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Identification of the historical drought occurrence on the Danube River and its tributaries

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In the presented paper, the changes in the minimum flows at five stations along the length of the Danube River and at its 5 selected significant tributaries were analyzed. Average daily flows with the longest possible series of observations (since 1901 or since 1921) were used as input data. In the first part, low water content, hydrological drought were statistically analyzed and long-term trends of 1- to 90-day minimum flows were identified. The second part presents changes in *T*- year minimum daily flows in selected stations. The most extreme drought at Hofkirchen occurred in 1921. Drought at Orsova occurred around 1862/63, 1882/83, 1900, 1920/21, 1946/47, 1961/62, 1971, 1991/92 and 2017 / 19. The analyzes show that there is a more or less regular alternation of water and low-water periods along the entire length of the Danube. Multi-annual dry periods along the length of the Danube occur in the same periods. In contrast, on the Danube tributaries, the dry seasons are time-shifted.

KEY WORDS: the Danube River basin, low flow and failure characteristics, hydrological drought, IHA model

Introduction

In the last decade after 2010, several dry years occurred in the entire Danube basin. E.g. Kukla et al. (2019) cites, that in the Czech Republic the year 2018 was the culmination of a number of few water years since 2014. The hydrological drought in 2018 affected practically the entire territory of the Czech Republic. In most rivers, their levels fell down to the level of hydrological drought (355 daily flow) for several weeks. In the Slovak part of the Morava river basin, 2017 and 2018 were also extremely dry. Mészáros (2018) cites, that in 2017, below-average flow was recorded in all stations in the Morava river basin, the most stations had more than 10-day periods with a flow below Q_{355} and eleven stations were more than one day below Q_{364}. In four water gauging stations there were days during which the riverbeds were dried and in two stations there were days with a flow rate of less than 0.001 $m^3 s^{-1}$. The lowest flows occurred from June to September, but also in January, which was extremely cold. In the water gauging station with the longest series of measured flows, Moravský Svätý Ján: Morava, the year 2017 was evaluated as the third driest since the beginning of measurements. The water shortage situation was repeated in 2018.

Drought is a natural hazard. However, it differs in several ways. Most natural hazard (floods, earthquakes) arise very quickly (sometimes without any warning) and have a rapid course (Pekárová et al., 2008). Drought is characterized by a slow onset and development that lasts for months. It can sometimes occur throughout a season, year, and even a decade. Determining the beginning and end of a drought is quite complex and requires the analysis of several meteorological as well as hydrological characteristics. The effects of drought are cumulative, the magnitude of the drought intensity increasing with each passing day. We encounter the effects of extreme drought for several years after the occurrence of average rains.

In Europe, drought occured in the Mediterranean, in Spain, Italy or Greece. But also in the Danube basin in the past there were several extremely dry periods, e.g. in 1921, 1947, 1992–93, 2003, 2015. In the studies of Slovak and foreign authors, eg: Dracup et al. (1980), Wilhite and Glantz (1985), Bonacci (1993), Fendeková and Némethy (1994), Lešková, (1997), Tallaksen et al. (1997), Byun and Wilhite (1999), Tate and Gustard (2000), Smakhtin and Hughes (2007), Brilly (2010), Klementová and Litschmannn (2001), Stahl (2001), Hisdal et al. (2001), Smakhtin (2001), Blinka (2004, 2005), Hrvoľ and Tomlain (2008), Halmová et al. (2011), Fendeková et al. (2017), Hanel et al. (2019), Hološ and Šurda (2021) we can find a number of drought definitions.

Wilhite and Glantz (1985) define the following four types of drought:

- Meteorological drought: usually assessed on the basis

of the deviation of precipitation from normal for a certain period of time. It thus expresses one of the primary causes of drought.
- Hydrological drought: expressed in terms of deficits in surface and subsurface water supplies.
- Agricultural (soil) drought: usually refers to the soil moisture needs of specific crops at a given time.
- Socio-economic drought: a definition linking drought with economic theory of supply and demand.

An overview of older works concerning the processing of low water characteristics in Slovakia can be found in Szolgay (1977), Drako and Majerčáková (1989), Balco (1990), Majerčáková (1995), Majerčáková et al. (1995, 1997), Burger (2005), Demeterová and Škoda (2004, 2005, 2009), or Kohnová et al. (2021). A detailed elaboration of the characteristics of low water content of Slovak streams can be found recently in Fendeková et al. (2017).
The aim of this paper is to identify the occurrence of hydrological drought in rivers in a uniform manner in selected stations on streams in the Danube river basin for the longest possible time periods. Therefore, in the statistical analysis, rivers were selected where there have been evaluated daily discharges at least since 1921.

Data

At statistical evaluation of minimum discharges and to identify the occurrence of extreme hydrological droughts, we used a database of average daily discharges, processed within the international project IHP UNESCO WATSIM.
We selected 5 stations on important Danube tributaries (Lech: Landsberg (1901–2019), Morava: Moravský sv. Ján (1901–2019, except 1917–1919), Váh: Liptovský Mikuláš (1921–2019), Tisza: Senta (1921–2019), Sava: Litija (1895–2019). The following stations were selected on the Danube: Hofkirchen (1901–2019), Achleiten (1901–2019), Bratislava (1876–2019), Orsova (1840–2005) and Reni (1921–2019) (Fig. 1).
The basic hydrological characteristics of the flows for the observation period are shown in Table 1. The example of average daily flow rates for Morava: Moravský sv. Ján is rendered on Fig. 2. From the course of 4-year moving averages of daily values it is obvious, that multi-annual dry periods occur more less regularly on the Morava River.
To evaluate the hydrological drought, it is evaluated:
- flow characteristics (minimum average daily flow rate (monthly and annual step, for the entire period), M-daily flow (curve of exceeding average daily flow), minimum monthly and annual flow rates, N-year minimum flow);
- failure characteristics: Time occurrence of dry periods (occurrence date, number of days of low flow period, longest dry season) and insufficient volumes.

Multiple time courses were assessed from average daily flow rates that represent a hydrological river regime (with an emphasis on hydrological drought):
- time series of average annual flow;
- time series of 1-, 3-, 7-, 30-, and 90-day minimum flow by calendar year;
- the time range of the annual minimum flow (the occurrence day of the extreme from 1 – to 365/366, 1 means the 1st January; 355/356 means 31. December);
- BFI (BASIC FLOW INDEX) – Basic drain index, calculated as a 7-day minimum flow / average flow rate per year.

An example of created rows for Morava River in Moravský sv. Ján is presented in Fig. 2 and 3.

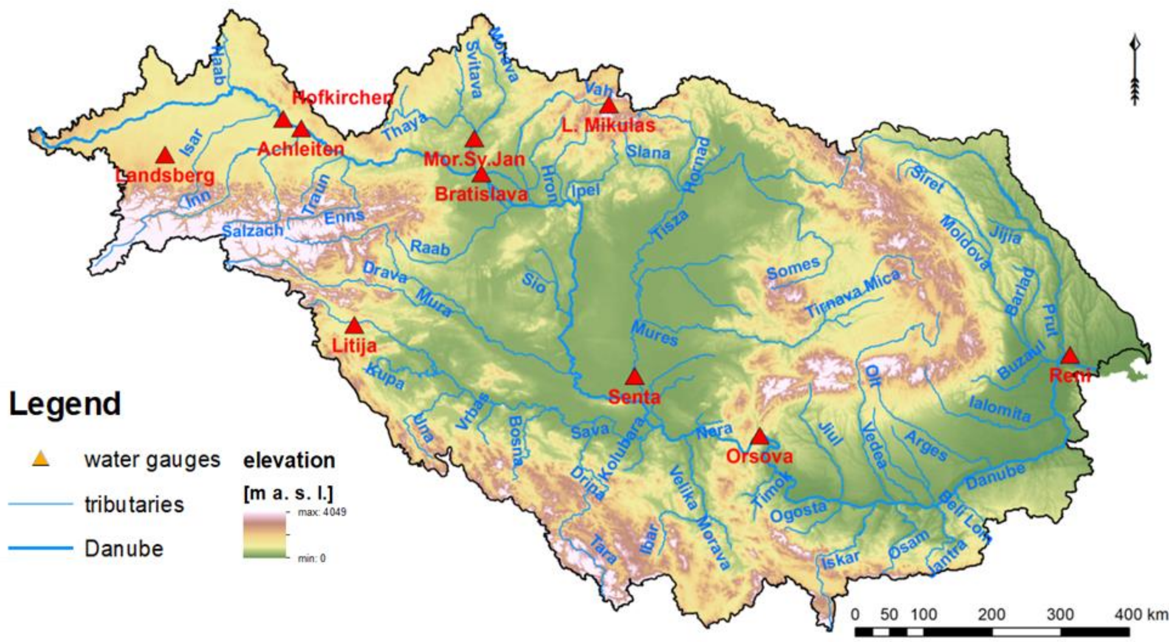


Fig. 1. Localization of used stations in the Danube Basin.

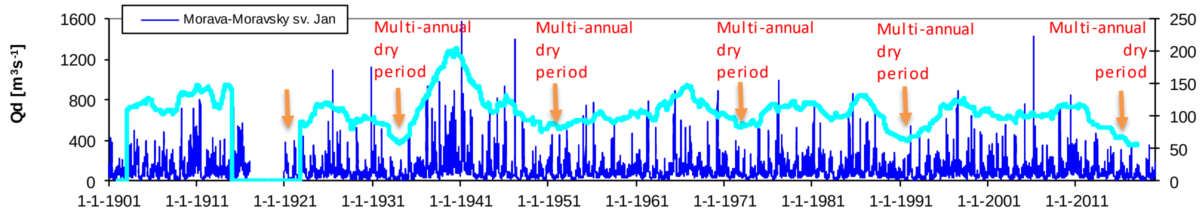


Fig. 2. The course of average daily flow on Morava: Moravský sv. Ján for the period 1901–2019 (dark blue line). The course of the 4-year-moving average (light blue line).

Table 1. Basic discharge (Q) characteristics and average long-term specific runoff (q_a)

	Area [km^2]	Q_{mean} [m^3 s^{-1}]	Q_{min} [m^3 s^{-1}]	Q_{max} [m^3 s^{-1}]	$Q_{330\text{-}day}$ [m^3 s^{-1}]	$Q_{30\text{-}day}$ [m^3 s^{-1}]	q_a [l s^{-1} km^{-2}]
Lech: Landsberg	2295	82	14.30	989	34	157	35.8
Morava: M. sv. Ján	24129	107	9.40	1573	29	247	4.5
Váh: L. Mikuláš	1107	21	4.20	300	7	44	18.5
Tisza: Senta	141715	782	79.0	3730	219	1739	5.5
Sava: Litija	4821	176	23	1992	59	373	36.4
Danube: Hofkirchen	47496	635	165	3450	337	1070	13.4
Danube: Achleiten	76653	1414	349	9300	740	2350	18.4
Danube: Bratislava	131338	2049	580	10810	1042	3420	15.6
Danube: Orsova	576232	5565	1060	15092	2760	9020	9.7
Danube: Reni	805700	6539	1280	15900	3260	10800	8.1

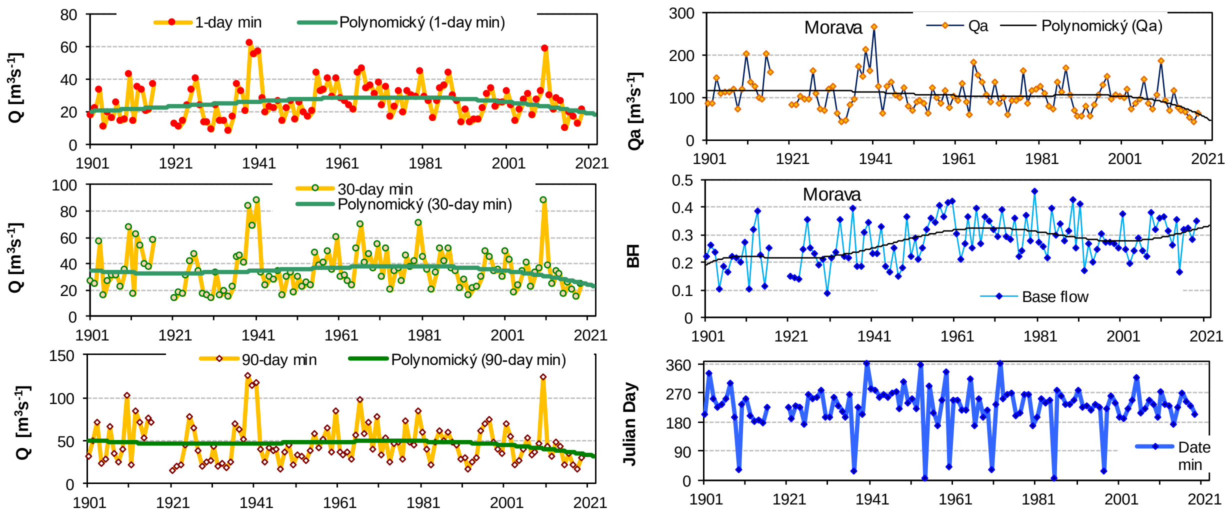


Fig. 3. Various minimum flow characteristics, Morava: Moravský sv. Ján, 7-day (7-day) minimum, date of minimum daily flow rate in year, 30-day (30-day) minimum, 90-day (90-day) minimum. Period 1901–2017 (1917–1919 missing data). Polynomial trend.

Methods

Statistical analyses

Statistical methods were used for data processing (time series, trend and frequency analysis) using special hydrological data processing software, e.g. AnClim (Štepánek, 2004), IHA (Indicators of Hydrologic Alteration) Software (The Nature Conservancy, 2007, 2009, Mathews and Richter (2007), Gao et al. (2009)), PeakFQ Software (Flynn et al., 2006) and STATGRAPHICS Plus.

Analysis of the frequency and duration of dry periods.

In the next step, the frequency of dry periods was evaluated. Hydrogram of average daily flow rates were separated into 5 types of flow:
1. low flows,
2. extreme low flows,
3. high flow pulses,
4. small foods,
5. large floods.

Periods of low flows are the dominant phenomenon in most rivers. In the natural riverbeds, after a period of rains or after melting the snow cover, the total (surface and subsurface) runoff from the catchment gradually decreases, while the runoff returns to its original flow state. These low flow rates are maintained by groundwater inflows into the streams. Extreme Low Flow periods occur during very long dry periods, when the river flows decrease and get into very low values.
The following criteria were used for hydrogram separation:
1. Extremely low flow rates - below 10% low flow rates.
2. Pulses / Periods of increased flow rates are all flow events with a flow over 25% (a flow wave begins if more than 25% per day will rise and ends if the decrease is less than 10% per day, while the flow does not fall below 50% value).
3. Small floods are defined as pulses / period of increased flow rates at least once in 2 years.
4. Large floods are defined as pulses / period of increased flow times with a recurence time at least once every 10 years.

An example of separation of average daily flow for large floods, small floods, periods of increased flow, low flow and extremely low flow periods in the Morava: Moravský sv. Ján is shown in Fig. 4. Long-term changes in separated flow were identified by trend analysis.
Hydrological software IHA (Indicators of hydrological alterations) version 7 was used to identify changes in daily flow regime. The software IHA has been developed by The Nature Conservancy (TNC) as an easy-to-use tool for calculating the characteristics of natural and altered hydrologic regimes. The method and software will work on any type of daily hydrologic data and the power of the IHA method is that it can be used to summarize long periods of daily hydrologic data into a much more manageable series of ecologically relevant hydrologic parameters.

Results

Statistical analyses

To characterize the periods of low water levels, which are the most significant manifestation of hydrological drought, parameters belonging to statistical, positional and probabilistic characteristics using time series of average daily flows are generally used. In addition to these characteristics, the volume and time characteristics of the drought are also determined. Methodically, the flow parameters of extreme flows in the region of the extreme minimum were assessed.
Rows of 4-year moving average daily specific runoff were calculated from the average daily discharges of selected five rivers in the Danube basin and from gauging stations on the Danube (Fig. 5a). The multi-annual small-water and water periods alternate more or less regularly cyclically along the entire length of the Danube in the same periods. Dry seasons occurred around 1862, 1882/83, 1900, 1920/21, 1946/47, 1961/62, 1971, 1991/92 and 2017/19. An extremely dry multi-year period occurred on the Danube at the Orsova station around 1863 and then around 1991. The cyclic repetition of dry periods on the Danube flow is shown by the red arrows in Figs. 5a, 5b. It is obvious that there is no significant shortening or lengthening of cycles.
From Fig. 5b on the example of the Morava River, it is evident that in the period 1921–1923, extreme 90-day dry periods occurred in three successive years. It was similar in 1932–1935; in 1947; in 1990–1994. Since 2013, an extremely dry period started again. The situation is similar on the Tisza River. The example of the Danube tributary Lech shows that extreme drought occurred at the turn of the 20th and 21st centuries, a more pronounced drought also occurred around 1960.
The results of the trend analysis are documented in Table 2. The analysis of selected characteristics of low water content of selected streams in the Danube basin shows that the period 1920–1921 was an extremely dry period, that the series of minimum discharges (1-, 3-, 7-, 30- and 90-day minimum discharges) in water gauging stations on the Danube River and selected tributaries are generally growing.
However, from the analysis of flows in the Danube: Orsova and Sava: Litija water gauging stations, it is clear that all evaluated minimum flows have a decreasing trend. For the Morava River, while the 7- day minimum flows are rising slightly, in the case of the 90-day minimums, the trend is slightly decreasing.
Regarding the occurrence of the minimum flow during the year, the differences are evident. In some water gauging stations their occurrence is evident at one time of the year (eg. Danube: Bratislava, Danube: Orsova, Lech: Landsberg, Morava: Moravský sv. Ján, Váh: Liptovský Mikuláš) and in others the minimum flow occurred throughout the year, whether in summer or winter (Danube: Hofkirchen, Sava: Litija).

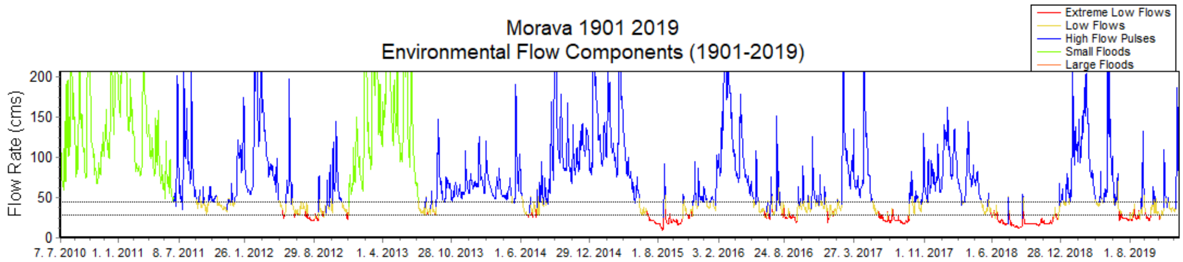


Fig. 4. Separation of daily flows into large floods, small floods, periods of increased flows, low and extremely low flows; at Morava: Moravský sv. Ján gauging station, detail from July 2010 to December 2019. The horizontal lines represent the flow boundaries for the separation of the hydrogram.

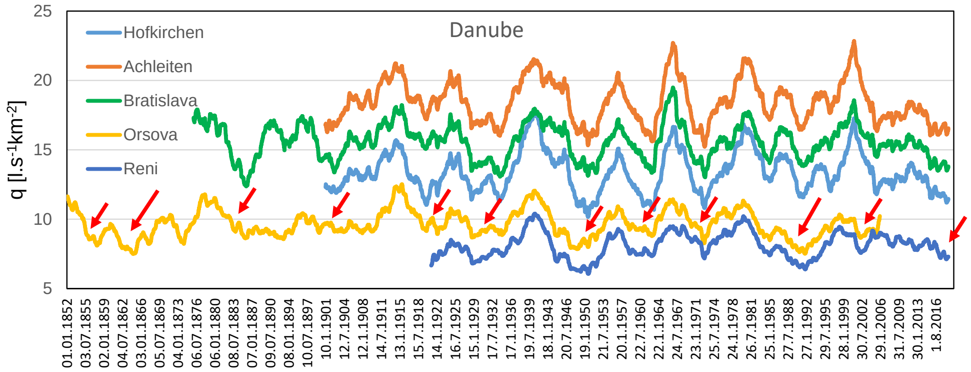


Fig. 5a. The course of 4-year moving average daily specific runoff of five selected gauging stations on the Danube River.

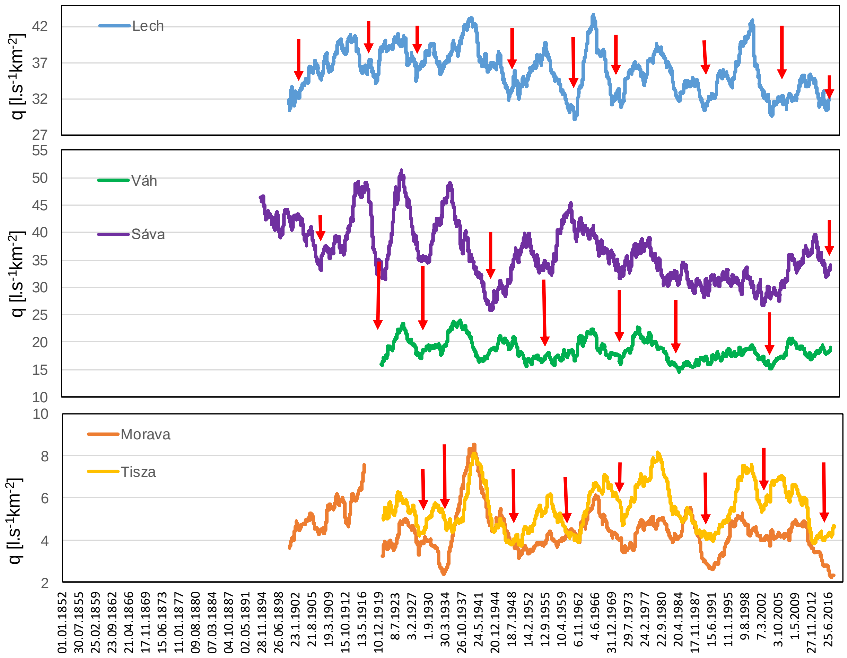


Fig. 5b. The course of 4-year moving averages of average daily specific runoff from water gauging stations of selected five tributaries of the Danube for the observed periods. The red arrows highlight the dry season.

Identification of historical droughts on the Danube and selected tributaries.

In the second part of the study, the duration of low and extremely low flow rates was evaluated. As mentioned in the Methods, we used IHA software to separate the hydrogram of average daily flows.

In order for the results of IHA outputs to be objective, it is necessary to have inputs from sufficiently long series of hydrological observations, which is fulfilled in our case. Examples of hydrogram separation for three stations on the Danube: Achleiten since 1901, Bratislava since 1876 and Reni since 1921 are depicted in Figs. 6. Extreme floods are better seen in the graphs. While floods occur in the Upper Danube region in the same years, the situation in the Lower Danube region is different. The wet period in the Lower Danube region was in the years 1939–1941. On the contrary, an exceptionally dry period in the Danube basin occurred in 1921, while low flows were recorded as early as November and December 1920, which is also evident from Fig. 7, where hydrograms of daily flows from 1920 and 1921 are plotted (graphs on the left) and from the dry years of 1947 and 2003, from selected water gauging stations on the Danube: Bratislava, Orsova (Turnu Severin) and Reni.

The IHA software methodology allows to evaluate selected characteristics of minimum flows (average of extremely low wave flows per year, day of occurrence, average duration of waves, number of waves per year) and subsequently present changes of extremely low flow events of the Danube (Fig. 8a). The trends of the extremely low flow event averages correspond to the trends of the average annual minimum flows. The time of occurrence of droughts and the duration of the drought at Hofkirchen station are interesting. The greatest drought occurred at this station in 1921. After 1970, changes in the date of the occurrence of extreme drought can be seen. The average duration decreased at all selected water gauging stations. At the same time, the number of these events has increased during the year, only at the Reni station it is slightly decreasing. This means that although droughts last for a shorter time, they occur more often a year. This results from the setting of input parameters in the IHA model. The annual averages of extremely low flows have almost

Table 2. Trend line slope coefficient of 1-, 3-, 7-, 30- and 90-day minimum flows at water gauging stations on the Danube River (Danube: Hofkirchen, Danube: Achleiten, Danube: Bratislava, Danube: Orsova, Danube: Reni) and water gauging stations on selected tributaries (Lech: Landsberg, Morava: Moravský sv. Ján, Váh: Liptovský Mikuláš, Tisza: Senta, Sáva: Litija). The negative slope coefficients are underlined.

Danube: Hofkirchen		Lech: Landsberg	
1-day minimum	0.2837	1- day minimum	0.0727
3- day minimum	0.2974	3- day minimum	0.0834
7- day minimum	0.2953	7- day minimum	0.0914
30- day minimum	0.2145	30- day minimum	0.0967
90- day minimum	-0.0027	90- day minimum	0.0980
Danube: Achleiten		**Morava: Moravský sv, Ján**	
1- day minimum	0.975	1- day minimum	0.0217
3- day minimum	1.050	3- day minimum	0.0271
7- day minimum	1.098	7- day minimum	0.0275
30- day minimum	1.062	30- day minimum	-0.0055
90- day minimum	0.765	90- day minimum	-0.0455
Danube: Bratislava		**Váh: Liptovský Mikuláš**	
1- day minimum	0.5138	1- day minimum	0.0108
3- day minimum	0.6531	3- day minimum	0.0095
7- day minimum	0.7763	7- day minimum	0.0080
30- day minimum	0.6962	30- day minimum	0.0031
90- day minimum	0,3950	90- day minimum	-0.0071
Danube: Orsova		**Tisza: Senta**	
1- day minimum	-0.7407	1- day minimum	0.934
3- day minimum	-0.2196	3- day minimum	1.075
7- day minimum	-0.1628	7- day minimum	1.145
30- day minimum	-0.6802	30- day minimum	1.294
90- day minimum	-2.0360	90- day minimum	0.799
Danube: Reni		**Sava: Litija**	
1- day minimum	7.094	1- day minimum	-0.0738
3- day minimum	7.098	3- day minimum	-0.0773
7- day minimum	6.896	7- day minimum	-0.0768
30- day minimum	6.564	30- day minimum	-0.1280
90- day minimum	4.778	90- day minimum	-0.2686

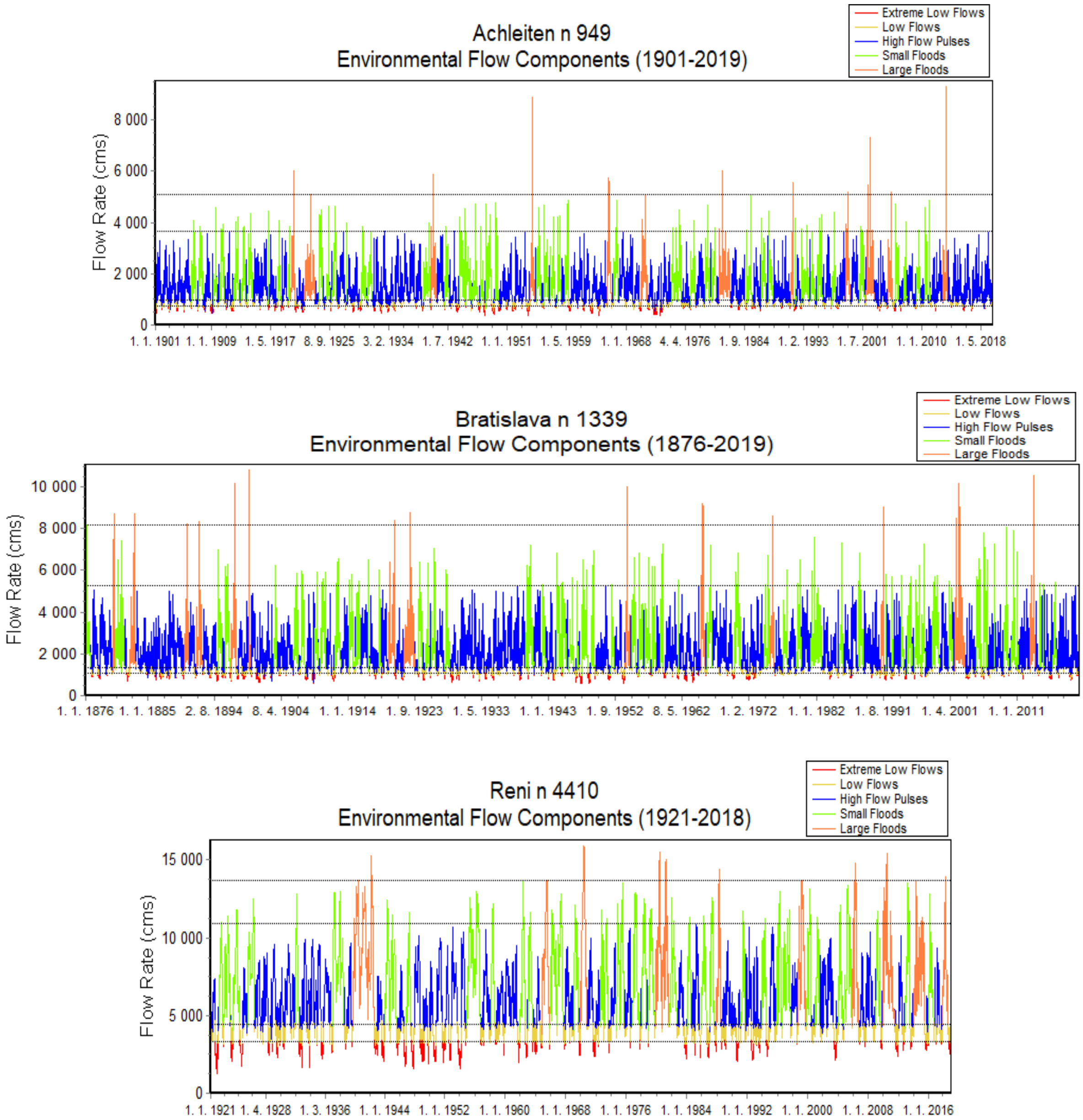


Fig. 6. Separation of daily flows into large floods, small floods, periods of increased flows, low flows and extremely low flow periods in selected water gauging stations on the Danube: Achleiten, Bratislava, Reni. The horizontal lines represent the individual flow limits for the separation of the hydrogram.

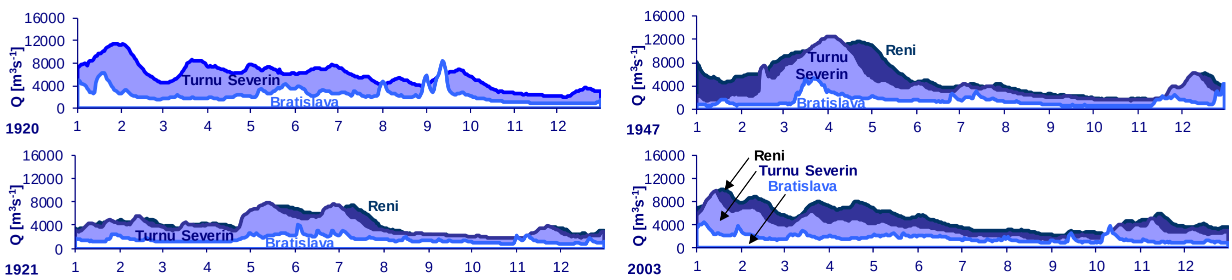
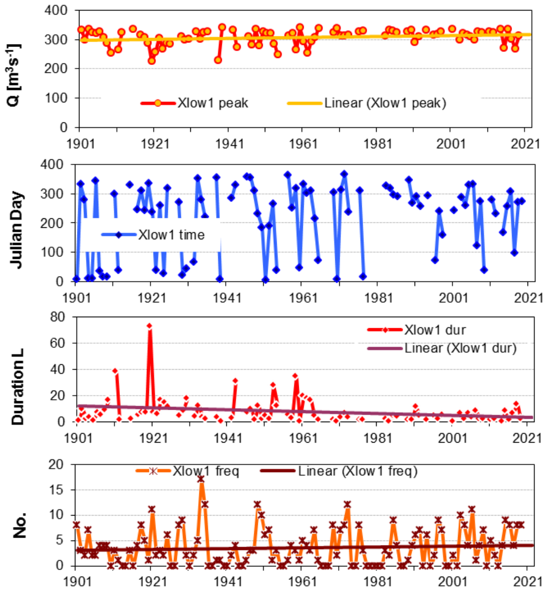
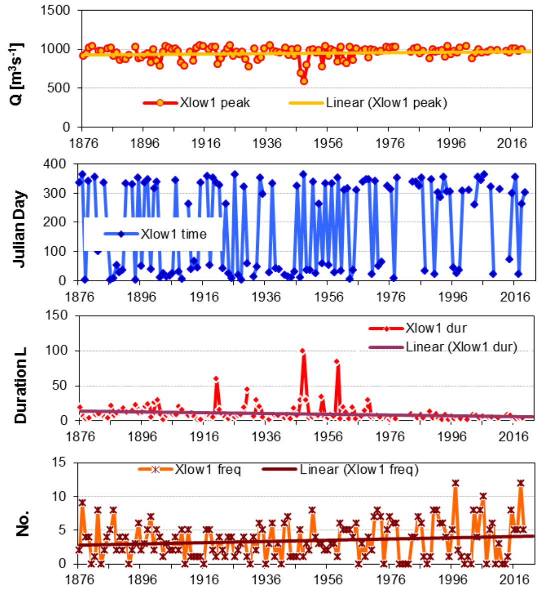


Fig. 7. Hydrograms of daily discharges from 1920 and 1921 (left) and from the dry years 1947 and 2003, from selected water gauging stations on the Danube: Bratislava, Orsova (Turnu Severin) and Reni.

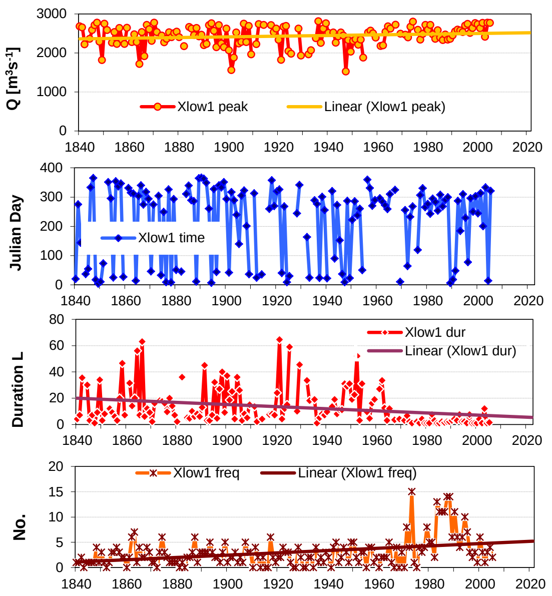
zero, resp. slightly increasing trend. They rise most significantly at the station Danube: Reni.
The same analysis we performed after processing the daily flows of selected tributaries of the Danube River (Lech, Moravia, Váh, Sava). Changes in the extremely low flow events of selected tributaries of the Danube River are shown in Figs. 8b. The annual averages of extremely low flows have almost zero, resp. slightly increasing trend (tributaries Váh and Morava). The average duration decreases in all selected water gauging stations except the Váh station: Liptovský Mikuláš.



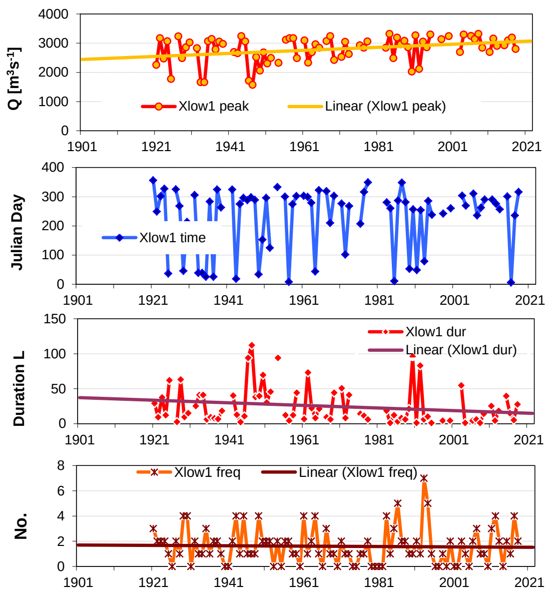
Danube: Hofkirchen



Danube: Bratislava

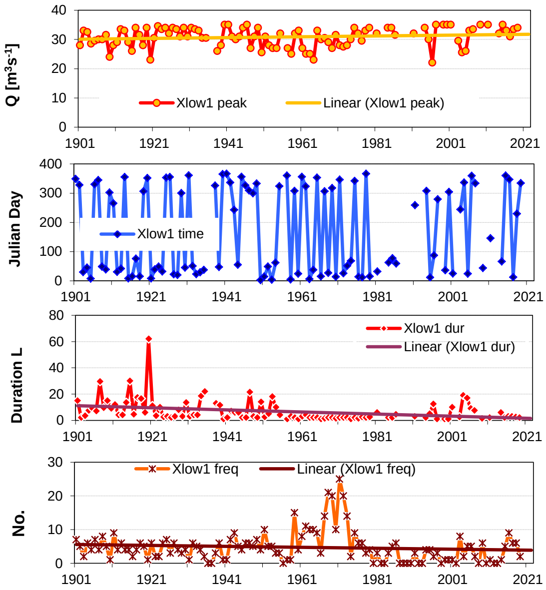


Danube: Orsova

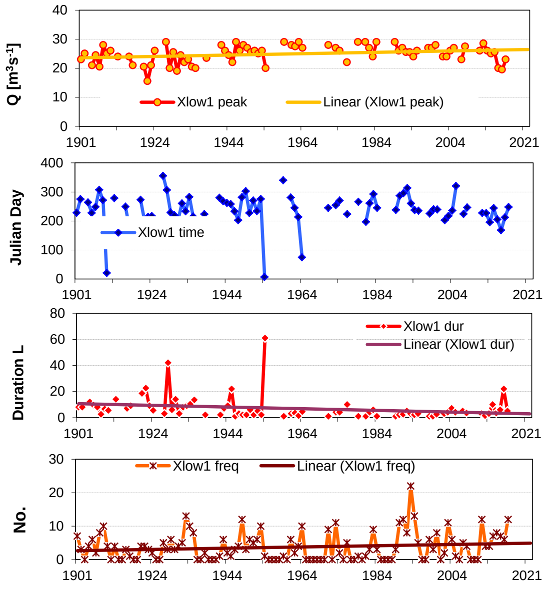


Danube: Reni

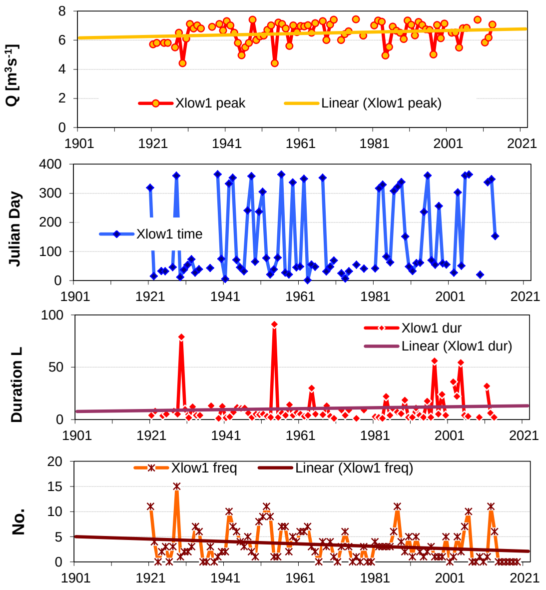
Fig. 8a. Evaluation of selected minimum flows characteristics (average of extremely low wave flows per year, day of occurrence, average duration of waves, number of waves per year). Danube: Hofkirchen, Bratislava, Orsova. and Reni, a linear trend.



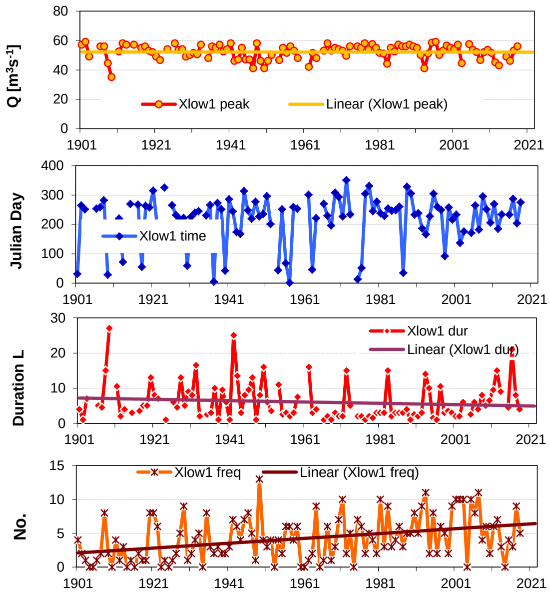
Lech: Landsberg



Morava: Moravský sv. Ján



Váh: Liptovský Mikuláš



Sava: Litija

Fig. 8b. Evaluation of selected minimum flows characteristics (average of extremely low wave flows per year, day of occurrence, average duration of waves, number of waves per year), selected Danube tributaries: Lech, Morava, Váh and Sava, linear trend.

Conclusion

The presented contribution focused on a uniform evaluation of the occurrence of dry periods in terms of minimum flows of selected rivers in the Danube river basin. Water gauging stations in which observations have existed since at least 1921 were selected. The analysis shows that high and low-flow periods alternate along the entire length of the Danube (Fig. 5a). On the Danube, minimal discharges occur in the same periods. In contrast, in the significant tributaries of the Danube Tisza and Sava rivers, droughts occur with a time shift – we could say that when dry years predominate in the Tisza, the Sava period is dominated by periods with higher flows (Fig. 5b). This is also true on a larger scale: in the years when extremely humid years prevailed in the Danube basin, more than 70% of US territory was affected by the longest drought. (Between 1933 and

1940, a known drought occurred in the United States under the name Dust Bowl, Andreadis et al., (2005); Ganguli and Ganguly (2016)).

The most extreme drought in the Hofkirchen water gauging station occurred in 1921. The time of occurrence of the droughts in the Orsova station is interesting. Dry seasons occurred around 1862/63, 1882/83, 1900, 1920/21, 1946/47, 1961/62, 1971, 1991/92 and 2017/19. An extremely dry multi-year period occurred on the Danube at the Orsova station around 1863 and then around 1991. We do not consider these results to be final, further detailed analysis is needed. The results suggest that dry seasons occur more or less regularly. Dry periods occur at both lower and higher air temperatures. However, a higher air temperature increases the evaporation and there is less water in the streams – e.g. in Slovakia, despite higher precipitation, flows have been declining in recent years.

The evaluation of minimum flows and basic low flow characteristics is one of the basic bases for the design, construction and operation of water management facilities and facilities on streams for the purpose of economic management of water resources, therefore it is necessary to pay attention to these issues.

Acknowledgement

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