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Historic Floods on the Danube

The present paper stems from the draft of the project “Flood Regime of Rivers in the Danube River Basin”, which is being prepared by the Slovak National Committee for IHP UNESCO at the Institute of Hydrology, Slovak Academy of Sciences, where the author of the paper is involved as a member of the Steering Committee and is the nominated expert from Serbia, contributing two separate chapters.

General characteristics of the Danube River Basin

The Danube River is a unique international waterway flowing across Europe. It is 2,857 km long. The Danube runs from the heights of the Black Forest mountain range and ultimately empties into the Black Sea. Nineteen countries share the Danube River Basin (DRB): Germany, Austria, the Czech Republic, Slovakia, Hungary, Croatia, Serbia, Slovenia, Bosnia and Hercegovina, Romania, Bulgaria, Moldova, Ukraine, Switzerland, Italy, Poland, Montenegro, Albania and Macedonia.

The Danube, with a multiyear mean discharge of about 6,500 m^3/s, is the second largest river in Europe after the Volga (3,740 km long, multiyear mean discharge 8,500 m^3/s). It is the 21st longest river in the world and ranks 25th by drainage area (817,000 km^2).

The Danube flows from west to east and its basin extends from central and southern Europe to the Black Sea. The boundaries of the basin are determined by longitude 80° 09’ at the sources of the formative streams Breg and Brigach in the Black Forest and longitude 290° 45’ in the Danube Delta at the Black Sea. The southernmost point of the DRB is at latitude 420° 05’, at the source of the Iskar in the Rila Mountains. The northernmost point is the source of the Morava River at latitude 500° 15’.

The upper catchments of the Danube’s tributaries border on those of the Rhine to the west and southwest, of the Weser, Labe, Oder and Visla rivers to the north, and of the Dniester to the northeast, and the catchments of the rivers that empty into the Adriatic Sea and Aegean Sea to the south.

Based on the geologic framework and geographic configuration, the DRB can be divided into three regions, namely the upper, middle and lower Danube basins.

The Upper Danube Basin is the region from the source in the Black Forest to the Devin Gate east of Vienna.

The Middle Danube Basin is a magnificent and unique geographic unit. It extends from the Devin Gate to the mighty fault between the southern Carpathian Mountains and the Balkan Mountains near the Iron Gate Gorge. The Middle Danube Basin is the largest of the three regions.

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The Lower Danube Basin comprises the Romanian and Bulgarian lowlands, the catchments of the Siret and Prut rivers, and the surrounding plateaus and mountains. It is bounded by the Carpathians to the north, the Bessarabian Plateau in the east, and the Dobrogea and Balkan mountains to the south.

Hydrometeorological information

The Danube River Basin is one of the most flood-prone regions in Europe. As such, there is a strong need for in-depth information on the flood regime so that generalisation is possible based on long-term observation across the basin.

From a floods perspective, the most significant hydrometeorological data on the DRB are mean daily discharges, daily precipitation totals and mean daily air temperatures, which are routinely collected and archived in all the Danube countries. Long time-series are of particular interest, to gain insight into historic floods. Such time-series of discharges are available from 20 gauging stations on the Danube and 77 on its main tributaries. There is a much larger number of weather (precipitation and temperature) stations; the study used those that provided the longest time-series.

Figure 1 shows a map of the DRB which illustrates the main stream and major tributaries of the Danube river basin and the gauging stations with the longest discharge time-series.

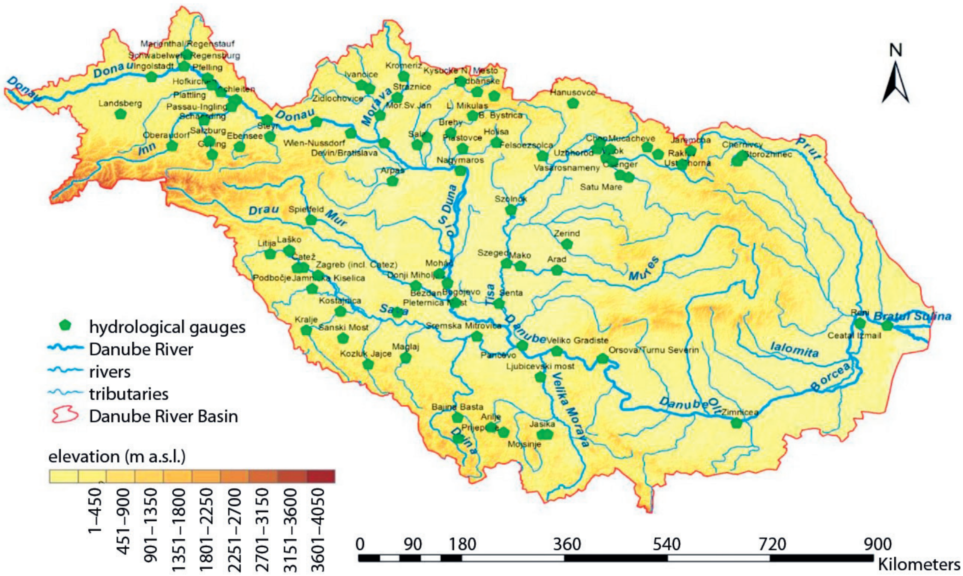


Figure 1. Gauging stations on the Danube and its tributaries [33]

Historic floods

Floods on the Danube have occurred throughout the river's history. Floods belong to the group of extreme natural phenomena. The first records of floods date back to the year 1012.

The Danube flood data can be classified as follows:

- archive data from 1012 to 1501
- registered historic traces (markers) from 1501 to 1820
- time-series recorded since 1821

Many authors have addressed DRB floods in written reports, including [14] [24] [10] [31] [9] [28] [29] [17] [21] [23] [27] [20] [26] [30] [16] [15] [18] [22] [25]. Most of them are related to the upper and middle DRB and archives were the main sources of information.

Historic floods from 1012 to 1501

Flood data are available in diverse historical documents, including original handwritten notes, newspaper articles, chronicles, formal letters, books, maps and photographs. The original handwritten notes usually include short descriptions of the floods, with an indication of peak water levels and cities located along the Upper Danube, where the floods were registered, such as: Passau, Linz, Mauthausen, Grain, Ybbs, Krems or Hainburg an der Donau.

According to [10] and [9], the oldest recorded flood on the Danube dates back to the year 1001. The other major floods in this group, according to historical data, occurred periodically, in several sequences – 1210, 1344, 1402, 1466, 1490, 1499 and 1501. [10] states that the 1501 flood peak was 11,000 m^3/s at Linz and 14,000 m^3/s at Stein Krems. [20] described in her doctoral thesis the floods during this period in the Austrian–Slovak–Hungarian sector. She highlighted the flood events in the summers of 1235, 1316, 1402, 1432 and 1490, shown in Figure 2.

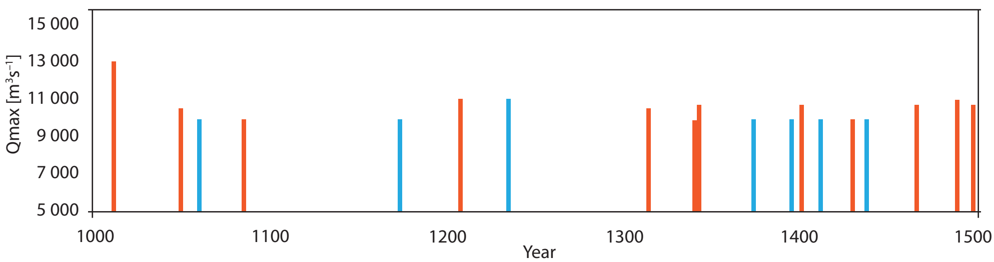


Figure 2. Historic floods on the Upper Danube up to Budapest from 1000 to 1500 AD according to [20]. Red bars – summer floods, blue bars – ice floods. [20]

The general conclusion was that most of the major floods occurred in the 15th century. [9] focused her research on Bratislava. Her published report describes flood occurrences based on a review of archive materials and concludes that many floods in Bratislava were caused by ice and ice jams under bridges. The city of Bratislava sustained considerable damage. In 1426, Sigismund of Luxembourg, king of Hungary, Croatia, Germany and Bohemia, ordered the damaged dikes along the Danube to be repaired. In 1439, he had a bridge built across the Danube in Bratislava, for which breakwaters and pontoons were used. Several floods damaged the bridge in the 15th century. For example, a flood on 20 March 1439 submerged a pontoon and another, on Easter Day of 1443, overtopped the entire bridge.

Matthias Corvinus, king of Hungary and Croatia, ordered a second bridge across the Danube in Bratislava to be built in 1472. The structure was similar to that of the first bridge. This bridge was damaged by a flood in early September 1478, and sustained further damage by an ice flood on New Year's Day in 1485. The bridge was also damaged in July 1485, and ultimately collapsed during the next flood event, on 1 September 1485. According to various chronicles, after the 1485 flood many people migrated from Bratislava to Bavaria. The bridge was damaged again in 1486 by an ice flood, at which time King Matthias Corvinus made considerable efforts to rehabilitate it. Major floods in Bratislava also occurred in 1490 and 1499.

Historic floods from 1501 to 1820

Water marks on old buildings remind us of the Danube's high stages in Germany and Austria. Some of the markers, recorded in cities along the Danube (Vilshofen, Passau, Linz, Mauthausen, Ybbs, Emmersdorf an der Donau, Durnstein, Spilz, Schönbühel, Stein-Krems, Hainburg and Budapest) are shown in [25]. The flood traces can only indicate the possible scale of the flood and serve as a basis for comparison over time. It should be noted, however, that many of the buildings were reconstructed at some point in time, so this information is not very reliable. Other sources of information also need to be used to assess the significance of the recorded floods.

The most significant flood event on the Danube, according to relatively authentic records, occurred between Passau and Bratislava in August 1501. This event has been studied by renowned hydrologists ([10] [28]). The flood wave was estimated to have peaked at 12,000 m^3/s in Linz and 14,000 m^3/s in Vienna. A discharge of 11,000 m^3/s at Ybbs exceeded the summer floods on 25 June 1682 and 31 October 1787, as well as the "rainy" flood on 3 February 1862. That flood caused enormous damage to bridges and swept away many fields and orchards, forcing farmers to migrate to safer areas. Figure 3 is a graphical representation of historic floods on the Danube between Kienstock and Bratislava from 1501 to 1876. Summer and winter floods are depicted separately. The figure also includes maximum annual discharges of the Danube recorded at Bratislava after 1876.

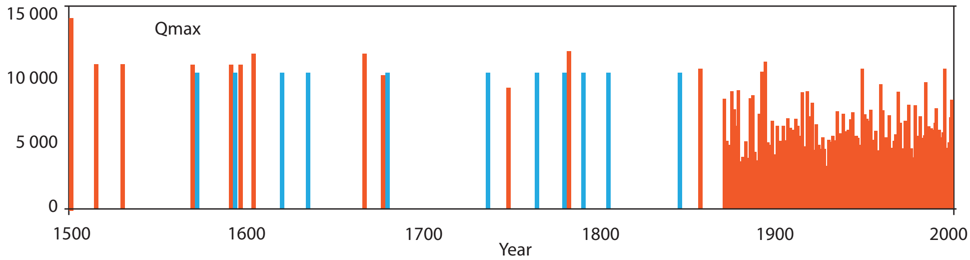


Figure 3. Historic floods on the Danube between Kienstock and Bratislava from 1500 to 1876. Red bars – summer floods, blue bars – winter floods; annual peaks, Qmax, recorded at Bratislava since 1876. [25]

Historic floods from 1821 to 2013

Several major flood events have occurred in the DRB in the past 15 years, particularly along the Upper Danube in August 2002 and June 2013, and the Middle Danube and Lower Danube in March–April of 2006 and 2014.

The highest discharge of the Upper Danube was recorded at Krems–Kienstock (11,900 m^3/s in 2013), followed by 11,306 m^3/s in 2002 and 11,200 m^3/s in 1899. At Bratislava, the highest peak was observed in 1899. Along the Lower Danube, in the Danube Delta, [7] estimated a discharge of 20,940 m^3/s during the July 1897 flood event.

The outcome of assessing a long-term trend in the time-series of maximum annual discharges (Qmax) is a highly questionable endeavour, given the quality of such an assessment of past events. Several disastrous floods occurred on the Upper Danube between 1840 and 1899, as shown in Figure 4.

The trends are indicative of increasing maximum annual discharges of the Upper Danube, upstream from Bratislava. Along the Middle Danube at Orsova – Turnu Severin, the multiyear trend of maximum annual discharges is constant. There are no sufficiently long time-series to assess the multiyear trend along the Lower Danube.

Contrary to the previous period, the years from 1901 to 1953 were relatively calm from a flood risk perspective. However, the period after 1953 was rather turbulent. Disastrous floods did not occur simultaneously on the Upper Danube (from the source to Bratislava), Middle Danube, and Lowr Danube (from the gauge at Orsova to the delta). The largest floods at Hofkirchen were recorded in 1845, 1862, 1882, 1854, 1999 and 2013; and between Passau and Bratislava in 1830, 1862, 1897, 1899, 1954, 2002 and 2013. There were similar occurrences along the Middle Danube in 1838, 1893, 1897, 1938, 1940, 1941, 1954, 1956 and 2006. According to [7], the largest floods on the Lower Danube occurred in 1845, 1853, 1888, 1895, 1897, 1907, 1914, 1919, 1924, 1932, 1940, 1941, 1944, 1947, 1954, 1955, 1956, 1958, 1962, 1965, 1970, 1975, 1980, 1981 and 1988. Some of these floods were caused by ice in winter and spring. The entire DRB experienced floods in 1897, 1965 and 2006. Figure 5 is a longitudinal representation of some of the extreme floods on the Danube.

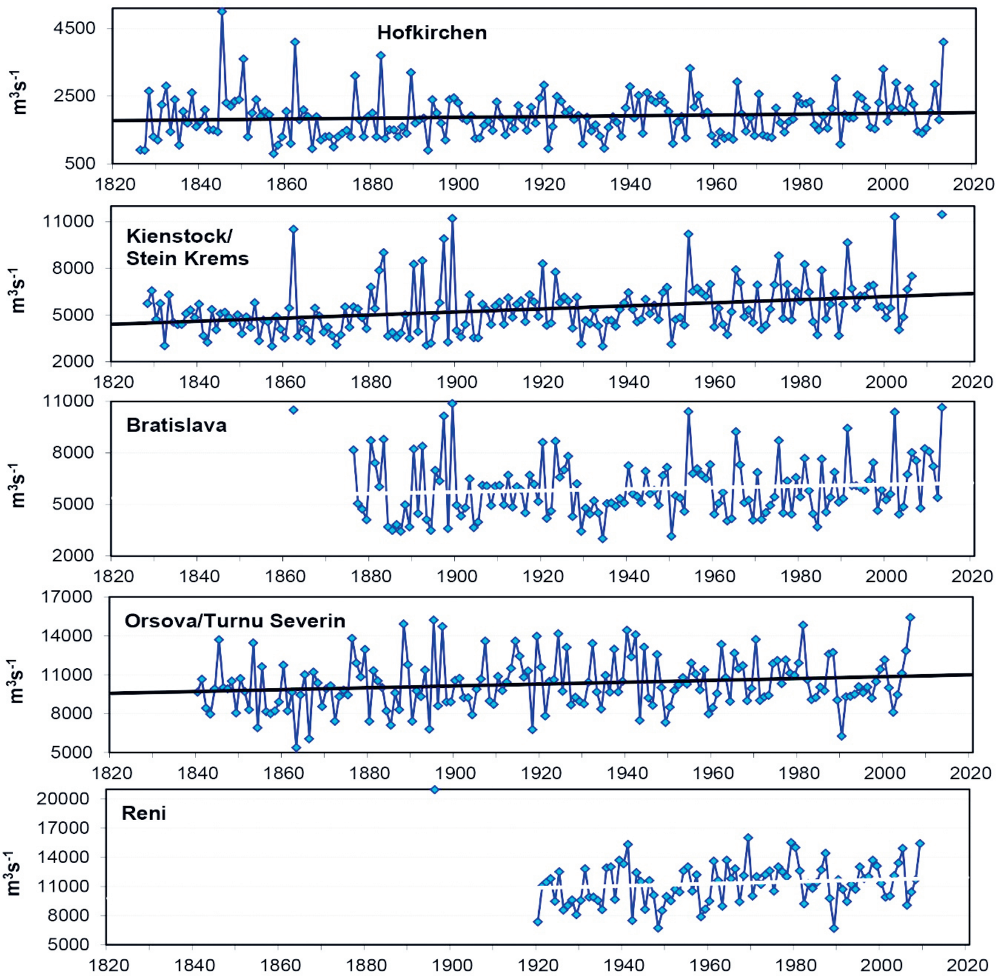


Figure 4. Maximum annual discharges at select stations along the Danube [1]

It is interesting to examine when floods on the Danube occur in a calendar year. Figure 6 shows annual hydrographs at output cross-sections of the gauging stations at Bratislava (Upper Danube), Orsova (Middle Danube) and Ceatal Izmail (Lower Danube). It is apparent that major flood events occur between April and July.

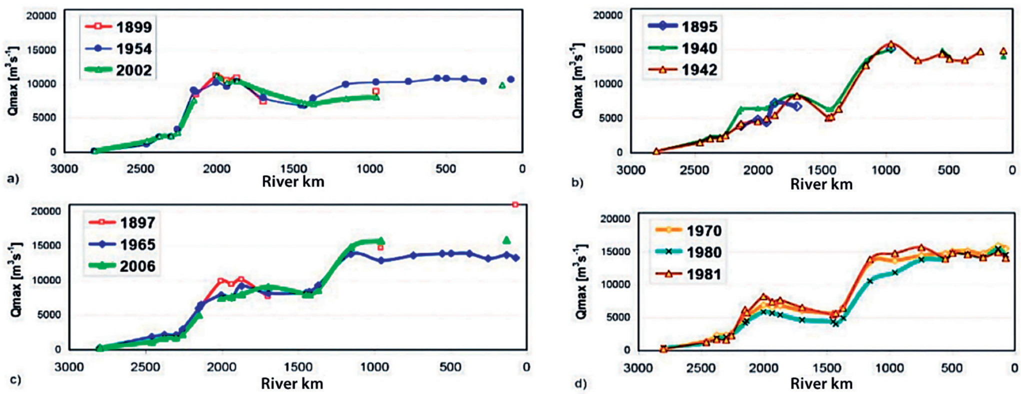
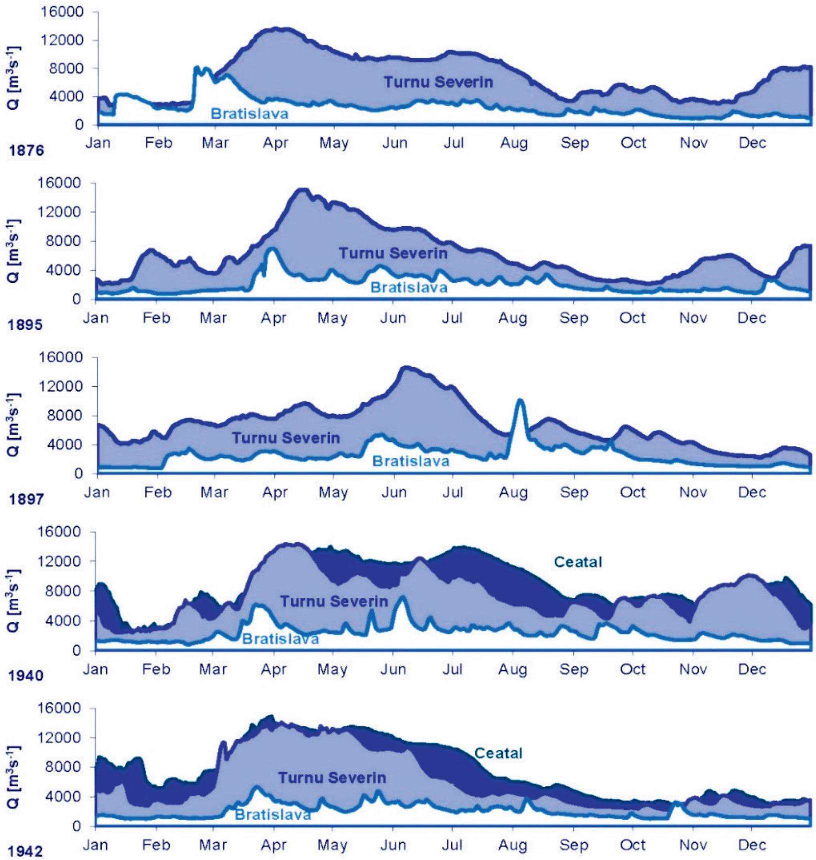


Figure 5. Extreme floods on the Danube [1]



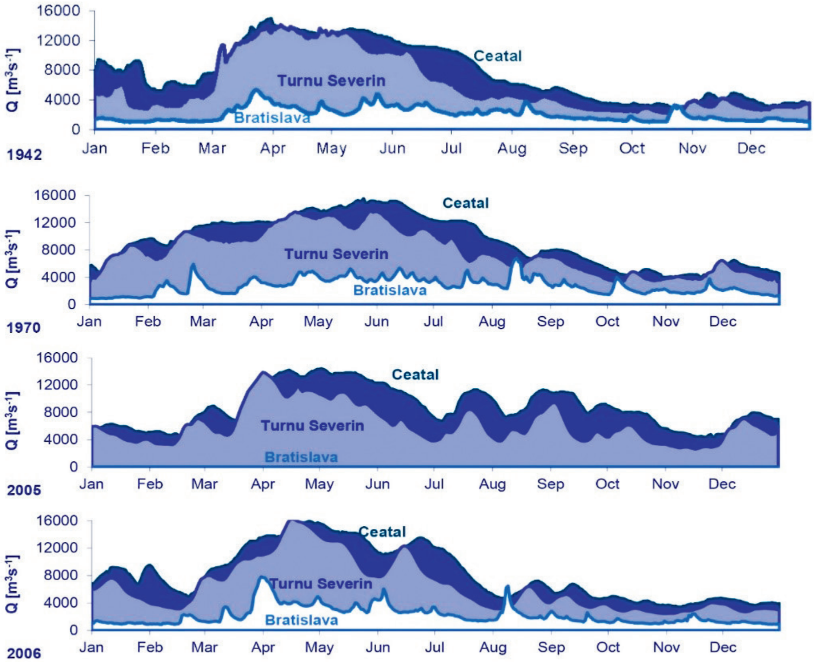


Figure 6. Daily discharges of the Danube at three gauges: Bratislava, Turnu Severin – Orsova and Ceatal Izmail (1940) [1]

Figure 7 is a longitudinal representation of maximum annual discharges along the Danube in the years 1964 and 2006.

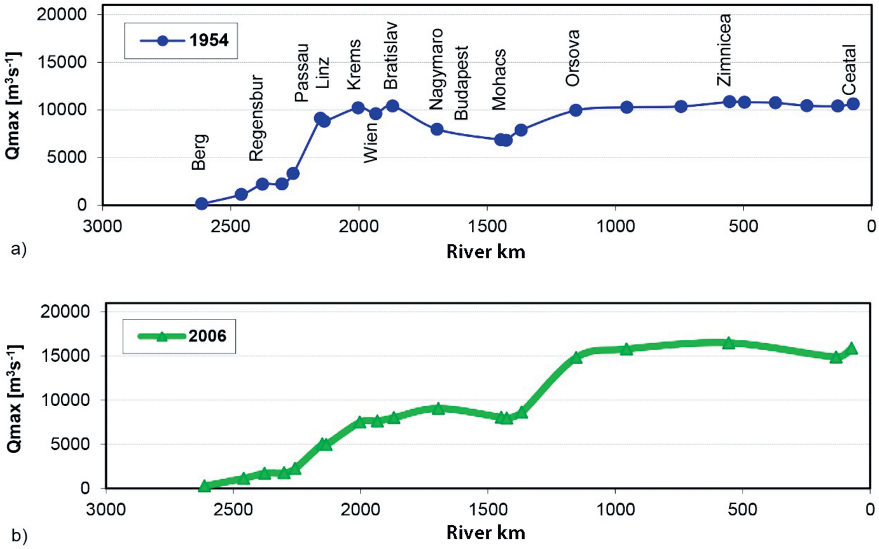


Figure 7. Flood peaks along the Danube in 1954 and 2006 [1]

Flood durations at Bratislava have been 5–10 days. High stages of the Lower Danube generally exceeded 40 days and at times lasted for as many as 200 days, as in the case of the 1965 flood.

The flood wave travel time from Hofkirchen (2,257 km) to Passau (2,226 km) is usually 25 hours, with a mean velocity of 30 km/hour. The travel time from Passau (2,226 km) to Bratislava (1,869 km) was 86 hours in 2002 (velocity 89 km/hour) and 130 hours in 1954 (velocity 66 km/hour). The travel time of the highest flood waves between Bratislava (1,869 km) and Orsova (955 km) has been about 16 days, at an average velocity of approximately 57 km/hour. The flood wave travel times from Passau to Nagymaros are shown in Figure 8.

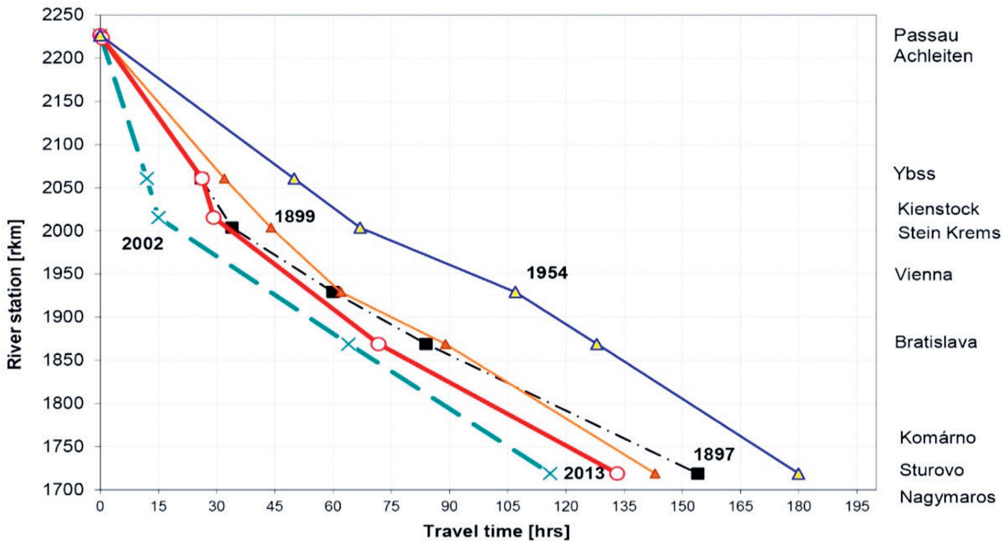


Figure 8. Travel times of the highest flood waves between Passau and Nagymaros [1]

According to [7], the travel times of the highest flood waves between Orsova and the Black Sea have been 15–20 days, at an average velocity of 53 km/hour.

The highest discharge of the Upper Danube (11,306 m^3/s) was registered at Krems–Kienstock in 2002, and the second largest (11,200 m^3/s) in 1899. On the Lower Danube, [7] estimated a discharge of 20,940 m^3/s in July 1897.

Figure 9 is a longitudinal representation of the most probable flood wave peak (50%) and the upper limit of the confidence interval – 99%. The graphic also includes estimated peak points of the highest flood wave on record (1501), at Kienstock, Bratislava and Ceatal Izmail.

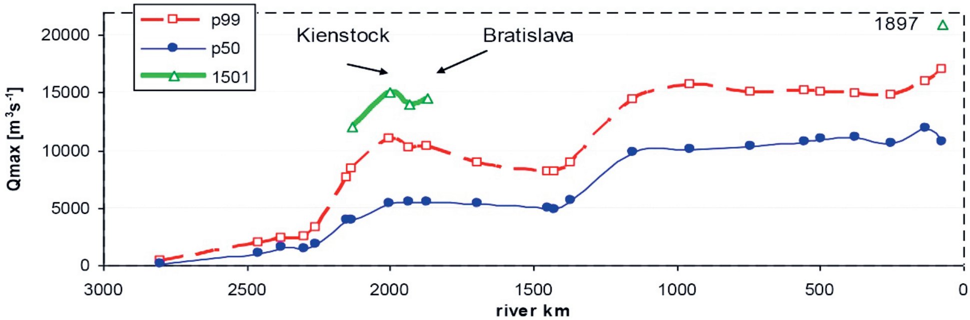


Figure 9. Percentiles of peak annual discharges of the Danube, 1876–2006, p99–99th percentile, p50–50th percentile, and historic flood in 1501 [1]

As an example, Figure 10 shows historic floods on the Vah, a tributary of the Danube, at Liptovsky Mikulas, where the highest peak was recorded in 1813 (1,100 m^3/s), which is more than twice the maximum discharge registered from 1921 to 2010 (540 m^3/s). The figure also includes the second largest historic peak, recorded in 1894.

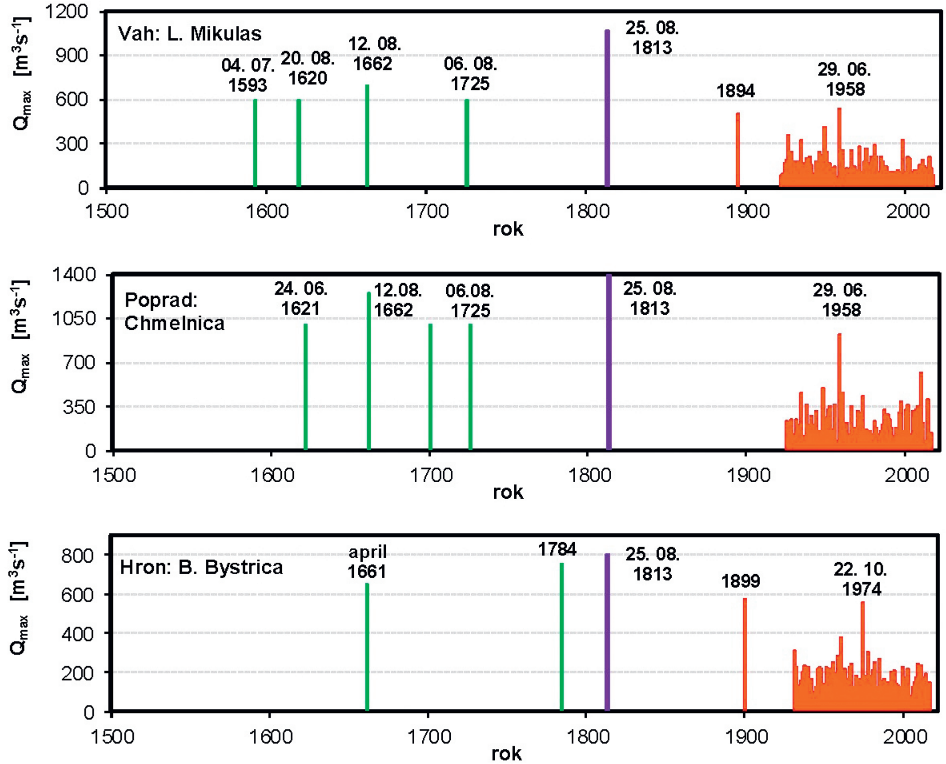


Figure 10. Maximum annual discharges of the Vah River at Liptovsky Mikulas during the observation period (1921–2016) and historic floods [1]

Long-term characteristics of hydrometeorological processes in the Danube River Basin

Long-term characteristics of hydrometeorological processes in the DRB can only be assessed on the basis of available data – precipitation and air temperatures. The longest time-series need to be examined. The objective is to determine the nature of variation in these parameters from year to year, in a multiyear time-series, and identify typical periods characterised by frequent floods or droughts.

With regard to precipitation, the most comprehensive analyses were undertaken for Slovakia, where 10-year averages from 1881–2016, based on 203 precipitation stations, and deviations from average annual precipitation totals were calculated for the entire territory of Slovakia. The results are shown in Figure 11, where a) identifies the wet and dry periods, and b) the 10-year average precipitation totals in Slovakia.

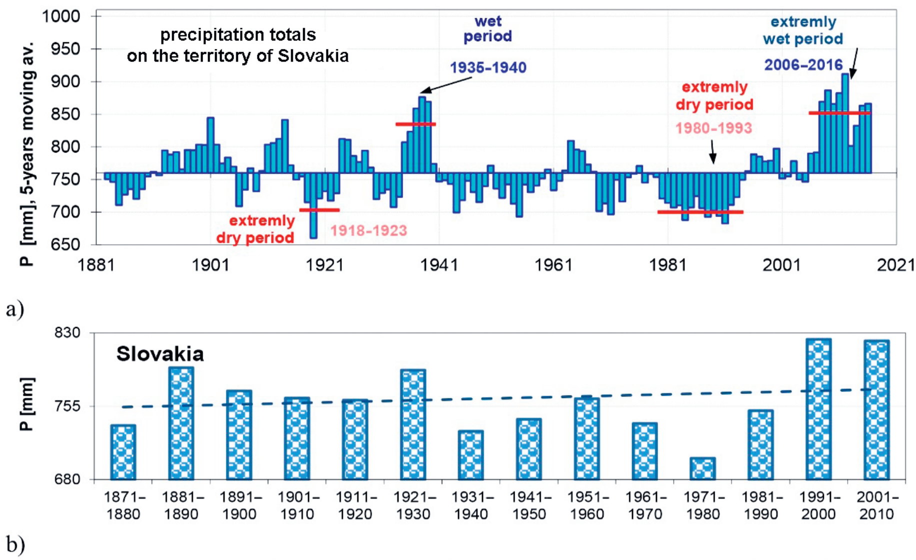


Figure 11. Moving averages of mean annual precipitation totals from 203 stations in Slovakia from 1881 to 2016, with 10-year averages [1]

It is apparent in the graphic that the periods from 1918 to 1923 and from 1980 to 1993 were extremely dry, and that the year 1938 and the period from 2006 to 2016 were wet. For example, in Slovakia, after 14 dry years (1980–1993) came a period of wet years, which began in 1996 and caused floods every year. These floods resulted in enormous damage to private and state property, and caused loss of life. There were a total of 47 fatalities during a disastrous flood in 1998 on the Mala Svinka River (eastern Slovakia), and another two during the summer floods in Slovakia.

The multiyear nature of the alternating dry and wet years was analysed at neighbouring weather stations – Hurbanovo (1871–2010), Mosonmagyaróvár (1861–2010), Vienna

(1841–2010) and Brno (1803–2010). The calculated 10-year average annual precipitation totals are shown in Figure 12.

The results lead to the conclusion that there have been two dry periods and one long rainy period, from 1871 to 1970 (nearly a hundred years) in this part of the DRB. The dry period from 1831 to 1870 was much drier than the other dry period, from 1971 to 2000. A multiyear trend in the precipitation time-series is the most obvious at Brno. The period from 1803 to 1830 agrees very well with the multiyear precipitation trend in the DRB lowlands. The long-term trend can be approximated by a 4th degree polynomial. Notable dry periods occur every 120–140 years.

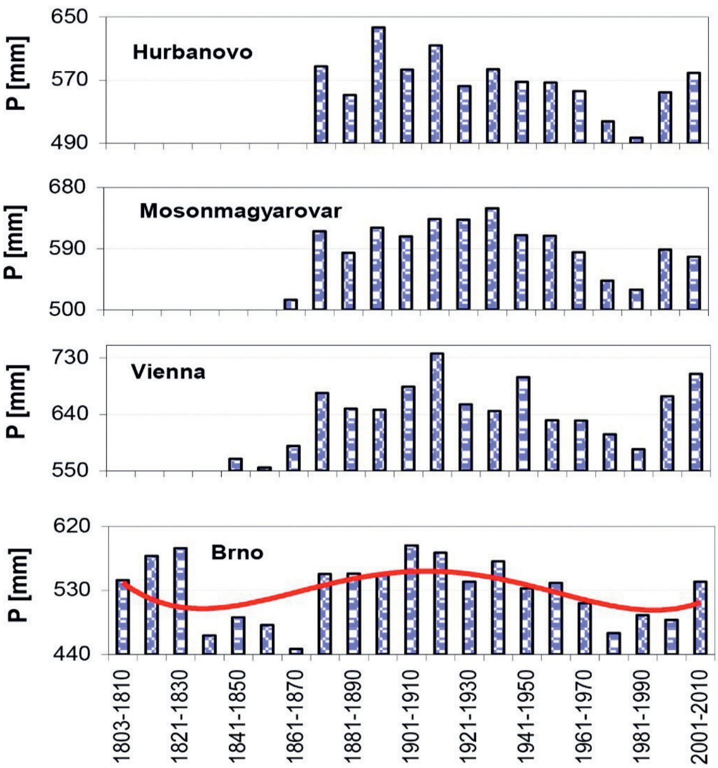


Figure 12. 10-year average precipitation at Hurbanovo (1871–2010), Mosonmagyaróvár (1861–2009), Vienna (1841–2009) and Brno (1803–2010) [1]

The multiyear nature of the air temperature regime in a large part of the DRB was also studied, based on mean annual air temperatures recorded by weather stations at Hohenpeissenberg, Vienna, Bratislava and Budapest. The DRB average annual air temperature ranges from –20 C° to +120 C°. The lowest value was observed at Sonnblick, whereas the highest mean annual temperature was recorded in a part of the Hungarian lowland (Figure 13) and on the Black Sea coast. DRB-wide, July is the warmest month and January the coldest [32].

For comparison, Figure 13 also shows mean annual discharges of the Danube at Orsova. The multiyear nature of air temperature variation is similar to all the considered weather stations. However, the nature of variation of mean annual discharges of the Danube differs, which means that there is no strong correlation between the Danube's discharges and air temperatures. The same applies to precipitation (Figure 11).

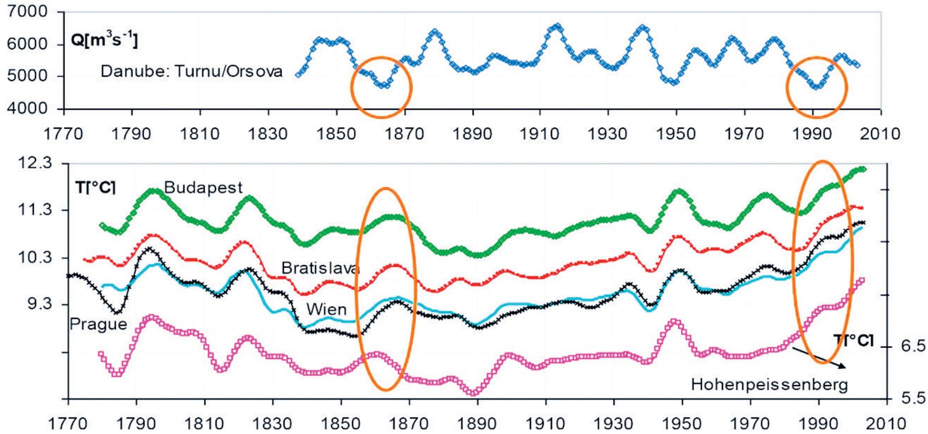


Figure 13. Filtered mean annual discharges of the Danube at Orsova and annual air temperatures, HP-filter lambda.50, Budapest, Bratislava, Prague, Klementinum, Vienna and Hohenpeissenberg stations, 1780–2004 [1]

The multiyear nature of discharge variation along the Danube is shown in Figure 14, via time-series of mean annual discharges and their 5-year moving averages. The 5-year moving averages were calculated for the selected gauging stations: Wasserburg on the Inn and Bratislava, Orsova and Reni on the Danube. The results are shown in Figure 13. They indicate that the nature of temperature variation is similar, from the mouth of the Inn through to the Danube Delta.

Data supplied by the gauging station at Bratislava from 1871 to 2006 was used for a detailed analysis of the nature of discharge variation of the Danube from year to year. Long-term 30-year discharges were examined in particular (Figure 15), as were the 7-year moving averages and long-term 10-year discharges (Figure 16).

The graphics lead to the conclusion that the wettest 30-year period was from 1916 to 1945, followed by 1886–1915 and 1976–2005. The driest 30-year period was 1946–1975. Analogous results for 10-year periods are: wettest 1911–1920, followed by 1961–1970 and 1891–1900.

All the statistical tests indicated that the time-series of the Danube's annual discharges were homogeneous. The trend analyses, whose results for select gauging stations (at Hofkirchen, Achleiten, Vienna, Bratislava, Orsova and Reni) are shown in Figure 17, indicated no statistical significance of the trends (equations also shown in the figure) along the entire course of the Danube.

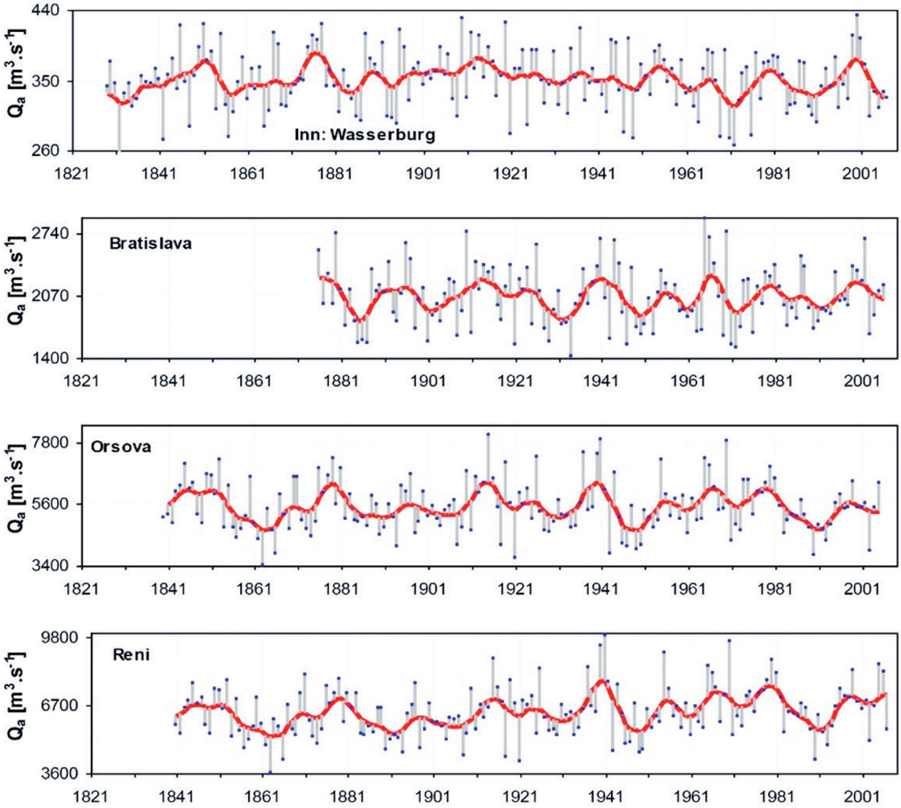


Figure 14. Average annual discharges of the Danube at selected points, deviation double 5-year moving average (hold time) [1]

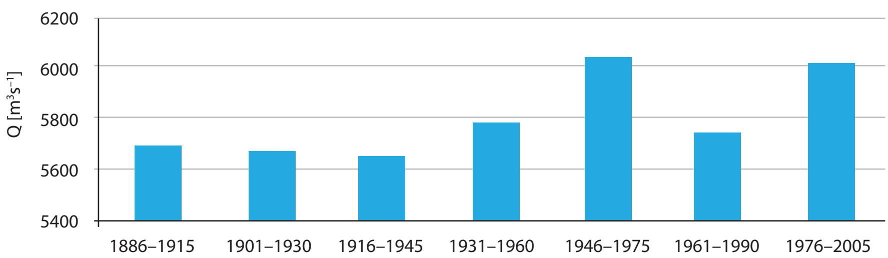
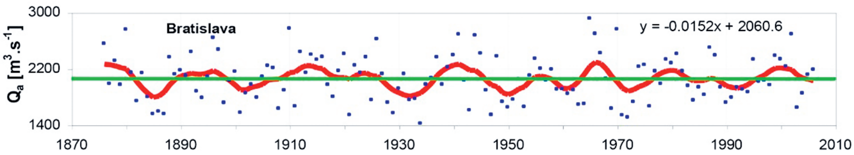
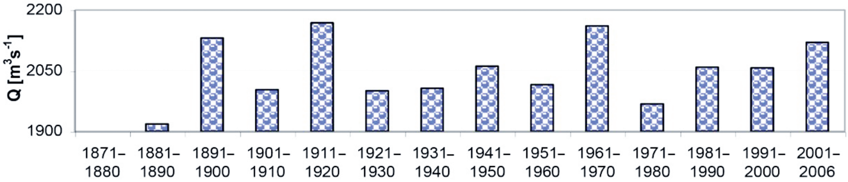


Figure 15. Long-term 30-year annual discharges of the Danube at Bratislava station [1]



Average anual discharge, diferences from 7-year moving averages.



Long term 10-year dichcharge.

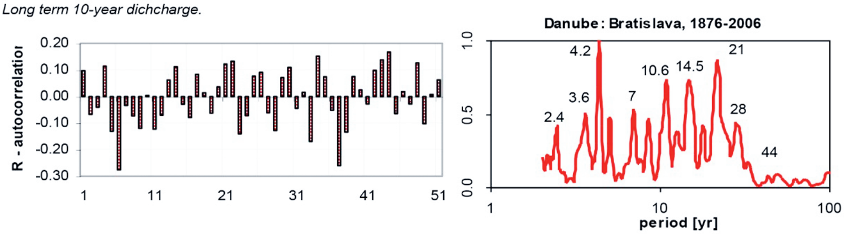


Figure 16. Annual discharges – differences from 7-year moving averages and long-term 10-year discharges of the Danube River at Bratislava station [1]

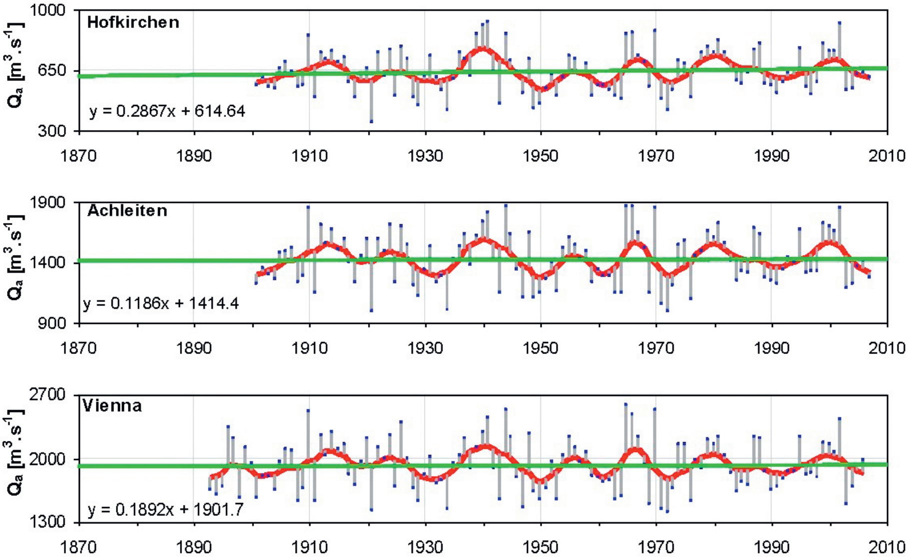


Figure 17. Long-term linear trends of mean annual discharges at selected stations on the Danube River [1]

A detailed analysis of the cyclical nature of the time-series of mean annual discharges of the Danube was conducted via calculations of the main stochastic characteristics: autocorrelation and spectral functions. The results for the gauging stations at Achleiten, Bratislava, Turnu Severin and Reni are shown in Figure 18. The computed autocorrelation functions suggest a multiyear cyclical and congruent nature of discharge formation on the Danube and its major tributaries.

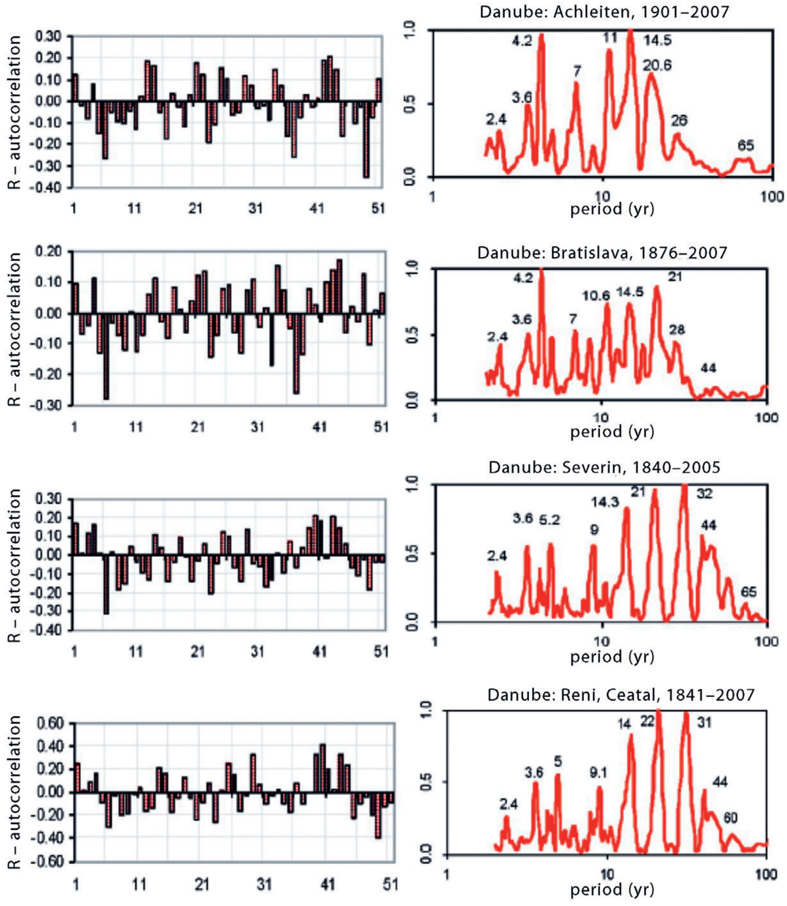


Figure 18. Autocorrelations (left column) and normalised periodograms (right column) of mean annual discharges of the Danube River, significant periods [1]

The spectral function provided a more detailed insight into the variation of cyclical periods along the Danube. The spectral function graphics identify the most prevalent periods in the time-series of mean annual discharges. It is apparent that the most common micro periods are 2.4, 3.6, 4.2 and 7 years and that the macro periods are 14, 22, 30 and 44.

According to [12], the 2.4-year period (cycle) is likely associated with the cyclic nature of the Quasi Biennial Oscillation (QBO) phenomenon. The cycle of about 3.6 years probably depends on the Southern Oscillation (SO), represented by the SO index. The 44, 22 and 11-year cycles are connected with solar activity. The cycle length of approximately 28–31 years is related to the Arctic Oscillation (AO), expressed by the AO index. Finally, the cycle of about 13 years is associated with the North Atlantic Oscillation (NAO), represented by the NAO index.

The analysis of the Danube's extreme annual discharge time-series indicates that the 1931–2005 time series is not representative, even though commonly used in the Danube countries. The last two decades of the 19th century abounded in disastrous floods across the DRB. Along the Upper Danube, there were only a few floods between 1900 and 1953. Since 1954, the flood variability has been higher and similar to the period 1876–1899. Consequently, the long-term trends tested for the period 1876–2005 at five gauging stations on the Danube, whose results are shown in Figure 19, indicate that there is no significant linear trend.

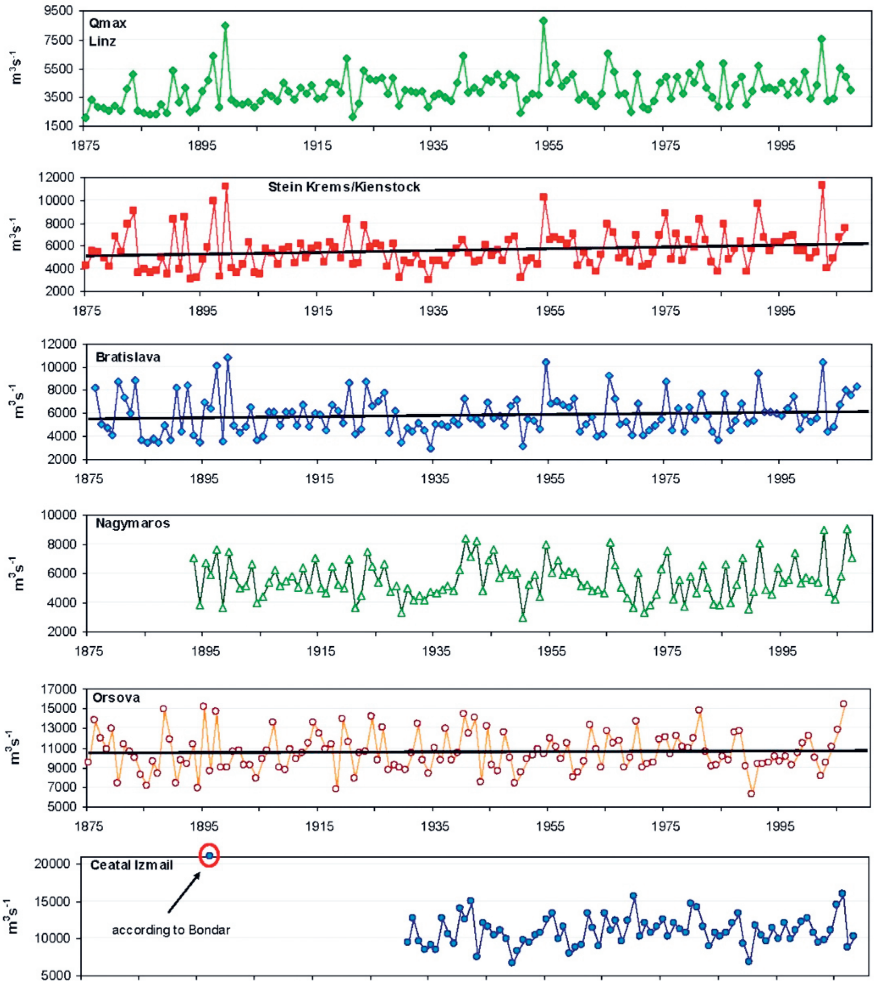


Figure 19. Long-term linear trends of maximum discharges at selected stations on the Danube River [1]

In general, the periods around the years 1915, 1940, 1965 and 1980 in the Danube River Basin were extremely rich in runoff. Contrarily, the period around 1947 was extremely dry and the period around 1863 even drier.

Modern approach to the assessment of statistical significance of historic floods

The statistical significance of historic floods is assessed in two ways, depending on the complexity of the river system:

- simple river systems with no significant impact of tributaries
- complex river systems, within significant impact of tributaries

In both cases the statistical significance of floods is assessed based on the theory of probability, assuming that floods on the main river (recipient) and a tributary are random events that adhere to the law of probability of one-dimensional and/or two-dimensional random variables.

Simple river systems

Simple river systems are those river sectors that are not affected by tributaries in the event of floods. The statistical significance is assessed using time-series of the basic flood hydrograph parameters, such as the peak hydrograph ordinate – Q_{max} and flood wave volume – W_{max}. These two parameters are assumed to be random quantities that adhere to a probability distribution theory. For example, the probability distribution function is calculated for Q_{max}, based on a multiyear time-series:

$$F(Q) = P(Q_{max} \geq q) = p$$

where p is the probability of occurrence of Q_{max}.

The probability of occurrence of a historic flood, Q_{hist}, is derived inversely – $p(Q_{hist})$ or its return period in years $T = \frac{1}{p(Q)}$, which will be described in more detail in Section *Flood Frequency Analysis*.

Complex river systems

Complex river systems are river reaches (sectors) where there is mutual influence of the recipient and a tributary in the event of a flood (flooding in the extended confluence area). There are several such sectors in the DRB, including the mouths of the Inn, Morava (the Czech Republic), Drava, Tisa, Sava, Velika Morava (Serbia) and Prut. Figure 20 is a schematic representation of such a confluence.

The symbols in Figure 20 are as follows:

QIN – discharge at the input cross-section in the zone of mutual influence of the Danube and a major tributary

QOUT – discharge at the output cross-section in the zone of mutual influence of the Danube and the tributary

qTR – discharge at the input cross-section of the tributary

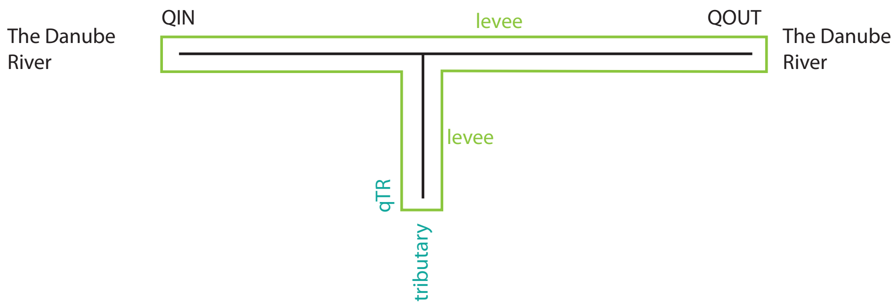


Figure 20. Schematic representation of the zone of mutual influence of the Danube and a major tributary (compiled by the author)

The extended area of the confluence of the Morava River and the Danube is used below as an example to illustrate the procedure for assessing the statistical significance of floods in complex river systems. In the specific case, the input cross-sections are gauging stations: QIN – Vienna on the Danube and qTR – Moravsky Jan on the Morava, and the output cross-section is QOUT – Bratislava on the Danube. The considered parameters are maximum annual discharges (Q_{max}) on these three locations.

The theoretical discharges of different probabilities of occurrence at the three stations were obtained by the conventional statistical-probabilistic approach:

$Q^{W}_{max,p}$ – theoretical maximum annual discharge of the Danube at Vienna, of probability of occurrence p

$Q^{B}_{max,p}$ – theoretical maximum annual discharge of the Danube at Bratislava, of probability of occurrence p

$Q^{MJ}_{max,p}$ – theoretical maximum annual discharge of the Morava at Moravsky Jan, of probability of occurrence p

The resulting probabilities (p) of maximum annual discharges at the three stations are shown in Table 1.

Table 1. Theoretical maximum annual discharges of the Danube and the Morava at different probabilities of occurrence – $Q_{max,p}$ (m³/s) (compiled by the author)

p (%)		Danube	Morava
	$Q^{W}_{max,p}$	$Q^{W}_{max,p}$	$Q^{MJ}_{max,p}$
0.1	12,922	13,760	2,170
1.0	10,309	10,906	1,541
2.0	9,519	10,042	1,362
5.0	8,463	8,890	1,131

In case of a flood in a complex river system, such as the confluence of the Morava and the Danube, the coincidence (simultaneous occurrence) of flood waves on both the recipient and the tributary is very important. A bivariate distribution of concurrent flood waves on the recipient and the tributary needs to be defined (i.e. the coincidence calculated).

To assess the statistical significance of a historic flood in the specific case, first the coincidences of all combinations of maximum annual discharge Qmax,p and corresponding (simultaneous) discharges QCOR,P of the recipient and tributary need to be defined for various probabilities of occurrence. In other words, a set of six coincidences [1] is identified.

1. $P\,[(OUT_{max} > qOUT_{max}) \cap (QTR_{cor1} > qTR_{cor1})] = p$ and $f\,(QOUT_{max}, QTR_{cor1}) = p$
2. $P\,[(QTR_{max} > qTR_{max}) \cap (QOUT_{cor2} > qOUT_{cor2})] = p$ and $f\,(QTR_{max}, QOUT_{cor2}) = p$
3. $P\,[(OIN_{max} > qIN_{max}) \cap (QTR_{cor1} > qTR_{cor1})] = p$ and $f\,(QIN_{max}, QTR_{cor1}) = p$
4. $P\,[(QTR_{max} > qTR_{max}) \cap (QIN_{cor2} > qIN_{cor2})] = p$ and $f\,(QTR_{max}, QIN_{cor2}) = p$
5. $P\,[(OUT_{max} > qOUT_{max}) \cap (QIN_{cor1} > qIN_{cor1})] = p$ and $f\,(QOUT_{max}, QIN_{cor1}) = p$
6. $P\,[(QIN_{max} > qIN_{max}) \cap (QOUT_{cor2} > qOUT_{cor2})] = p$ and $f\,(QIN_{max}, QOUT_{cor2}) = p$

where:

p – probability of occurrence.

Table 2 shows the coincidence calculation results for the extended zone of the confluence of the Morava and the Danube.

Table 2. Design discharges of different flood coincidence probabilities of the Danube and the Morava (compiled by the author)

p (%)	GS at Vienna			GS at Bratislava			GS at Moravsky Jan		
	$Q^{W}_{max,p}$	$Q^{B}_{cor1,p}$	$Q^{MJ}_{cor1,p}$	$Q^{B}_{max,p}$	$Q^{W}_{cor1,p}$	$Q^{MJ}_{cor2,p}$	$Q^{MJ}_{max,p}$	$Q^{W}_{cor2,p}$	$Q^{B}_{cor2,p}$
0.1	12,922	6,000	31	13,760	6,500	22	2,170	2,100	2,500
1.0	10,309	5,800	30	10,906	6,100	19	1,541	1,700	1,800
2.0	9,519	5,500	29	10,042	5,700	17.5	1,362	1,550	1,600
5.0	8,463	5,300	28	8,890	5,100	16	1,131	1,250	1,500

In the present case it is of interest to analyse the return periods of exceedance coincidences of the floods in Bratislava in July 1954 and June 2013, or, in other words, to define their statistical significance. Only the significance of recorded simultaneous combinations of discharges on the Danube at Bratislava and the Morava at Moravsky Jan is addressed here, as follows.

Table 3. Recorded simultaneous combinations of discharges on the Danube at Bratislava and the Morava at Moravsky Jan (compiled by the author)

Year	Q Bratislava (m^3/s)	Q Moravsky Jan (m^3/s)
2013	10,640	52.34
1954	10,400	130

The probability of exceedance of the constellation of maximum annual discharges of the Danube at Bratislava and the corresponding discharge of the Morava at Moravsky Jan in 2013 is (Figure 5):

$$P\{(Q^{B}_{max} \geq 10640) \cap (Q^{MJ}_{cor2} \geq 52.34\} = 0.009,$$

or the return period is:

$$T = \frac{1}{P} = \frac{1}{0.009} = 111 \text{ years}$$

The probability of exceedance of the constellation of maximum annual discharges of the Danube at Bratislava and the corresponding discharge of the Morava at Moravsky Jan in 1954 is (Figure 21):

$$P\{(Q^{B}_{max} \geq 10400) \cap (Q^{MJ}_{cor2} \geq 130)\} = 0.005,$$

or the return period is:

$$T = \frac{1}{P} = \frac{1}{0.005} = 200 \text{ years}$$

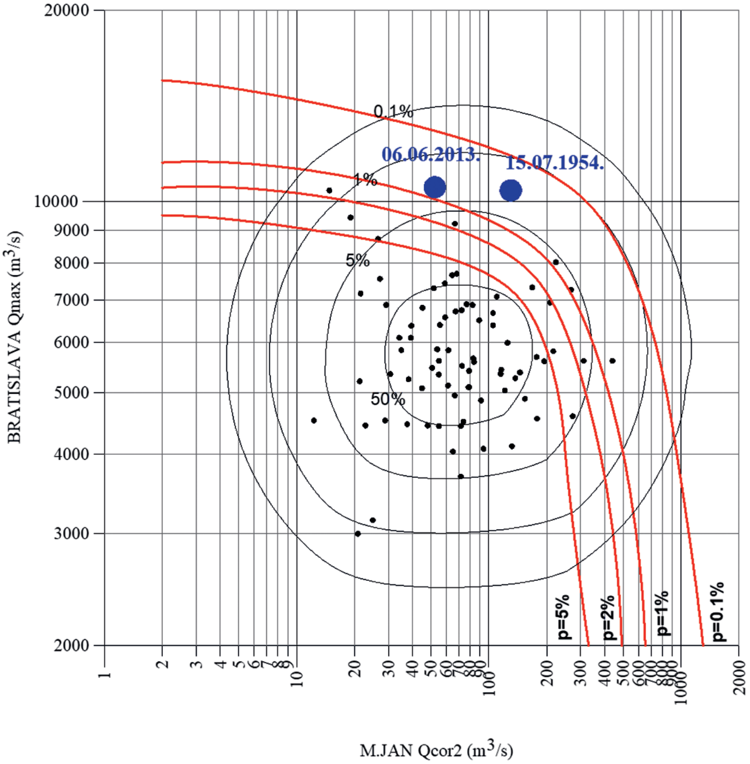


Figure 21. Coincidence of maximum annual discharges of the Danube at Bratislava and corresponding discharges of the Morava at Moravsky Jan, indicating floods on the Danube at Bratislava [1]

Consequently, from the standpoint of statistical significance of simultaneous occurrences of maximum annual discharges of the Danube at Bratislava and the corresponding discharges of the Morava at Moravsky Jan, which are highly relevant to flood protection, the most significant flood waves were registered in July 1954 (200-year event) and June 2013 (100-year event), even though when viewed separately both maximum discharges of the Danube at Bratislava were below the 100-year return period.

Flood marks of historical floods along the Danube river

The analysis of the historical floods occurrence on the upper part of the Danube is in the first part of this paper. It is based on the historical flood marks in Passau, Linz, Mauthausen, Ybbs, Melk, Spitz, Krems, Hainburg, Bratislava, Šturovo and Budapest. The oldest evidence of floods on the Danube goes back to 1012 (see Figure 2). Other floods with severe consequences, as documented in historical annals, occurred in 1051, 1060, 1086, 1173 and 1210.

The occurrence of the Danube medieval floods on its Austrian–Slovak–Hungarian stretch has been described in detail by the dissertation of [20]. As very high floods were denoted those in years 1235, 1316, 1402, 1414, 1432 and 1490. In general, the 15th century is known by a high flood occurrence. From the 15th century, mainly the references about the Bratislava ice floods (ice jams, ice barriers) damaging the bridge are preserved. These floods damaged seriously also the city buildings by ice floes.

Figure 22. Building with the Danube flood marks in Schönbühel (Photo taken by Pavla Pekárová, 2010.)

The water level marks of the highest Danube floods (after 1500) remained on historical buildings in Germany, Austria, Slovakia and Hungary. Such examples are shown on the following photos, taken from [2], for cities located close to the river (Passau, Melk, Emmersdorf an der Donau, Spitz, Schönbühel and Bratislava). These marks make it possible to imagine a real Danube water level elevation, and to compare them each with the others. It should be taken into account that the Danube River channel morphology changed several times in the course of the centuries.

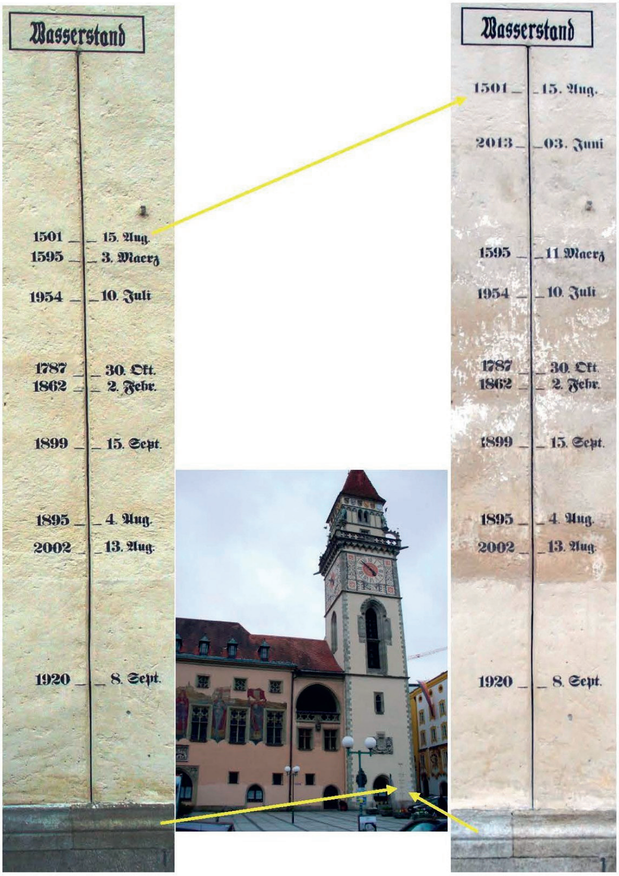


Figure 23. The Danube flood marks, Passau (Photo taken by Pavol Miklánek, left [2010], right [2014]). After the June 2013 flood the mark of 1501 was increased

Figure 24. The Danube flood marks, Melk, detail (Photo taken by Pavol Miklánek and Pavla Pekárová, 2014)

Figure 25. The Danube flood marks, Emmersdorf an der Donau (Photo taken by Alexander Szép, 2014)

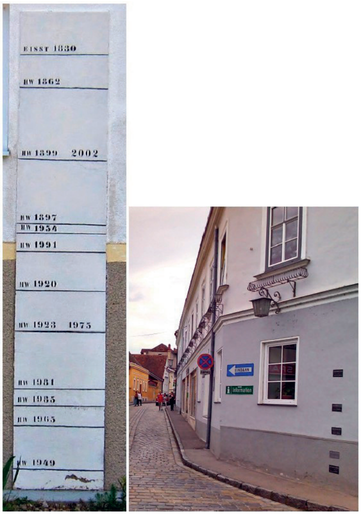


Figure 26. The Danube flood marks, Spitz (Left photo taken from the internet, right photo taken by Pavol Miklánek, 2014)

Figure 27. The frozen Danube at Bratislava in winter 1928–1929 (Archives of the City of Bratislava, Photo Hofer)

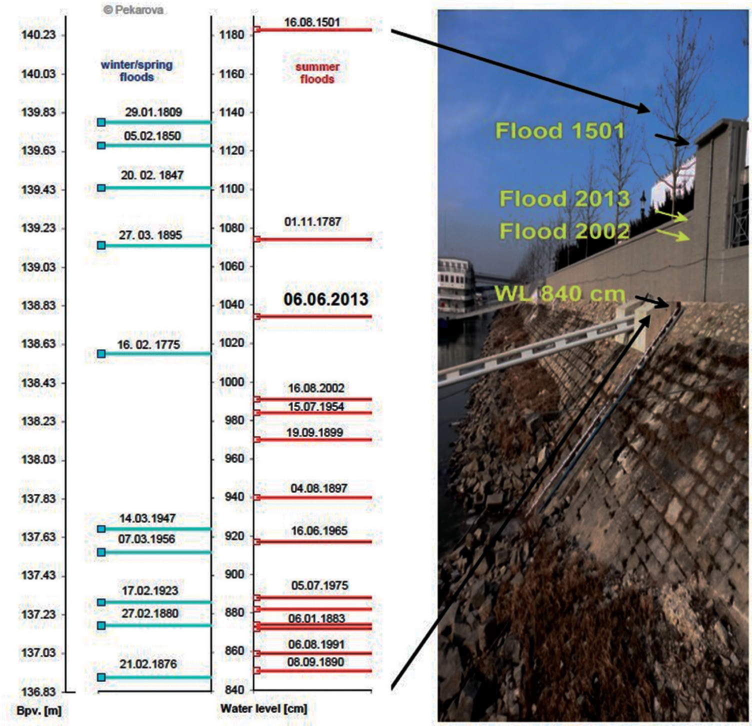


Figure 28. Measured and estimated water levels of significant floods at Bratislava gauge. Left column (blue points) – ice floods, right column (red points) – summer floods (Photo taken by Pavla Pekárová, 2012)

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