtopped the bund was 18 mil. m$^3$. Without the bund overtopping, the estimated flood peak at Lekárovce would reach $1,250 \text{ m}^3\text{s}^{-1}$.

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**Figure 3b.** Average maximum annual discharge $Q_{\text{max}}$ of the Uh River at Uzhhorod (calendar year) and Lekárovce (hydrological year 1. Nov–31 Oct) stations.

**Figure 4.** a) Average daily discharge of the Uh River at Lekárovce during July 1980 summer flood, b) Average daily discharge of the Uh River at Lekárovce during November 1992 flood. Red points denote maximum discharge.
At the beginning of November 1998, another flood situation developed over the territory of eastern Slovakia. On the Uh River at Lekárovce water level has risen by 8 meters within 18 hours, to a water stage of 1057 cm, corresponding to discharge of 820 m$^3$s$^{-1}$. Water started to overtop the embankments at the road bridge in Lekárovce, as well as the protective bund on the state frontier with Ukraine. This situation called for an intentional bund breaching. This protected neighbouring communities against flooding. The reconstructed flood peak was of about 920 m$^3$s$^{-1}$. The low Uh River channel discharge capacity called for its later reconstruction in the river section between Lekárovce and Pinkovce.

### 4.1.2. Long-term trend and multi-annual variability of the Uh River runoff

The Uh flood distribution at Uzhhorod and at Lekárovce since 1950 indicates a prevailing winter flood regime (figure 5, left). Floods occur mostly in the winter season (November – March). On the other hand, minimal discharge (during hydrological year) occur mostly in the months of August – November (figure 5, right).

![Figure 5](image)

**Figure 5.** The day of the 1-day maximum (left) and minimum (right) discharge occurrence, Uh River at Lekárovce within 1951–2007.

The multiannual variability was detected by autocorrelation (figure 6) and spectral analysis (periodogram and MESA method according to Štěpánek [8], see figure 8). For $Q_a$, the 3.6–4.5, and 11-year periods were found. For $Q_{max}$, the 3.6- and 5–6-year periods were found. Periods of 11-years (and 5–6-years) are probably connected by 10.5 years Sun activity.

![Figure 6](image)

**Figure 6.** Power spectrum, MESA, plot for the average annual discharge $Q_a$ (left) and maximum annual discharge $Q_{max}$, Uh River at Lekárovce, period 1931–2019.

The Mann-Kendall test and Sen’s slope estimates were used to estimate the long-term trend in maximum annual discharge series (figure 7, left). The software AnClim [8] was used to analyse the change in linear trend. Plot of changes in linear trend of maximum annual $Q_{max}$ discharge series is presented in the figure 7 right.

![Figure 7](image)
Figure 7. Long-term linear trend (left) and changes in linear trend of the measured maximum annual discharge series (right), Uh River at Lekárovce, period 1931–2019, peak floods 1992 and 1998 are reconstructed according to Uzhhorod.

4.1.3. Comparison of Qmax in three different periods
The 89 years long time series of Qmax were divided into three 30-years sets in order to show the different character of selected periods. In figure 8a you can see differences in Box-and-Whisker Plot of the Qmax in the three subperiods 1931–1960, 1961–1990, and 1990–2019. We tested the hypothesis whether subsets have the same distribution. We tested changes in mean values, in standard deviation, and in median. For testing the hypothesis of the mean change of Qmax, we used the well-known t-test, for comparison of the standard deviation we used the F-test, and for comparison of the median values we used the Mann-Whitney (Wilcoxon) test. From results it follows, that we can reject the null hypothesis on 0.05 confidence level, that 1st and 2nd subperiods have the same mean value, median, as well as standard deviation. In the case of 1st and 3rd subperiod, there is not a statistically significant difference between the two distributions at the 95.0% confidence level. These results show that the extreme floods occur more frequently on Uh at Lekárovce in the second subperiod. Last 10-year period was dry, without extreme floods.

Figure 8. a) Box-and-Whisker Plot of three subperiods of the maximum annual discharge; b) Qmax density functions between subperiods 1931–1960 and 1961–1990; c) Qmax density functions between subperiods 1961–1990 and 1990–2019.

4.2. Frequency analysis and T-year discharge design values
Flood-frequency information is important for defining flood-hazard areas, for managing floodplains, and for designing bridges, culverts, dams, levees, and other structures. Flood-frequency analysis commonly is performed on records of annual maximum peak discharges Qmax collected systematically at streamflow gauging stations. In this work we tested 11 types of distribution, e.g.: Log-normal distribution, Log-Pearson Type III. distribution, Erlang distribution, Gamma distribution, Logistic distribution, Weibull distribution, etc. To verify whether specified distribution types could adequately represent the observed data, the χ² test, Kolmogorov-Smirnov test (K-S test) and Anderson-Darling test (A-D) can be used. The best statistical characteristics have the log-Pearson type III distribution (figure 9, Table 1).
adjusted so that its peak equals to the station Lekárovce was determined on base of the reconstructed maximum calculated from the daily flows at the Uh August during the period 1990 and in the southern Bohemia during August 2002. The measured daily flows at the Uh (Lekárovce)

In that study they developed two rainfall scenarios based on rainfall totals measured in Austria (Ybbs) and in the southern Bohemia during August 2002. The measured daily precipitation in each month of August during the period 1990–1999 was scaled according to these scenarios. Subsequently, the average daily flows at the Uh-Lekárovce station were simulated with the HBV-light model. Peak flows were calculated from the daily averages using the derived empirical relationship between average daily and maximum flows.

4.2.1. Summer disaster flood scenario
Pekárová et al [6] used the HBV-light model to simulate the course of an extreme summer flood wave. In that study they developed two rainfall scenarios based on rainfall totals measured in Austria (Ybbs) and in the southern Bohemia during August 2002. The measured daily precipitation in each month of August during the period 1990–1999 was scaled according to these scenarios. Subsequently, the average daily flows at the Uh-Lekárovce station were simulated with the HBV-light model. Peak flows were calculated from the daily averages using the derived empirical relationship between average daily and maximum flows.

In Miklánek and Pekárová [9] the scenario of the winter-spring 100-year flood hydrograph for Lekárovce was determined on base of the reconstructed major flood of the last 30 years at the Uzhhorod station - the one of November 1992. The observed hourly flows of the November 1992 flood were adjusted so that its peak equals to the 100-year discharge at Uzhhorod station.

**Table 1.** T-year discharge of the Uh River at Lekárovce [m$^3.s^{-1}$] 1947–2007, and Uzhhorod 1947–2007, LP3 theoretical distribution

| T [years] | P [%] | Uh Lekárovce | Confidence limits | Uh Uzhhorod | Confidence limits |
|-----------|-------|--------------|------------------|-------------|------------------|
| 10        | 0.1   | 906          | 1024             | 817         | 1190             | 1435 | 1022 |
| 50        | 0.02  | 1277         | 1499             | 1121        | 1657             | 2090 | 1380 |
| 100       | 0.01  | 1438         | 1711             | 1248        | 1839             | 2355 | 1516 |
| 200       | 0.005 | 1600         | 1929             | 1375        | 2012             | 2613 | 1644 |
| 500       | 0.002 | 1818         | 2228             | 1544        | 2229             | 2940 | 1801 |
| 1000      | 0.001 | 1987         | 2462             | 1673        | 2385             | 3179 | 1912 |

**Figure 9.** Empirical and theoretical – log-Pearson type III distribution curve of the annual maximum discharge Q$_{max}$, 5% and 95% confidence limits, Uh: Lekárovce, and Uh: Uzhhorod, period 1947–2007.

We can see, that the 100-year discharge of the Uh River at Lekárovce is about 1 438 (in interval 1 248–1 711) m$^3.s^{-1}$, and the 1000-year discharge is about 1 978 (1 673–2 462) m$^3.s^{-1}$, respectively (Table 1). In Uzhhorod, the values are significantly higher, 100-year discharge is about 1 839 (in interval 1 516–2 355) m$^3.s^{-1}$, and 1000-year about 2 385 (1912–3179) m$^3.s^{-1}$, respectively (Table 1). This result also confirms the assumption that the peak flows between Uzhhorod and Lekárovce have become more transformed in the past.
Since 1998 there has been no flood above 1000 m$^3$s$^{-1}$ in the Uh catchment. However, in July 2008 a catastrophic flood occurred in the neighbouring Dniester basin. According to the estimates, it was the heaviest flood in the region in the last 100 years. According to personal communication (Sosedko and Lukianetz, 2008) [10] the following daily precipitation was observed at the Jeremca precipitation station during this flood, between 22 and 26 July 2008: 44, 47, 129, 47 and 84 mm, a total of 351 mm (figure 10). Heavy rain over the Carpathians led to severe flooding in eastern Romania, western Ukraine and Moldova, where the rivers Siret, Prut and Dniester reached some of their highest levels since records began. If this precipitation moved a little to the North-west, it would completely hit the Uh River basin. Fortunately, the Uh basin was not hit fully by the rains and no important flood occurred on the Uh River.

Figure 10. Precipitation totals in [mm] over the upper Dniester basin, July 22–27, 2008 according to Sossedko and Lukianetz. Location of the Uh River basin.

After each catastrophic flood caused by an extreme runoff event, it is time to ask "What would such precipitation totals bring to another river basin?". It would be interesting to know what high summer flood would come in Uh river after the rainfall events, similar to the July, 22–27, 2008 rainfall situation in the Dniester basin, Ukraine. The scenario of the summer 100-year flood hydrograph for Lekárovce was determined on base of the reconstructed major flood from the July 1980. The observed flows of the July 1980 flood were adjusted so that its peak equals to the 100-year discharge at Uzhhorod station. The measured hourly flows were multiplied by a constant so that the peak of the wave reached the 100-year discharge of 1839 m$^3$s$^{-1}$ (figure 11). A minimum of 11 million m$^3$ of water (up to 27 million m$^3$ of water) must be retained to ensure that the maximum acceptable discharge of 1 100 m$^3$s$^{-1}$ is not exceeded. This estimate is consistent with earlier calculations [2, 11]. Dzubák and Turčan [11] selected profiles for the location of retention reservoirs on the right-side tributaries of the Ulička and Ublianka rivers, most of whose catchment area is in the Slovak Republic, which would reduce peak flows. The profiles of the dams were proposed on the territory of Ukraine. Another retention reservoir was proposed on the most important tributary of the Uh, on the Turja River above the village of Turja Remety. They also considered creating a polder above Uzhhorod. The parameters of the reservoirs were proposed (Table 2). After the calculations were performed, the reductions in peak flows due to the retention reservoirs and the total (resulting) effect of the retention reservoirs on the peak flow of the Uh in Lekárovce were determined.
5. Discussions

By treaty with Hungary, the Bodrog discharge at its outlet on the state border is limited to 1 100 m$^3$s$^{-1}$. To cope with this restriction under real flood conditions, additional storage is necessary on the Ukrainian catchment part. Rising or reconstructing the protective bunds is not a definite solution. To determine the extent and location of this flood control storage, there is a need to simulate several critical rainfall-runoff flood scenarios by a suitable mathematical catchment model. Final results of such study might be a proposal of the system of reservoirs (storages) on the uncontrolled catchment part for the optimum control of flood flows of the river flowing in its lower reach through densely populated land with intensive agriculture. At the same time, the rainfall-runoff model would be also a solid base for a coherent flood forecasting system of Bodrog on the Slovak and Ukrainian territory.

6. Conclusions

In this study the analysis of the flood regime of the Uh River at Lekárovce and Uzhhorod station was done (period 1930–2019). The analysis shows, that:

- The average annual discharges $Q_a$ oscillates in about 11–13-years cycle. The long-term decreasing trend of the average annual discharge ($r$-test for coefficient $b = -0.0461$) was not significant (on the level alpha $= 0.05$).

- The maximum annual discharges $Q_{max}$ fluctuate in about 11–13-years cycle, as well. At the same time the long-term decrease of extreme runoff on the Uh River at Uzhhorod is observed in 1947–2006.

The series of annual maximum discharges $Q_{max}$ of the Uh River at Lekárovce station were reconstructed based on water levels of the Uh River at station Uzhhorod (Ukraine). The reconstructed series was used for assessment of the $T$-year design discharges. Using the discharge of the July 1980 flood we created the summer 100-year flood scenario for the Uh River at Lekárovce station.

The results show:

- the decrease of water accumulation in the Uh River basin and increase of the catastrophic flood risk at Lekárovce water gauge;

![Figure 11. Scenario of the 100-year flood, Uh: Lekárovce, 5 and 95 % confidence intervals, hourly discharges.](image)
• rising or reconstructing the protective bunds is not a final solution;
• for the optimum control of flood flows, additional storage is necessary on the Ukrainian basin part.

In the case of transboundary rivers, the evaluation periods of the mean annual and maximum annual series should be taken into account. Historically, in Slovakia the series of maximum annual flows are evaluated per hydrological (water) year, in Ukraine per calendar year. In Slovakia it would be appropriate to reconsider the methodologies for evaluating $Q_{max}$ time series.

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