Comparison of the September 2024 Danube Flood with Historical Floods in the Bratislava-Nagymaros Section

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Abstract

Each year, we witness the devastating effects of floods in Central Europe and worldwide. In September 2024, a flood wave passed through the Danube in Bratislava with a discharge of approximately 9,400 m^3s^{-1}. Over the past 20 years, two floods in Bratislava have reached peak discharges exceeding 10,000 m^3s^{-1} – in August 2002 and June 2013. A comparison of flood waves since 1991 indicates a slight increase in extreme peak discharges in Bratislava and Nagymaros, along with a significant rise in peak water levels of the Danube. The first part of this paper describes the gauging stations along the Danube in Bratislava/Devín. It presents a series of maximum annual discharges (Qmax) from 1876 to 2024, supplemented by historical flood records dating back to 1501. The second part focuses on the statistical analysis of average and maximum annual discharges from the gauging stations in Bratislava and Nagymaros. The third part compares the September 2024 flood with the September flood of 1899. Finally, the paper discusses possible reasons for the rise in water levels in the Bratislava–Nagymaros section over the past 100 years. The main factors contributing to these trends are as follows: i) In the past, the Danube naturally meandered and regularly flooded adjacent areas, which facilitated greater flood wave transformation and reduced water velocity. ii) Historically, breaches in flood protection levees helped mitigate flood risks in cities. For instance, during the 1787 flood, the Viennese Road (a flood protection levee) was breached in six places over a total length of 600 meters, preventing the flooding of Bratislava. Similar levee breaches occurred around Bratislava in 1897, 1899, 1954, and 1965. iii) The Danube riverbed is gradually silting up, which affects flow dynamics and peak water levels.

Keywords: *Danube flood, Bratislava, Nagymaros, flood risk*

1. Introduction

Almost every year, we witness the devastating consequences of catastrophic floods in our country, Central Europe, and worldwide. In 2002, Prague (Czech Republic) experienced severe flooding, with the city center inundated. In 2008, floods in Ukraine's Dniester River basin caused damages worth billions. Similarly, the catastrophic floods in the province of Valencia, Spain, in late October and early November 2024 took even the hydrological community by surprise.

The Danube River is no exception. In September 2024, a flood wave with a peak discharge of 9,441 m^3s^{-1} passed through Bratislava, while extreme rainfall on the Morava River in the Czech Republic led to extensive flooding. Floods on the Danube have been documented throughout history, with the first known records dating back to 1012. Over the past millennium, at least five major floods (in 1012, 1210, 1501, 1670, and 1787) likely exceeded a discharge of 11,500 m^3s^{-1} in Bratislava. On the Slovak stretch of the Danube, from Devín to Nagymaros, two significant floods occurred in 2002 and 2013, with peak discharges at the Bratislava water gauge exceeding 10,000 m^3s^{-1}. Since systematic discharge observations began in 1876, only five floods in Bratislava have reached peak discharges above this threshold—recorded in 1897, 1899, 1954, 2002, and 2013.

It appears that in Bratislava, maximum flood discharges are not increasing; however, water levels at the Bratislava station have risen significantly. The situation differs at Nagymaros station, where peak discharges have also shown an upward trend.

Determining the causes of rising peak water levels and discharges is a complex task. It requires long-term discharge observations, an understanding of riverbed modifications, and an assessment of flood control measures upstream of the studied station, including reservoir construction and flood levees.

The first part of this study aims to describe the Danube water gauge profile in Bratislava and analyze annual maximum discharge series (*Qmax*) from 1876 (or 1893) to 2024, supplemented with historical flood records dating back to 1501. Extending the annual maximum discharge series with historical observations is beneficial for estimating *T*-year flood discharges with long return periods.

The second part focuses on the statistical analysis of a 149-year dataset (1876–2024) of average daily and annual maximum discharges from the Bratislava/Devín water gauge, and from the Nagymaros station since 1883 (142-year dataset).

The third part compares the September 2024 flood with the September flood of 1899. Finally, potential reasons for rising water levels in the Hainburg-Bratislava-Nagymaros section over the past 100 years are discussed.

2. Material and methods

The Danube River basin has been described in several publications [5–8]. The Danube originates in the Black Forest (Germany, at an elevation of 1,078 m) and flows into the Black Sea (Romania). It has a total length of 2,857 km and a basin area of 817,000 km^2. The main tributaries of the Danube are the Inn, Drava, Sava, and Great Morava rivers. The Danube connects multiple countries, spanning from Central Europe to Eastern Europe, from Germany to Ukraine.

From a hydrological perspective, the Danube is divided into three sections (Fig. 1): the Upper Danube (from its source to Bratislava), the Central Danube course (from Bratislava to the Iron Gates in Romania), and the Lower Danube (from the Iron Gates to its mouth). In Slovakia, the Danube flows from river kilometer 1,708.2 (the mouth of the Ipeľ River) to river kilometer 1,880.2 (the mouth of the Morava River), covering a distance of 172 km. Of this length, 7.5 km forms the national border with Austria, 22.5 km lies within Slovak territory, and the remaining 142 km constitutes the border with Hungary.

As the Danube transitions from the Vienna Basin to the Danubian Lowland, it flows with a significant gradient in a concentrated riverbed. Upon leaving the slopes of the Little Carpathians, it maintains a relatively steep gradient, flowing through its alluvial cone in a complex network of branches up to Palkovičovo (Sap). Below Bratislava, the river's gradient decreases significantly, leading to intense sediment deposition, which requires substantial efforts and costs for removal.

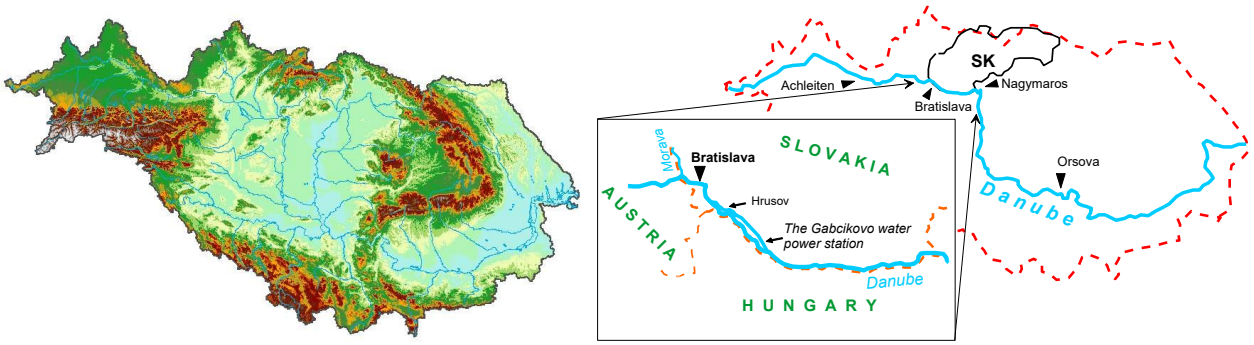


Fig. 1. The Danube River Basin scheme: a) Orography; b) Location of Bratislava and Nagymaros stations.

The Bratislava: Danube hydrological station is one of the oldest in the Danube basin, providing exceptionally high-quality water level observations. According to Horváthová [7], the first water stage observations on the Danube were recorded in Komárno in 1805, followed by Vienna in 1821 and Bratislava in 1823. Average daily discharges (*Qd*) and maximum discharge series (*Qmax*) from the Bratislava station have been available since 1876 [8], and from the Nagymaros station since 1893.

The basic hydrological characteristics of the two selected stations for the period 1901–2020 are presented in Table 1. The driest year was 1934, while the wettest year was 1965. The average annual discharges at the Bratislava station decreased by 0.39 m^3s^{-1} per year during the period 1901–2020, whereas at the Nagymaros station, the decline was as much as 1.62 m^3s^{-1} per year (see Fig. 2).

Tab. 1. Basic characteristics of the selected water gauges on Danube River: *Qa* – long-term average annual discharge; *qa* – long term specific runoff; *Qa,min* – annual minimum; *qa,max* – annual maximum, (1901–2020).

Water gauge	Country	Area	River km	Altitude Baltic	*Qa*	*qa*	*Qa,min*	*Qa,max*	trend
		km^2		m a.s.l.	m^3s^{-1}	$l.s^{-1}km^{-2}$	m^3s^{-1}	m^3s^{-1}	
Devin/Bratislava	SK	131 338	1 869	132.86	2 040.0	15.5	1420	2910	-0.39
Nagymaros	HU	183 534	1 695	99.37	2 308.0	12.6	1629	3214	-1.62

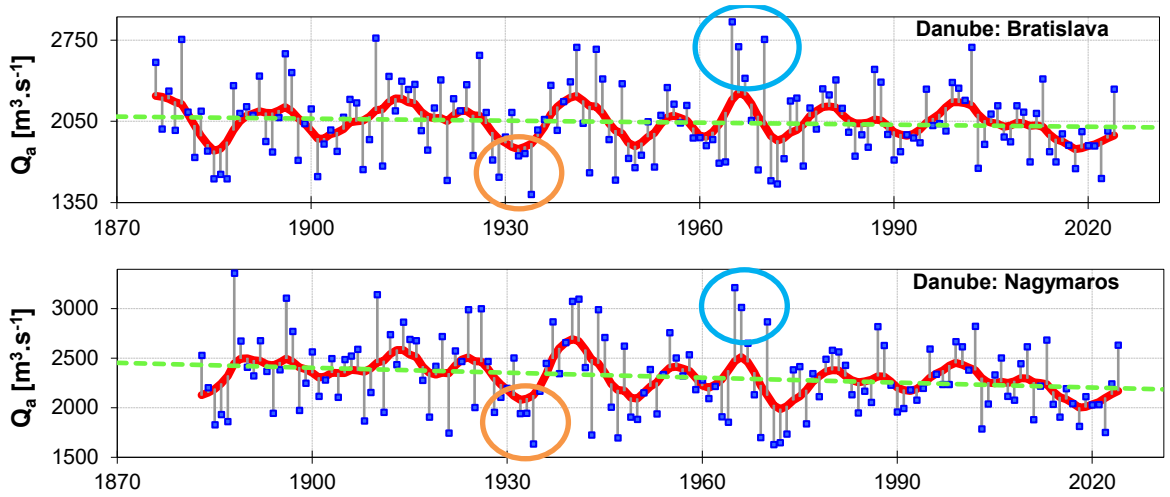


Fig. 2. The course of the average annual discharge from Bratislava and Nagymaros water gauge on the Danube River (blue point), double 5-year moving average of annual discharge (red line), long term linear trend (green line).

The Mann-Kendall nonparametric test (M-K test) was applied to determine significant trends in the monthly and annual variations of discharge series. Nonparametric tests are considered more suitable for detecting trends in hydrological time series, which are typically irregular and contain numerous extremes. The MAKESENS two-tailed test was employed for four different α significance levels. The

significance level α of the test is selected from the interval between 0 and 1, or 100%, with lower values being preferable; however, α = 0.05 (or 5%) is most used. A significance level of 0.05 indicates a 5% probability that the values of x_i originate from a random distribution, implying a 5% chance of error in rejecting H_0 (the null hypothesis) of no trend. A significance level of 0.001 suggests a high likelihood of a monotonic trend.

In this study, the significance of the trend was evaluated at the selected significance levels.

*** if the trend is at α = 0.001 – the validity of H_0 is improbable

** if the trend is at α = 0.01 - 1% error in rejecting H_0

* if the trend is at α = 0.05 - 5% error in rejecting H_0

\+ if the trend is at α = 0.1 - 10% error in rejecting H_0

Empty - the level of significance is greater than 0.1, we cannot rule out that H0 is true.

The most important trend is assigned three stars (***), with the gradual decrease in importance, the number of stars also decreases. Statistically, we evaluate the significance of a trend using the Z value. A positive Z value indicates an upward (growing) trend, while a negative value indicates a decreasing trend. If the absolute value of Z is less than the significance level, there is no trend.

Spectral analysis was used to identify the multi-year variability of discharge time series [9]. This method allows for the detection of periodic components within the data, revealing dominant cycles and long-term fluctuations. By applying spectral decomposition, significant frequency patterns were extracted, helping to understand hydrological variability.

3. Results

3.1 Historical Danube floods on Upper Danube reach up to Bratislava water gauge dating back to 1501.

According to [1], [2] and [3], the earliest documented evidence of flooding on the Upper Danube dates back to the year 1012. Other major floods with severe consequences, as recorded in historical chronicles, occurred in 1210, 1344, 1402, 1466, 1490, 1499, 1501, 1526, 1572, 1594, 1598, 1670, 1682, 1721, 1787, 1809. Indirect accounts suggest that floods after 1501 were comparable in magnitude to those of 1899 and 1954 (Fig.3).

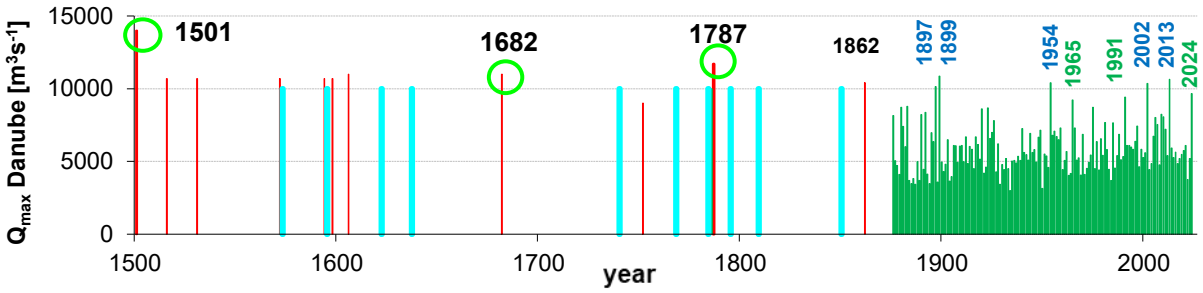


Fig. 3. Occurrence of the historical large Danube floods between the years 1501–1875 (red columns - summer floods, blue columns – ice floods), and measured discharge during 1876–2024 (green columns) at Bratislava

The flood of August 1501 is considered the highest ever observed in the Upper Danube reach, including Bratislava, based on reliable historical records from the Austrian Hydrographic Service. The peak discharge in Vienna was estimated to have reached up to 14,000 m^3s^{-1}. Additional accounts indicate significant floods occurred in the 16th and 17th centuries, particularly in 1594, 1598, 1670, and 1682. One of the most devastating floods of the 18th century took place in 1787, later known as the "All Saints' Flood," striking at the end of October and early November. According to historical records from the Austrian Hydrographic Service, the peak discharge at Vienna was recorded at 11,800 m^3s^{-1} [4].

The first recorded flood in the Slovak section of the Danube dates back to 1526 and is documented in the municipal archives of Bratislava. However, the river's morphology was significantly different at that time. During the medieval period, either no flood defences or only minimal dikes existed along the riverbanks. The river channel had a low capacity, frequently inundating the lower parts of the Bratislava city, including sections of the historical downtown, such as Main Square. The flood of 1526 struck unexpectedly overnight, resulting in 53 fatalities. Several severe floods subsequently impacted Bratislava between 1721 and 1809. In the winter of 1809, flooding and ice sheets destroyed numerous houses near the river. The most severely affected areas included Zuckermandel, Vydrica, Gorkého Street, Jesenského Street, Laurinská Street, and Grösslingova Street. The suburban settlement of Petržalka (then known as Engerau) was completely devastated.

After nearly three decades, on January 27, 1837, floodwaters returned, overtopping two ice barriers and inundating the surrounding areas. Only through the courageous efforts of a few individuals who managed to break the barriers was the water able to flow freely, preventing further destruction. During the flood of February 5, 1850, the streets of Bratislava were once again submerged. High-water marks on historical buildings in the city centre still indicate the extent of past floods, including those from medieval times. Notably, the water level during these historic floods was nearly 200 cm higher than that of the significant 1954 flood.

3.2 Statistical analysis of discharges from the Bratislava and Nagymaros station since 1883

As previously mentioned, during the observation period, five floods with a discharge exceeding 10,000 m^3s^{-1} occurred in Bratislava (Fig. 4). The flood of September 2024 at the Bratislava station ranks 6th based on peak discharge. At the Nagymaros station, the 2024 flood ranks as the fifth highest in terms of peak discharge

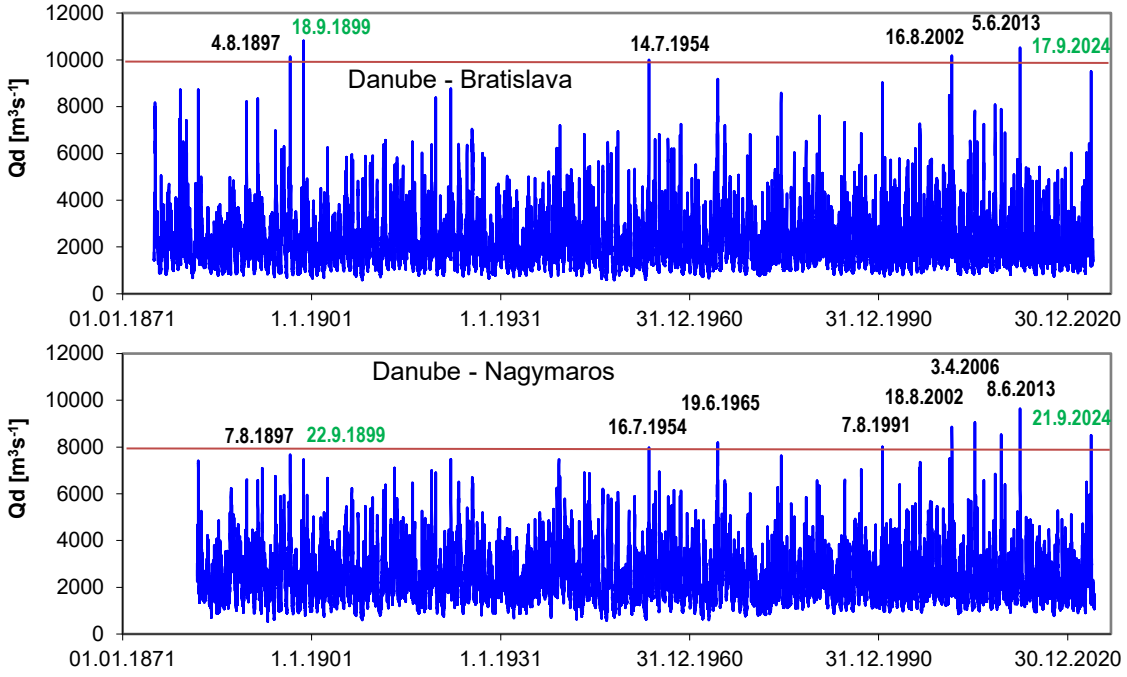


Fig. 4. Average daily discharge of the Danube at Bratislava and Nagymaros stations. Date of significant floods.

For the Central Danube in Bratislava, summer floods are the most typical. During the period 1828–2020, as much as 51% of floods occurred between June and August. The frequency of *Qmax* occurrences (for the period 1828–2020) in individual months is illustrated in Fig. 5.

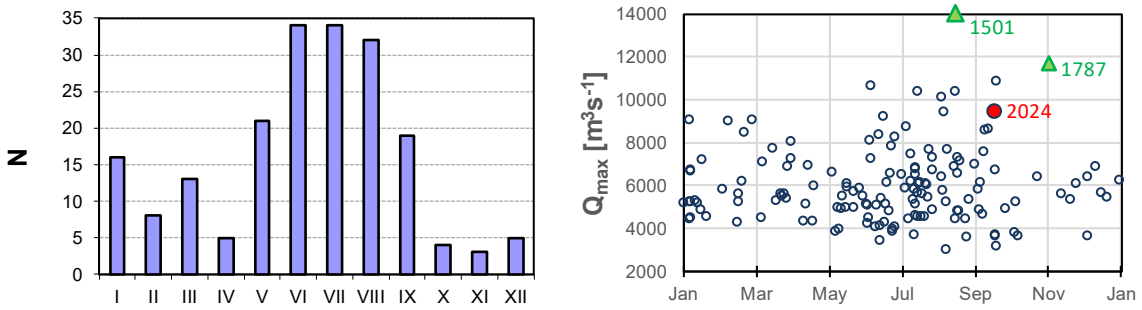


Fig. 5. Frequency of occurrence (N) of maximum annual discharges in individual months over the 195-year period 1828–2024 at the Danube station: Bratislava/Devín (left), occurrence of maximum annual discharges (Qmax) during the year for the period 1876–2024, and the two largest historical floods on the Upper Danube since 1500 (August 1501 and November 1787).

Long-term trends of average annual discharges and maximum annual discharges for the period 1883–2024 from the Bratislava and Nagymaros stations are evaluated in Table 2.

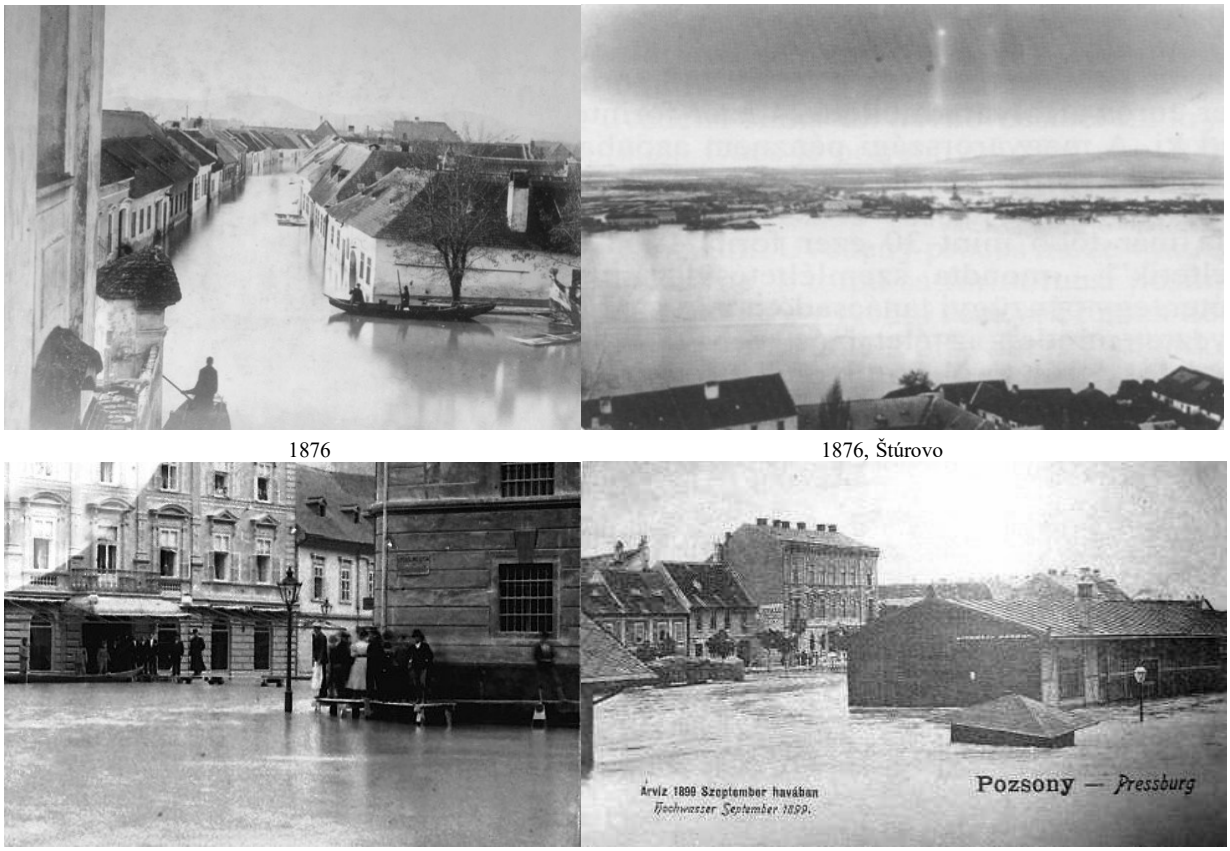
From a long-term perspective, the average annual discharge in Bratislava shows an insignificant decline of 0.34 m^3s^{-1} per year, while in Nagymaros, it decreases at the lowest significance level ($\alpha = 0.1$) by 1.6 m^3s^{-1} per year. On the other hand, the maximum annual discharges in Bratislava increase at the significance level of $\alpha = 0.05$ by 7.2 m^3s^{-1} per year. In Nagymaros, the increase in maximum annual discharges is not significant.

Tab. 2. Trend statistics.

Time series	Test Z	Signif.	A	Amin99	Amax99
Qa,Bratislava	-0.56		-0.342	-2.105	1.399
Qmax,Bratislava	2.28	*	7.243	-1.000	14.689
Qa,Nagymaros	-1.94	+	-1.594	-3.733	0.537
Qmax,Nagymaros	0.09		0.196	-6.860	7.707

At the Nagymaros station, however, an increase in peak discharges of the largest floods (e.g., in 1991, 2022, 2026, 2013, and 2024) is evident compared to the Bratislava station. This is primarily due to the fact that since 1966, there have been no breaches of the Danube flood protection levees.

In the past, floods often caused levee breaches and the inundation of adjacent areas. For example, in 1876, due to warming, the Danube's water level rose significantly after heavy rainfall that began in the second half of February. This flood was the largest recorded in Budapest until it was surpassed by the flood of 2013. Downstream Bratislava, the consequences were catastrophic: a total of 58,000 hectares of Žitný ostrov (Rye Island) were flooded, and 40 villages were destroyed.



1876 1876, Štúrovo

1897, Bratislava 1899, Bratislava

Fig. 6. Flood 1876 at Štúrovo (Photo: Sándor Beszédes, 1876). Flood 1897 in Bratislava city (Photo: Bratislava City Museum). Flood 1899 at Bratislava (Photo: Archduchess Isabella, 1899).

During the 1897 flood, levees were breached in Hungary and on Žitný ostrov; in 1899, levees near Komárno on the Slovak side failed; in 1954, levees on the Hungarian side were breached; and in 1965, levees failed at two locations in Slovakia, near Patince and Čičov. In the past, the lower-lying parts of Bratislava were frequently flooded (Fig. 6). The elevation of levees and other measures to protect the area from flooding lead to an increase in peak discharges of Danube floods at Nagymaros (Fig 7.).

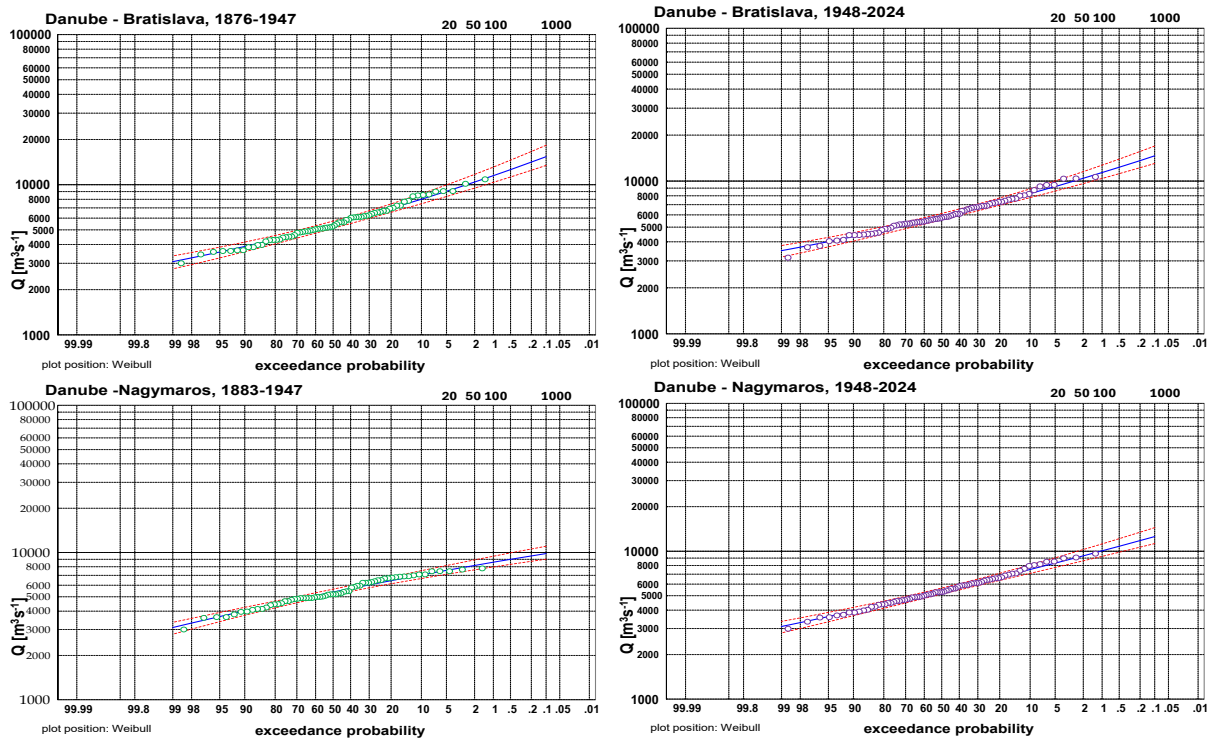


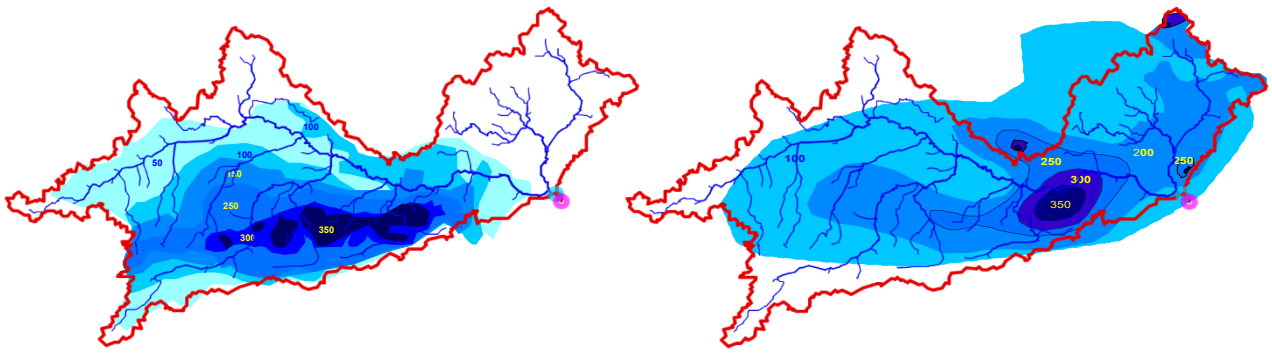
Fig. 7. Log Pearson distribution curves of the Danube in Bratislava and Nagymaros for two periods.

The peak discharges of floods with a long return period (over 20 years) have not changed at the Bratislava station. However, the peak discharges of large floods (with a return period of over 20 years) at the Nagymaros station have increased. The peak discharges of smaller floods with a shorter return period at this station have decreased.

3.3 Comparison of the September 2024 flood with the September flood of 1899

Flood of 1899

Due to the distribution of precipitation, the course of the Danube flood in September 1899 was relatively straightforward. Several factors in September 1899 helped prevent an even greater disaster in Austria. Notably, low initial water levels at the onset of the flood and the advanced time of year contributed to mitigating the impact, as a significant portion of precipitation in the upper parts of the basin fell in solid form (Fig. 8a). Additionally, a prolonged dry period preceding the flood allowed the soil to absorb a substantial amount of rainfall. Another contributing factor was that the Bavarian section of the Danube played only a minor role in the formation of the flood. At the Austrian gauge Stein-Krems, the flood peaked on September 17, 1899, around 6:00 AM, reaching a water level of 927 cm, corresponding to a discharge of 11,200 m^3s^{-1}. In Vienna, the discharge reached 10,500 m^3s^{-1}. On the Slovak section, the flood wave culminated in Bratislava on September 19, 1899, with a water level of 970 cm and a discharge of 10,870 m^3s^{-1}.



a) 1899 b) 2024

Fig. 8. a) Seven-day precipitation totals in Austria between September 8 and September 14, 1899, according to [10].
b) Illustrative scheme of five-day precipitation totals in Austria, Moravia, and Slovakia for the Danube River basin up to Bratislava between September 12, 2024, and September 16, 2024.

Flood of 2024

The flood situation in September 2024 was nearly identical (Fig. 9). Heavy rainfall from September 12, 2024, associated with the low-pressure system Boris, triggered floods along the Austrian section of the Danube as well as its right- and left-bank tributaries. In Moravia (Czech Republic), adjacent Poland, and the eastern half of Austria, total precipitation ranged from 150 to 250 mm, with localized amounts exceeding 300–400 mm in mountainous areas (Fig. 8b). These were exceptionally high precipitation totals for the region, with snowfall occurring above 1,400 meters. This intense rainfall not only ended the dry period across the entire region but also caused a significant rise in water levels, leading to flood warnings and widespread flooding. In Moravia and its tributaries in the Czech Republic, Austria, and Slovakia, extreme precipitation resulted in severe floods, causing billions in property damage. According to the Slovak Hydrometeorological Institute (SHMÚ), the peak discharge in Bratislava reached 9,441 m^3s^{-1}, which was 1,400 m^3s^{-1} lower than in 1899. However, the water level in Bratislava was 985 cm, 15 cm higher than in 1899.

In Nagymaros, the peak discharge in 1899 was 7,460 m^3s^{-1}, while in 2024, it increased to 8,496 m^3s^{-1}. The flood wave propagated more rapidly in 2024, and since there were no levee breaches, the transformation of the flood wave was less pronounced.

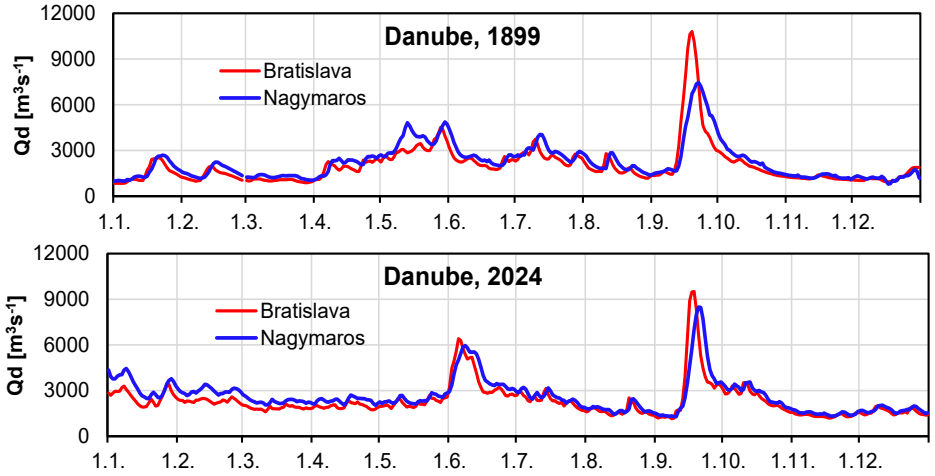


Fig. 9. Average daily discharge in 1899 (up), and 2024 at Bratislava and Nagymaros gauges.

4. Conclusion

From flood marks along the Danube, from Passau to Melk, it is evident that the flood of 1501 was the largest recorded flood in the Upper Danube for at least the past 500 years. This flood also affected the river basins of the Elbe and the Thaya. The flood protection levees in Bratislava and other cities in the Upper Danube region were built with this flood in mind. However, we must remain aware that an even greater flood could occur in the future [11, 12]. Although the likelihood of a larger flood is very low, it is not entirely excluded. Therefore, we must be prepared for such an event. The experience of the 2002 flood on the Vltava River in Prague and the 2024 flood on the Danube should serve as a warning.

After a relatively calm period in Bratislava from 1965 to 2002, when no floods exceeding 10,000 m^3s^{-1} occurred, a wetter period has returned. Such alternations between wet and dry periods have occurred several times throughout history. In the long term, this is not unusual. However, in the context of an individual's lifespan, a catastrophic flood is a unique event, which can impact a person's life for many years.

At the same time, we must recognize that runoff conditions in any river basin, including the Danube River Basin, are constantly changing. Over the past 110 years, there has been a rise in the Danube water levels by more than 60 cm in Bratislava, a notable increase. It is difficult to pinpoint the exact reasons for the rise in water levels at Danube stations, but it is likely due to several factors:

- The reduction of the gauging cross-section area due to the construction of dykes and embankments in Bratislava and both upstream and downstream of the city.
- The accumulation of sediments and gravel in the river channel near the gauge.
- The absence of dyke breaches in the Slovak/Hungarian Danube reach in 2002, 2006, 2013, and 2024, which resulted in slower transformation of the flood wave and higher water levels compared to 1894, 1899, 1954, and 1965, when the Danube dykes downstream of Bratislava were breached.
- The alluviation of the channel in the middle Danube below Devin Gate, a natural process resulting from changes in the Danube's bottom slope.

Acknowledgments

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