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Comparison of winter design floods between Austrian and Ukrainian Danube River tributaries

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The consequences of large-scale floods in several regions have drawn attention to prevention and protection of territories from such natural phenomena. Therefore, it is important to determine the expected magnitudes of floods, their differences, as well as to understand the factors controlling the magnitude of snowmelt design floods. This paper compares snowmelt design floods in 24 catchments situated in two regions in Austria (the upper Steyr River Basin) and Ukraine (the upper Rika River Basin). The two regions are similar in terms of catchment sizes and elevation but differ in climate characteristics, because the Ukrainian catchments are influenced by increased continentality. The aim of this paper is thus to compare the magnitude of design floods with 2-, 5-, 10-, 50-, and 100-year return periods occurring during the cold periods of the year (November–April). The objective is to estimate design values of winter floods and to explore factors controlling their differences. The results show that the design floods scaled with catchment area are larger in the upper Rika River Basin (Ukraine) than in upper Steyr River Basin (Austria) for all examined periods. The winters in Ukrainian catchments tend to be warmer and occur earlier. The magnitude of scaled floods in Ukrainian catchments is larger, even the mean annual maximum snow depth (D_{mam}) is approximately 40% lower than in the Austrian catchments. The results of this initial analysis can improve the understanding and hence management of water resources in catchments with similar hydrological characteristics, but slightly different climate characteristics.

KEY WORDS: flood frequency analysis, design floods, winter floods, climate zones

Introduction

Floods are one of the most pressing societal issues catchment hydrology has to face. Flood frequency hydrology is based on the extreme river flow data analysis to obtain the probability distribution of floods (Merz and Blöschl, 2008). The previous flood frequency studies showed that one of the statistical approaches mostly used to model design flood data (Zelenhasic, 1970; Mujere, 2011; Bertola et al., 2020) and often provided the best fit is the Gumbel distribution (Onen and Bagatur, 2017). However, it is still not well understood which factors are causing the differences in design flood magnitude in different regions (Blöschl et al., 2019).

The seasonality assessment of floods in the Alp-Carpathians region (Jeneiova et al., 2016; Parajka et al., 2010) indicates that while summer floods are dominant in the Alps, winter floods occur mainly in the northern upper Danube River tributaries. The timing of winter floods there is very diverse (Jeneiova et al., 2016), which impacts the flood magnitude.

This study presents a comparison the magnitude of design winter floods in two regions (Ukraine and Austria) situated in the Danube River catchment. The increased continentality of Ukrainian catchments is hypothesized to explain the difference in design flood magnitudes in selected study regions.

Material and methods

Study area

This study is carried out for small and medium size Ukrainian and Austrian, unaffected mountainous catchments of the Danube River Basin (Fig. 1). The Austrian part consists of ten catchments (6 small and 4 medium) located in the upper Steyr River basin, which belongs to the Upper Danube River Basin (Table 1). The 14 Ukrainian catchments (12 small and 2 medium) are situated in the upper Rika River basin, which belongs to the Central Danube River Basin (Table 2). The mean catchment elevation for the Austrian catchments is slightly higher (ranging between 951 and 1506 m a.s.l.) than for the Ukrainian catchments (ranging between 747 and 1000 m a.s.l) (Table 1 and 2). The catchment areas in the upper Steyr River range from 18 to 545 km^2, while they range from 3.2 to 550 km^2 in the upper Rika River. The study river basins have different forest cover, from

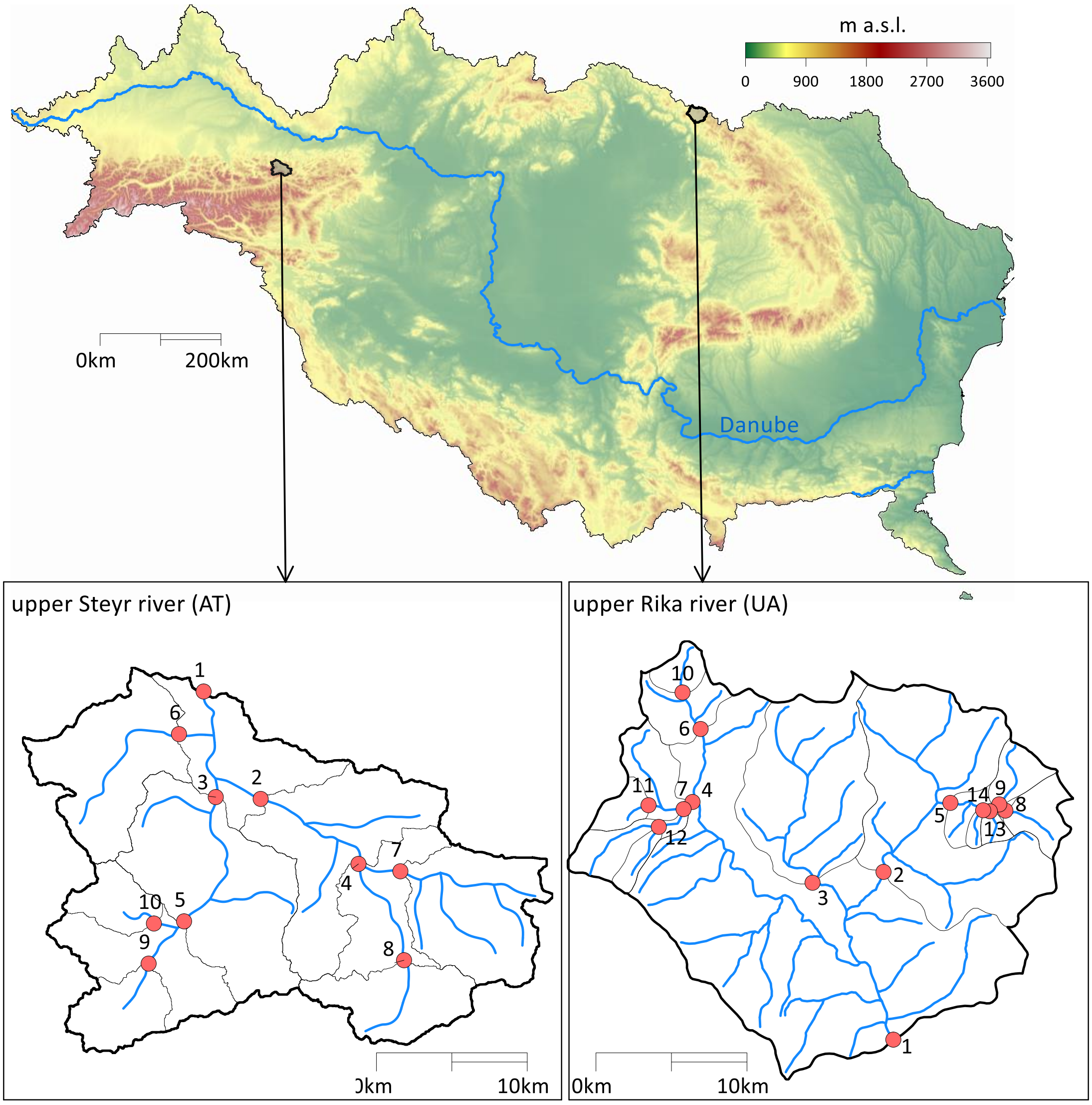

Fig. 1. Study area: location of Austrian (bottom left panel) and Ukrainian (bottom right panel) catchments in the Danube River basin. Labels of symbols refer to ID number in Table 1 (upper Steyr river, Austria) and Table 2 (upper Rika River, Ukraine).

Table 1. Characteristics of the Austrian catchments (area, forest cover) and the corresponding gauging station (mean elevation) and the length of the study period

ID	Gauge	Area [km^2]	Mean elevation [m a.s.l.]	Forest cover [%]	Study period
1	Steyr River – Klaus an der Pyhrnbahn	542	1059	65	1952–2016
2	Teichl River – St. Pankraz	233	1009	63	1976–2016
3	Steyr River – Kniewas	185	1213	58	1952–2016
4	Teichl River – Teichlbrücke	149	1015	61	1952–2016
5	Steyr River – Hinterstoder	82	1358	46	1977–2016
6	Steyrling River – Steyrling	72	951	85	1957–2016
7	Dambach River – Windischgarsten	67	1016	63	1972–2016
8	Teichl River – Spital am Pyhrn	40	1205	71	1967–2016
9	Steyr River – Dietlgut	25	1375	46	1952–2016
10	Krumme Steyr River – Polsterlucke	16	1506	38	1977–2016

Table 2. Characteristics of the Ukrainian catchments (area, forest cover) and the corresponding gauging station (mean elevation) and the length of the study period

ID	Gauge	Area [km^2]	Mean elevation [m a.s.l.]	Forest cover [%]	Study period
1	Rika R. – Mizhhiria v.	550	800	41	1958–2016
2	Rika R. – Verkhnii Bystryi v.	165	920	64	1958–2016
3	Holiatynka R. – Maidan v.	86	790	40	1958–2016
4	Pylypets R. – Pylypets v.	44	854	19	1958–2016
5	Lopushna R. – Lopushne v. (nyzhn.)	37	897	78	1958–2016
6	Studenyi R. – Nyzhnii Studenyi v.	25	800	18	1958–2016
7	Ploshanka S. – Pylypets v. (nyzhn.)	20	983	29	1958–2016
8	Lopushna R. – Lopushne v. (verkhn.)	13	925	93	1960–2016
9	Branyshche S. – Lopushne v.	10	916	72	1958–2016
10	Studenyi R. – Verkhnii Studenyi v.	8	809	20	1959–2016
11	Pylypets R. – Podobovets v.	7.4	747	12	1958–2016
12	Pylypetskyi S. – Pylypets v.	5.7	1000	37	1958–2016
13	Ziubrovets S. – Lopushne v.	3.2	871	91	1958–2016
14	Serednii Zvir S. – Lopushne v.	2.2	984	95	1958–2016

R. – River; S. – Stream; v.–village

38% (Krumme Steyr River – Polsterlucke) to 85% (Steyrling River – Steyrling) in the Austrian basins, and from 12% (Pylypets River – Podobovets village) to 95% (Serednii Zvir Stream – Lopushne village) in the Ukrainian basins (Table 1 and 2).
According to the Köppen-Geiger climate classifications system (Kottek et al., 2006) the entire Ukrainian study area is located in the warm summer continental climatic zone, while most of the analyzed Austrian catchments belong to the temperate oceanic climatic zone. This means that the Ukrainian catchments experience an increased continentality effect, which can translate to the difference in snow accumulation and melt processes and mechanisms of flood generation in the cold period of the year.

Data

The discharge data for this study are obtained from the Hydrographic Service of Austria (https://ehyd.gv.at/) and from the archive of the Central Geophysical Observatory of Ukraine. The analysis is based on mean daily discharges (Q_{mean}). The winter flood maxima (Q_{max}) are selected from the winter half-year (November–April). The length of the series is various. The longest series are in four Austrian gauges: Steyr River – Klaus an der Pyhrnbahn, Steyr River – Kniewas, Teichl River – Teichlbrücke and Steyr River – Dietlgut (1952–2016); while the shortest series are collected in two Austrian catchments: Krumme Steyr River – Polsterlucke and Steyr River – Hinterstoder (1977–2016) (Table 1). The study period for most Ukrainian gauges is 1958–2016 (Table 2).
Snow depth data are obtained from one Austrian and one Ukrainian station, which are located approximately at the same elevation. Daily snow depth data (D) for the Austrian catchments, for the period 1970–2016, is obtained from a station at Spital am Pyhrn located at 630 m a.s.l. Five daily snow depth data for the Ukrainian catchments, for the period 1935–2016, is obtained from a station at Nyzhnii Studenyi located at 629 m a.s.l. (from 1952 located at 615 m a.s.l.).

Methods

The basic assumptions for the application of the flood frequency analysis are the following:

- the observations are identically distributed, statistically independent and random,
- the annual maximum daily discharges (Q_{max}) measurements are stationary with respect to time (data series homogeneity). This requires that the river has not been regulated within the duration of the time series, i.e. not affected by human modifications such as reservoir, urbanization, etc.,
- observed daily discharge data are available for more than 10 years with good quality. Only such data are deemed sufficient for the estimation of design flood values associated to low return periods.

Hydro-genetic analysis

The assessment of the homogeneity and stationarity of winter floods is based on hydro-genetic analysis proposed by Gorbachova (2014). The method uses the mass curve, the residual mass curve and the combined graph to identify long-term fluctuations and cycles of winter floods. Homogeneity is defined as the absence of unidirectional changes of the flood time series against the backdrop of their variability due to long-term cyclical fluctuations (Gorbachova et al., 2018). The stationarity of winter floods time series is characterized by the persistence of average floods over time if the time series have at least one full closed cycle (dry and wet phase) of long-period fluctuations. More details about assumptions and applications of the methodology are presented in Gorbachova (2016) and Zabolotnia et al. (2019).

Flood frequency analysis

In order to estimate the design floods with 2, 5, 10, 20 and 100 year return periods, a direct, at site frequency analysis is chosen. First, a sample of annual daily flood maxima is compiled for each gauge. For each year, the maximum daily discharge value in winter period (November–April) is selected. Second, the plotting positions, i.e. the empirical return periods T_s are estimated according to (1)

$$T_s = \frac{1}{1 - F_s} \quad (1)$$

where
F_s – is the return probability or cumulative frequency, which can be calculated according to (2)

$$F_s = \frac{k}{1 + N} \quad (2)$$

where
k – rank of each flood peak, ranging between 1 and N,
N – total number of observed peaks.

Third, a distribution function is fitted to the data. In this study, the Gumbel distribution is chosen (Gumbel, 1954). The cumulative distribution function F(x) of the Gumbel distribution is as follows (3)

$$F(x) = \exp\left[-\exp\left(-\frac{x-c}{d}\right)\right] \quad (3)$$

where
x – random variable, in this case daily flood maximum,
c, d – parameters of the distribution, which are estimated from the flood data.

As a final step, the design flood with a specific return period x_T is calculated, according to (4)

$$x_T = \mathrm{c} - \mathrm{d} \cdot \ln\left[-\ln\left(1 - \frac{1}{T}\right)\right] \quad (4)$$

where
T – return period (in years) and the parameters can be estimated based on the method of moments according to (5)

$$d = \frac{\sqrt{6}}{\pi} \cdot \sigma \quad \text{and} \quad c = \mu - 0.5772 \cdot d \quad (5)$$

where
μ – mean,
σ – standard deviation,
0.5772 – Euler-Mascheroni constant.

The calculations are performed in R (R Core Team, 2016) that is an open-source programming language and software environment for statistical computing (linear and nonlinear modelling, classical statistical tests, time-series analysis, classification, clustering, etc.) and graphics. It includes an effective data handling and storage facility, a suite of operators for calculations on arrays, in particular matrices, a large, coherent, integrated collection of intermediate tools for data analysis and others.

Seasonality of winter floods

The mean seasonality and the variability of the winter floods is assessed for the two largest catchments, i.e. Steyr River – Klaus an der Pyhrnbahn and Rika River – Mizhhiria village, using the Burn index (Burn, 1997; Parajka et al., 2009). First the day of the year is calculated for each peak. Then the day of the year values are transformed into angles, i.e. each peak is treated as a unitary vector in the direction of the calculated angle; and the average of the vectors is calculated in order to obtain the mean seasonality. The variability of the seasonality is expressed as the length of the mean seasonality vector, which can range between zero (uniform distribution) and one (all extremes occur on the same day).

Results and discussion

Hydro-genetic analysis

The assessment of the homogeneity and stationarity of the winter floods in the upper Rika River basin and its tributaries according to Gorbachova's methodology shows that the series of observations for all 14 study gauges are homogeneous and stationary (Bauzha and Gorbachova, 2013; Gorbachova et al., 2018; Zabolotnia et al., 2019; 2021).
The mass curves of the winter and spring floods in the upper Steyr river basin are not characterized by "jumping", "emissions" or unidirectional deviation and do not break the general trend of the curve, which indicates that the climatic conditions and flood generation processes in the study area are homogeneous (Fig. 2). Therefore, the series of observations in the Austrian catchments are also homogeneous and stationary in accordance with the hydrological genetic (graphical) methods. Fig. 2 shows only 3 out of 10 gauges, as the other 7 have similar trends in discharge fluctuations.

Flood frequency analysis

The estimated flood design values (Q_T) and observed minimum (Q_{min}) and maximum (Q_{max}) winter floods for Austrian and Ukrainian catchments are presented in Tables 3 and 4. The flood frequency analysis shows that the largest flood (with maximum instantaneous flow of 246 $m^3 s^{-1}$) in the upper Steyr River is the event of 1962, which corresponds to an empirical return period of 66 years, while the lowest flood flow of 2.7 $m^3 s^{-1}$ was recorded in 1953. For the upper Rika River the maximum flow of 471 $m^3 s^{-1}$ was observed in 1958, which has an empirical return period of 60 years, while the lowest flood flow of 55.1 $m^3 s^{-1}$ was observed in 2015.
The estimated flood frequency curves for Austrian and Ukrainian catchments are presented in Fig. 3. The shapes of the curves look very similar.

The estimated design floods with 2yrs, 5yrs, 10yrs, 50yrs and 100yrs return periods are listed in Table 3 for Austria, and in Table 4 for Ukraine. The results show that the estimated design floods with 100-yr return period scaled with the catchment area are larger for the Ukrainian catchments compared to Austrian catchments (Fig. 4). The results are similar for the other return periods as well. One outlier Austrian catchment is Polsterlucke on the Krumme Steyr River (ID 10), where the logarithm of the 100-yr return period specific discharge is 0.05 $m^3 s^{-1} km^{-2}$, which is the smallest as well as highest catchment among the Austrian catchments.

The comparative assessment of selected physiographic characteristics shows that topography or vegetation do not differ significantly between the selected regions. The proportion of catchment area covered by forest shows a large variety between catchments (Table 1 and 2), and therefore does not explain the difference between Austrian and Ukrainian catchments. The mean catchment elevation is slightly higher for Austrian than Ukrainian catchments (Table 1 and 2), but the difference is not large. More noticeable difference is expressed by the increased continentality of Ukrainian catchments. Fig. 5 compares the seasonality of winter floods.

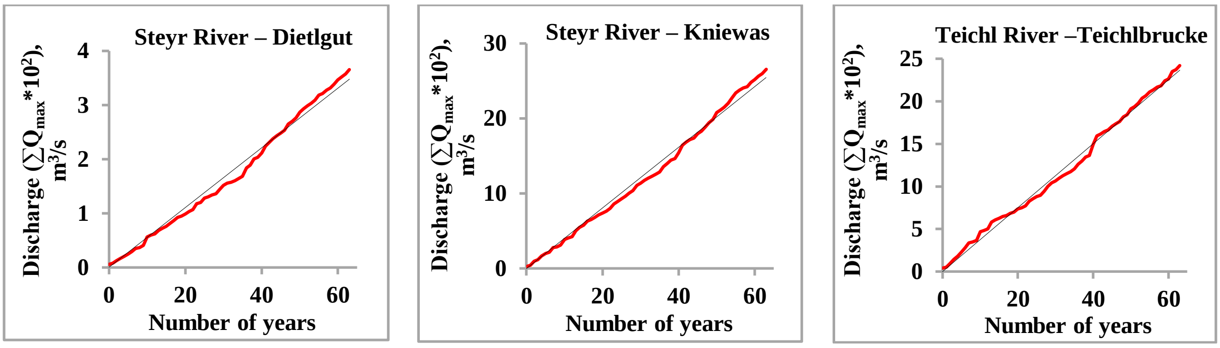

Fig. 2. Mass curves of the winter floods in the upper Steyr river basin.

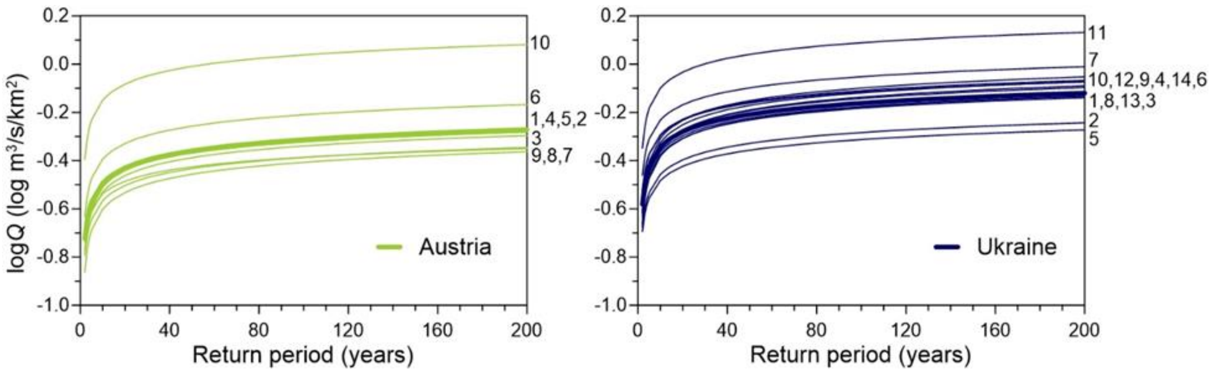

Fig. 3. Flood frequency curves of the Austrian (left) and Ukrainian (right) catchments (catchment IDs listed on the right sides of the plots correspond to the IDs listed in Table 1 and 2; bold lines show the largest Austrian and Ukrainian catchments).

Table 3. Estimated design floods with 2, 5, 10, 50 and 100 years return periods [$m^3 s^{-1}$], largest (Q_{max}, $m^3 s^{-1}$) and lowest (Q_{min}, $m^3 s^{-1}$) observed winter flood discharges for all Austrian study catchments

Gauge / $Q_{T\text{-}year}$	Q_2	Q_5	Q_{10}	Q_{50}	Q_{100}	Q_{min} [year]	Q_{max} [year]
Steyr River – Klaus an der Pyhrnbahn	102.3	145.5	174.1	237.1	263.7	42.7 (1953)	246.0(1962)
Teichl River – St. Pankraz	44.4	62.1	73.8	99.6	110.5	19.6 (1991)	109.0(1993)
Steyr River – Kniewas	30.6	45.1	54.7	75.7	84.7	10.1 (1960)	80 (1965)
Teichl River – Teichlbrücke	25.2	37.7	46.0	64.3	72.0	10.8 (1969)	74.0 (1965)
Steyr River – Hinterstoder	15.1	21.5	25.8	35.1	39.0	6.1 (1984)	41.9 (1993)
Steyrling River – Steyrling	16.8	24.2	29.1	39.8	44.4	5.6 (1963)	45.4 (1965)
Dambach River – Windischgarsten	9.2	13.7	16.8	23.4	26.2	3.8(1991)	27.0 (1993)
Teichl River – Spital am Pyhrn	7.7	10.1	11.6	15.0	16.4	4.2(1991)	18.2 (1993)
Steyr River – Dietlgut	4.0	5.7	6.8	9.2	10.3	1.6 (1984)	10.7 (1975)
Krumme Steyr River – Polsterlucke	6.4	9.4	11.3	15.7	17.5	2.2 (1984)	15.7 (1993)

Table 4. Estimated design floods with 2, 5, 10, 50 and 100 years return periods [$m^3 s^{-1}$], largest (Q_{max}, $m^3 s^{-1}$) and lowest (Q_{min}, $m^3 s^{-1}$) observed winter flood discharges for all Ukrainian study catchments

Gauge / $Q_{T\text{-}year}$	Q_2	Q_5	Q_{10}	Q_{50}	Q_{100}	Q_{min}[year]	Q_{max}[year]
Rika River – Mizhhiria village	144.4	207.2	248.7	340.2	378.9	55.1 (2015)	471.0 (1958)
Rika River –Verkhnii Bystryi village	34.7	48.4	57.5	77.4	85.9	9.5 (2015)	93.8 (1999)
Holiatynka River – Maidan village	20.0	29.8	36.2	50.5	56.5	7.58 (2015)	74.1 (1958)
Pylypets River – Pylypets village	13.2	18.8	22.4	30.5	33.9	3.86 (2003)	27.3 (1973)
Lopushna River – Lopushne village (nyzhn.)	7.5	10.4	12.3	16.4	18.2	2.9 (2003)	25.6 (1958)
Studenyi River – Nyzhnii Studenyi village	6.1	9.4	11.5	16.3	18.3	2.4 (2015)	26.0 (1999)
Ploshanka Stream – Pylypets village (nyzhn.)	6.9	9.8	11.7	15.9	17.6	1.00 (2015)	14.4 (1985)
Lopushna River – Lopushne village (verkhn.)	2.8	4.4	5.5	7.8	8.8	1.2 (1960)	11.0 (1999)
Branyshche Stream – Lopushne village	2.5	3.9	4.9	6.9	7.8	0.6 (2015)	11.2 (1958)
Studenyi River – Verkhnii Studenyi village	2.0	3.2	3.9	5.6	6.4	1.0 (1973)	8.0 (1999)
Pylypets River – Podobovets village	3.3	4.9	5.9	8.2	9.1	0.76 (2015)	7.6 (1986)
Pylypetskyi Stream – Pylypets village	1.7	2.4	2.9	4.0	4.4	0.42 (2015)	5.1 (1985)
Ziubrovets Stream – Lopushne village	0.8	1.1	1.4	1.9	2.1	0.2 (2003)	2.9 (1958)
Serednii Zvir Stream – Lopushne village	0.5	0.8	1.0	1.4	1.6	0.1 (2003)	2.4 (1999)

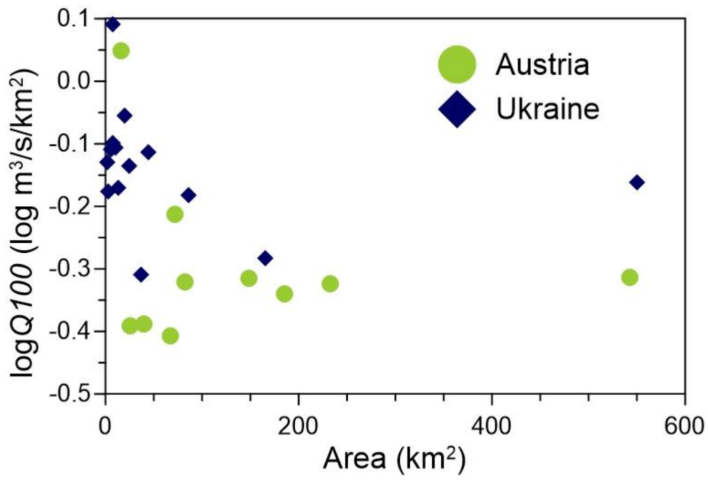

Fig. 4. Logarithm of 100-year floods scaled with catchments area as a function of catchment area) in the upper Steyr River (Austria, green points) and upper Rika (Ukraine, blue points) basins.

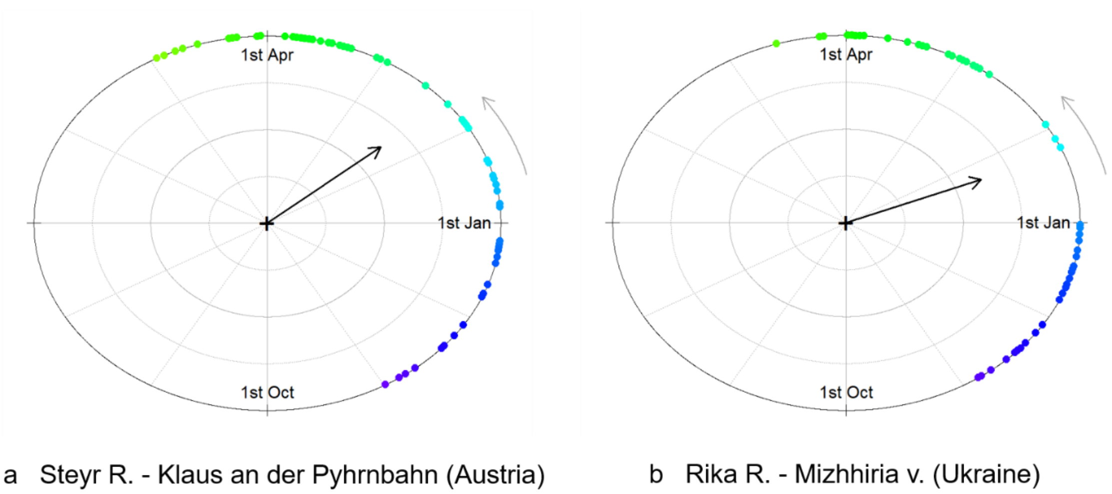

Fig. 5. Mean seasonality of the outlet of the Austrian catchments, Steyr River – Klaus an der Pyhrnbahn (a) and of the outlet of the Ukrainian catchments, Rika River – Mizhhiria village (b).

As it is evident from Fig. 5, the floods in upper Rika catchment tend to occur earlier. The comparative assessment of observed snow depth at climate stations shows that the average annual maximum snow depth (D_{aam}) is 38 cm at the Ukrainian station, and 68 cm at the Austrian station. The approximately 40% smaller average annual maximum snow depth (D_{aam}) again proves the increased effect of continental climate on the Ukrainian study catchments.

Conclusion

In this study we explore the impact of increased continentality on the magnitude of snowmelt design floods in hydrologically homogeneous Ukrainian and Austrian basins of Danube River regions. The study catchments are similar in terms of catchments size and elevation, but slightly differ climate characteristics, i.e. the Ukrainian catchments experience the effect of larger continentality. The main results of the present study can be summarized in the following points:

- Winter floods with 2 yrs, 5 yrs, 10 yrs, 50 yrs and 100 yrs return periods are estimated for all the study catchments, which may be useful for various management purposes (for designing bridges and dams, floodplain management, barrages etc.).
- It is found that the design floods scaled with the catchment areas are larger in the upper Rika River Basin in Ukraine than in the upper Steyr River Basin in Austria.
- We explain the found difference by the effect of increased continentality in the Ukrainian catchments.
- The mean seasonality of winter floods in Ukrainian catchments tend to occur 2–3 weeks earlier compared to the Austrian catchments.

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