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Fluctuations of Winter Floods in Small Austrian and Ukrainian Catchments

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Abstract: Studying the changes in extreme river runoff induced by climate change is of utmost importance, as the variability of floods directly affects life and human activities. This study examines the fluctuations and persistence of winter floods in 14 catchments in the Rika River Basin (Ukraine) and ten catchments in the Steyr River Basin (Austria). The catchments represent typical hydrological regimes in the Danube River region. The fluctuations and persistence of floods are analyzed by the hydro-genetic method and a seasonality analysis for the period 1951–2015. The results show a much more pronounced fluctuation pattern in the upper Rika catchments than in the upper Steyr catchments. This pattern indicates an increase in winter flood magnitudes between the mid-1960s and the 1990s, followed by a decrease until recently. The flood seasonality shows a large inter-annual variability in both regions. The most significant winter floods tend to occur in November and December. The winter flood fluctuations are compared with changes in associated climate characteristics, i.e., seven-day maximum precipitation, a melt index, and annual maximum snow depth. The seasonality of these characteristics has a strong inter-annual variability and only partly explains the winter flood fluctuations.

Keywords: winter floods; small mountain catchment; fluctuations; seasonality

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1. Introduction

With recent climate changes, many regions are observing modifications and fluctuations in extreme hydrological events, such as floods. Recent studies attribute the differences in seasonality and magnitude of floods to changes in autumn and winter precipitation, decreasing evaporation or snow cover, and snowmelt [1,2]. Due to recent climatic warming, changes in the timing of snow accumulation and melt are observed mainly in northeastern and eastern Europe and in mountain regions [3]. Recent analyses in Eastern Europe [4,5] indicate a simultaneous increase in number of winter floods as a result of thawing and a general increase in winter flow volumes. The changes in snow cover are known also to affect the hydrological regime and hence floods, but how this effect varies between regions is still not well understood.

The Danube River Basin is Europe's second-largest river basin and the world's most international river basin. Floods have repeatedly caused significant damage to the population and economy within this region [6–8]. Therefore, understanding the factors that control timing, magnitude, and changes of floods is essential for design, water resources, and flood risk management. In the Ukrainian part of the Danube, the Carpathians mountains are one of the most sensitive regions in terms of flood formation and flood risk. The most significant floods frequently occur in spring and are generated by snowmelt and rain-on-snow events [9–11]. These floods are hazardous in a wet phase of a global atmospheric circulation pattern [12–15]. In the Austrian part of the Danube basin, snowmelt and rain-on-snow floods are one of the main flood types and flood generation processes, particularly in alpine and pre-alpine regions [16,17]. Methods of comparative hydrology and examining the winter floods from the different areas can help to improve the understanding of how and why the winter floods fluctuate in time and space and how these changes are associated with the flood seasonality and changes in snow cover.

The main objective of this study is to compare and evaluate fluctuations of winter floods in two distinct physiographic regions situated within the Danube River basin. The aim is to examine the long-term fluctuations and seasonality of winter floods in selected small catchments and to investigate the factors that control these changes. The term 'winter flood' used in this study refers to floods occurring in the cold season of the year (i.e., November to April). The analysis is based on the combination of hydro-genetic [18], and seasonality [19] approaches. While the hydro-genetic method has been tested and applied to evaluate river flow fluctuations in Ukrainian catchments [11,20–28] and others, the seasonality assessment as an indicator of changes in flood generation mechanisms has been examined in the alpine catchments [29,30]. A combination of both approaches and a comparative hydrology approach [17,31] will allow us to learn from the differences in the two selected regions and improve the understanding of winter floods fluctuations. Overall, this research aims at comprehensively understanding the historical trends of the maximum winter runoff for two study regions in the last six decades, and is important for water management and planning.

2. Data

2.1. Study Area

This study region consists of two groups of catchments situated in the Ukrainian and Austrian parts of the Danube River Basin (Figure 1). The distance between the groups is about 700 km.

Table 1. Characteristics of the catchments and geographical coordinates of the catchment outlets in the upper Rika River Basin (Ukraine).

ID	Catchment	Area (km^2)	Latitude	Longitude	Mean Elevation (m a.s.l.)
UA 1	Rika River—Mizhhiria village	550	48°32′20″	23°29′47″	800
UA 2	Rika River—Verkhnii Bystryi village	165	48°37′36″	23°30′50″	920
UA 3	Holiatynka River—Maidan village	86	48°36′54″	23°27′17″	790
UA 4	Pylypets River—Pylypets village	44	48°40′15″	23°20′29″	854
UA 5	Lopushna River—Lopushne village (nyzhn.)	37	48°39′13″	23°34′46″	897
UA 6	Studenyi River—Nyzhnii Studenyi village	25	48°42′38″	23°22′06″	800
UA 7	Ploshanka Stream—Pylypets village (nyzhn.)	20	48°40′14″	23°20′27″	983
UA 8	Lopushna River—Lopushne village (verkhn.)	13	48°38′41″	23°37′39″	925
UA 9	Branyshche Stream—Lopushne village	10	48°38′56″	23°37′22″	916
UA 10	Studenyi River—Verkhnii Studenyi village	8.0	48°45′03″	23°21′22″	809
UA 11	Pylypets River—Podobovets village	7.4	48°40′32″	23°18′36″	747
UA 12	Pylypetskyi Stream—Pylypets village	5.7	48°39′43″	23°19′00″	1000
UA 13	Ziubrovets Stream—Lopushne village	3.2	48°38′44″	23°36′49″	871
UA 14	Serednii Zvir Stream—Lopushne village	2.2	48°38′48″	23°36′28″	984

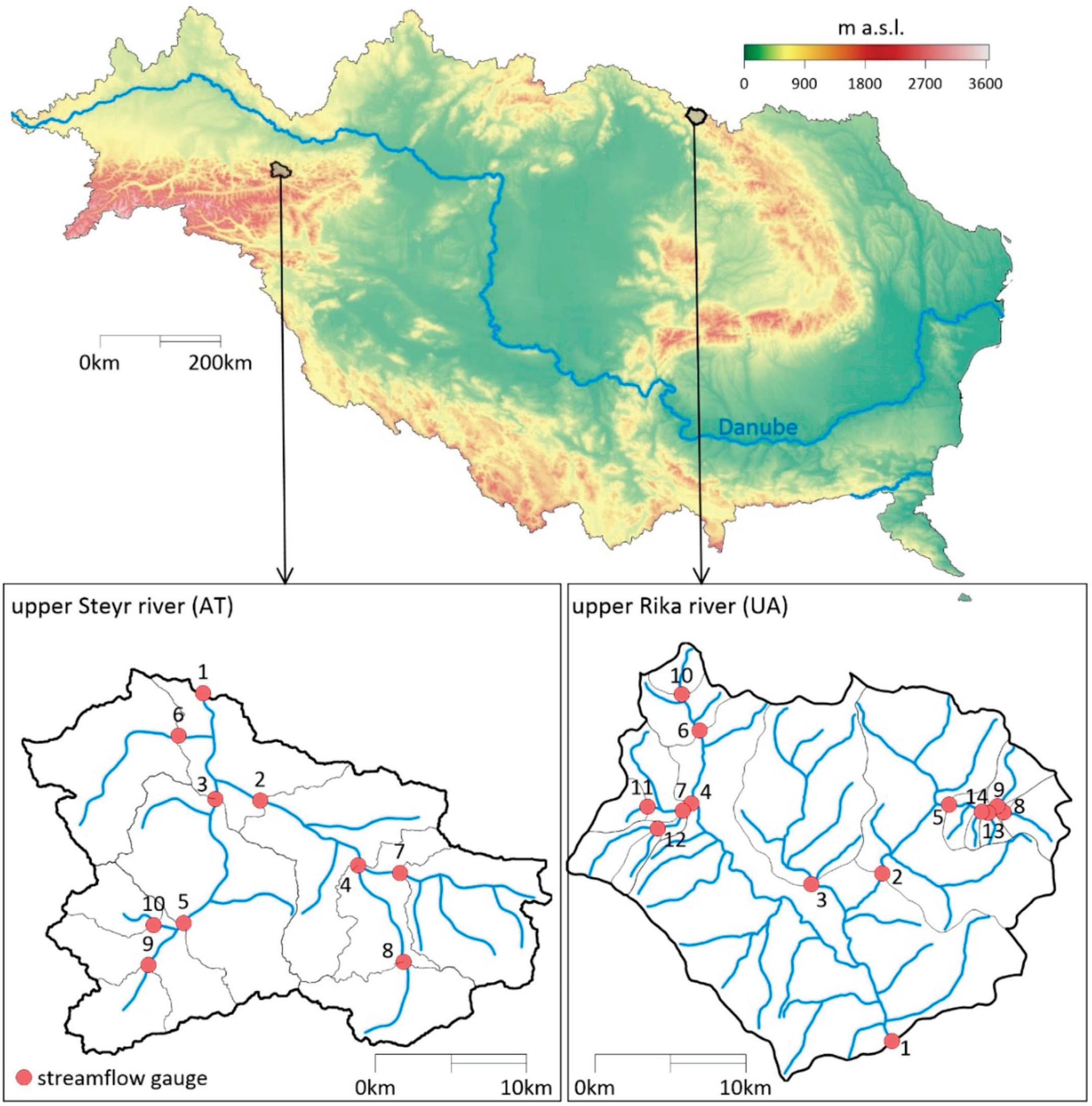


Figure 1. Location of the study catchments in the Danube River basin. The Austrian part consists of 10 catchments located in the upper Steyr basin (**bottom left** panel). The 14 Ukranian catchments are situated in the Rika River basin (**bottom right** panel). Labels of symbols refer to ID number in Table 1 (upper Rika River) and Table 2 (upper Steyr river).

Table 2. Characteristics of catchments and geographical coordinates of the catchment outlets in the Steyr River basin (Austria).

ID	Catchment	Area (km^2)	Latitude	Longitude	Mean Elevation (m a.s.l.)
AT 1	Steyr River—Klaus an der Pyhrnbahn	545	47°49′51″	14°09′37″	1059
AT 2	Teichl River—St. Pankraz	231	47°45′59″	14°12′35″	1009
AT 3	Steyr River—Kniewas	190	47°46′04″	14°10′12″	1213
AT 4	Teichl River—Teichlbrücke	147	47°43′37″	14°17′44″	1015
AT 5	Steyr River—Hinterstoder	86	47°41′38″	14°08′27″	1358
AT 6	Steyrling River—Steyrling	72	47°48′20″	14°08′17″	951
AT 7	Dambach River—Windischgarsten	66	47°43′20″	14°19′57″	1016
AT 8	Teichl River—Spital am Pyhrn	39	47°40′09″	14°20′05″	1205
AT 9	Steyr River—Dietlgut	26	47°40′08″	14°06′33″	1375
AT 10	Krumme Steyr River—Polsterlucke	18	47°41′34″	14°06′51″	1506

In Ukraine, 14 catchments within the upper Rika River Basin (the right tributary of the Tysa River) are evaluated (Table 1). Most of the catchments are small—11 out of 14 are less than 50 km^2. The largest catchment is the outlet of the upper Rika River at the gauge Mizhhiria, with a catchment size of around 550 km^2. This region is situated on the southwest slopes of the East Carpathians. The mean catchment elevation ranges between 747 and 1000 m above sea level [32]. This area is characterized by significant variability of the physiographic characteristics, and hence, different conditions of the runoff generation. The mean forest coverage in the Upper Rika catchment is 41% and varies between 12–95% in the analysed sub-catchments [33]. The mean annual precipitation is between 800 and 1250 mm and mean annual air temperature varies in range 3–7 °C. The mountain rivers of the Carpathians are characterized by an unstable thermal regime and frequent transitions from negative to positive air temperatures during winter, which leads to numerous snow melt events. During these events, the runoff generation is often with a mixture of snow melt and rain-on-snow events. In such a case, floods with very high runoff peaks tend to occur. More detailed characteristics of this part of the study region are presented in [20].

The Austrian part of the study region consists of 10 catchments situated in the Steyr River Basin (Figure 1, Table 2). River Steyr is a southwestern tributary of the River Enns in Upper Austria, and it is situated in the southern foothills of the Totes Gebirge Mountains. The size of the upper Steyr River basin is 545 km^2 [34]. The analyzed catchments are slightly larger, but six out of ten are less than 100 km^2. The mean catchment elevation is slightly higher than for the Ukrainian catchments, and it varies between 951 and 1506 m a.s.l. The mean forest cover is between 38% and 85% [33]. The mean annual precipitation in the Steyr River basin ranges between 1400 and 2000 mm, and mean annual air temperature varies between 2 and 8 °C.

All analyzed catchments represent a natural regime and are not affected by a significant human impact in terms of winter flood seasonality or flood magnitude. The flood data in Austria has been quality checked within the recent national flood risk zoning project (https://www.hora.gv.at, accessed on 2 February 2022) and existing small ski resorts do not have any impact on the occurrence or magnitude of flood peaks.

2.2. Hydrological and Meteorological Data

The date and magnitude of winter floods are obtained from daily runoff observations carried out by the Central Geophysical Observatory named after Boris Sreznevsky in Ukraine and the Hydrographic Service of Austria. The winter flood maxima represent the mean daily maximum discharge in the winter half-year (November–April) from 1951–2015. The length of flood records slightly differs between the catchments. Table 3 shows the length of flood time series used in this study and the range (i.e., minimum and maximum) of observed winter floods and maximum annual discharges. Table 3 and Figure 2 also compares the magnitude of maximum winter floods to annual maximum floods. This comparisons shows that in both regions, most of the winter floods correspond to annual maximum, particularly in the upper Rika catchment.

Table 3. The length of flood records, coefficient of variation Cv (November–April) and the largest and smallest winter (November–April) and annual (November–October) flood discharges.

ID	The Name of Gauge	$Q_{\text{max. cold period}}$, m^3/s		$Q_{\text{max. annual}}$, m^3/s		C_v	Period
		Max	Min	max	min		
UA 1	Rika R.—Mizhhiria v.	471 (12/1957)	55.1 (03/2015)	471 (12/1957)	55.1 (03/2015)	0.46	1957–2015
UA 2	Rika R.—Verkhnii Bystryi v.	93.8 (11/1998)	9.53 (03/2015)	93.8 (11/1998)	13.0 (05/2015)	0.42	1957–2015
UA 3	Holiatynka R.—Maidan v.	74.1 (12/1957)	7.58 (03/2015)	74.1 (12/1957)	7.58 (03/2015)	0.51	1957–2015
UA 4	Pylypets R.—Pylypets v.	27.3 (11/1972)	3.86 (04/2003)	32.8 (09/1968)	4.73 (01/2015)	0.44	1957–2015
UA 5	Studenyi R.—Nyzhnii Studenyi v.	26.0 (11/1998)	2.39 (03/2015)	26.0 (11/1998)	3.48 (07/1961)	0.55	1957–2015
UA 6	Lopushna R.—Lopushne (nyzhn.) v.	25.6 (12/1957)	2.89 (03/2003)	25.6 (12/1957)	3.44 (05/2015)	0.47	1957–2015
UA 7	Ploshanka S.—Pylypets (nyzhn.) v.	14.4 (01/1985)	1.00 (03/2015)	14.4 (01/1985)	1.22 (05/2015)	0.44	1957–2015
UA 8	Pylypets R.—Podobovets v.	7.60 (12/1985)	0.76 (03/2015)	8.72 (10/1992)	0.76 (03/2015)	0.49	1957–2015
UA 9	Branyshche S.—Lopushne v.	11.2 (12/1957)	0.57 (01/2015)	11.2 (12/1957)	0.91 (05/2015)	0.67	1957–2015
UA 10	Pylypetskyi S.—Pylypets v.	5.14 (01/1985)	0.42 (03/2015)	5.14 (01/1985)	0.78 (10/2015)	0.46	1957–2015
UA 11	Ziubrovets S.—Lopushne v.	2.89 (12/1957)	0.22 (04/2003)	2.89 (12/1957)	0.25 (10/2003)	0.53	1957–2015
UA 12	Serednii Zvir S.—Lopushne v.	2.40 (11/1998)	0.14 (04/2003)	2.40 (11/1998)	0.23 (06/2015)	0.68	1957–2015
UA 13	Studenyi R.—Verkhnii Studenyi v.	7.99 (11/1998)	0.97 (11/1972)	7.99 (11/1998)	0.99 (07/1961)	0.60	1958–2015
UA 14	Lopushna R.—Lopushne (verkhn.) v.	11.0 (11/1998)	1.16 (03/1960)	11.0 (11/1998)	1.16 (03/1960)	0.57	1959–2015
AT 1	Steyr River—Klaus an der Pyhrnbahn	246 (12/1961)	42.7 (11/1952)	393 (08/1959)	74.5 (01/1986)	0.44	1951–2015
AT 2	Teichl River—Teichlbrücke	74.0 (11/1964)	10.8 (04/1969)	110 (06/2013)	15.5 (04/1986)	0.52	1951–2015
AT 3	Steyr River—Kniewas	80.0 (11/1964)	10.1 (02/1960)	109 (08/2006)	28.1 (05/1986)	0.49	1951–2015
AT 4	Steyr River—Dietlgut	10.7 (12/1974)	1.56 (04/1984)	24.2 (07/1977)	3.72 (06/2003)	0.44	1951–2015
AT 5	Steyrling River—Steyrling	45.4 (11/1964)	5.65 (03/1963)	87.0 (08/1959)	10.3 (07/1990)	0.46	1956–2015
AT 6	Teichl River—Spital am Pyhrn	18.2 (11/1992)	4.20 (03/1991)	26.3 (08/1991)	6.39 (10/2003)	0.33	1966–2015
AT 7	Dambach River—Windischgarsten	27.0 (11/1993)	3.80 (03/1991)	42.7 (08/2002)	5.96 (12/2002)	0.52	1971–2015
AT 8	Teichl River—St. Pankraz	109 (11/1992)	19.6 (03/1991)	197 (06/2013)	33.7 (05/1986)	0.42	1976–2015
AT 9	Steyr River—Hinterstoder	41.9 (11/1992)	6.07 (04/1984)	65.6 (08/2002)	19.0 (09/2003)	0.45	1976–2015
AT 10	Krumme Steyr River—Polsterlucke	15.7 (11/1992)	2.15 (11/1983)	27.0 (07/1997)	10.5 (05/1994)	0.48	1976–2015

R.—River; S.—Stream; v.–village.

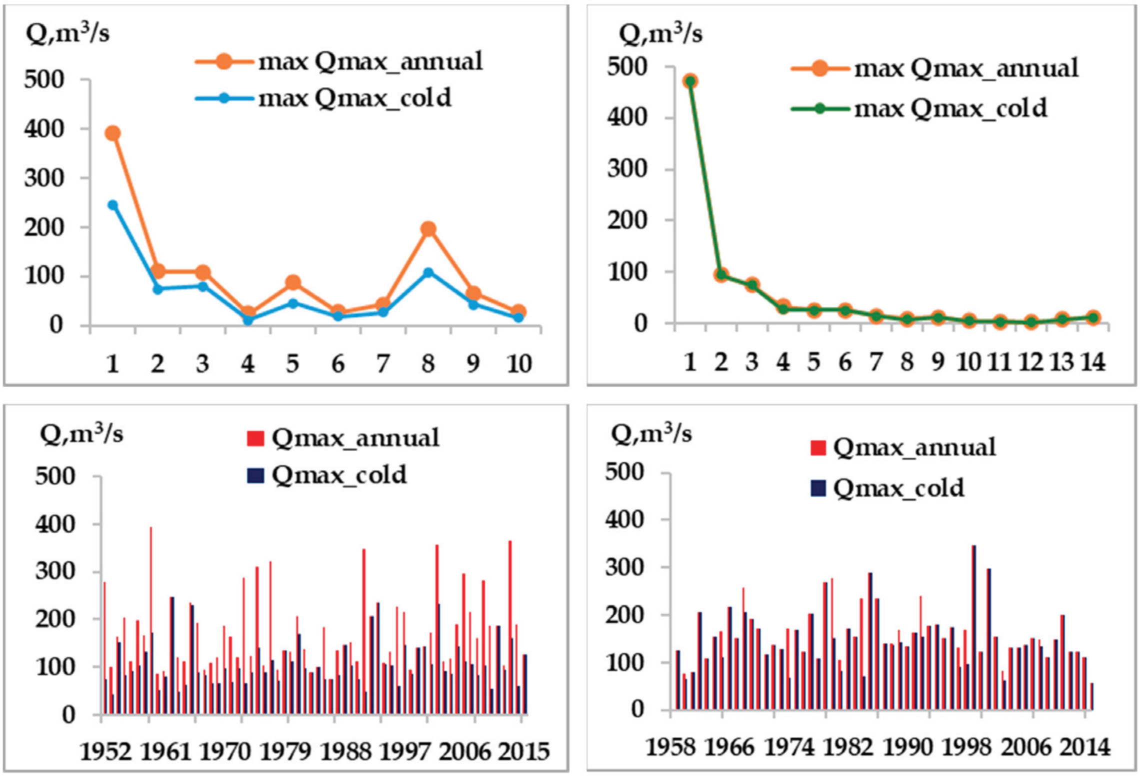


Figure 2. Comparison of the long-term maximum winter and annual floods in the upper Steyr (**top left**) and the upper Rika (**top right**) catchments. Labels of symbols refer to ID number in Table 1 (upper Rika) and Table 2 (upper Steyr), **bottom left**—Steyr River—Klaus an der Pyhrnbahn, **bottom right**—Rika River—Mizhhiria.

To analyze factors controlling the maximum winter floods formation, we use observations of daily air temperature, precipitation, and snow depth at selected climate stations. For the upper Rika catchment, daily precipitation records from three climate stations (Mizhhiria, Nyzhnii Studenyi, Verkhnii Bystryi) and daily air temperature records from the Mizhhiria climate station are collected (Table 4). The daily mean air temperature and precipitation in the Steyr River basin are estimated from the gridded Spartacus dataset [35,36]. Daily snow depth measurements are available from five stations (Maidan, Nyzhnii Studenyi, Verkhnii Studenyi, Verkhnii Bystryi, Mizhhiria) in the upper Rika [37] and five stations (Hinterstoder, Spital am Pyhrn, Windischgarsten, St. Pankraz, Klaus an der Pyhrnbahn) in the upper Steyr River basins (Table 4). The Austrian stations have observations from 1970–2016, the data in the upper Rika are mostly from 1946–2016.

Table 4. The list of stations with snow depth observation (D) in the Steyr River Basin (Austria, AT) and Rika River Basin (Ukraine, UA).

Climate Station	Elevation, m a.s.l.	D_{max}, cm	$D_{average}$, cm	Period
UA:Nyzhnii Studenyi	615	144	38	1946–2016
UA:Verkhnii Studenyi *	600–700	143	49	1956–2016
UA:Verkhnii Bystryi	545	123	38	1949–2016
UA:Mizhhiria	456	119	32	1949–2016
UA:Maidan	499	73	28	1983–2016
AT:Windischgarsten (Schule)	604	173	71	1970–2016
AT:Hinterstoder	590	170	66	1970–2016
AT:Spital am Pyhrn	630	169	68	1970–2016
AT:St. Pankraz	598	170	61	1970–2016
AT: Klaus an der Pyhrnbahn	461	110	42	1970–2016

* represents regular snow course measurements.

3. Methods

3.1. Hydro-Genetic Method

Fluctuations of winter floods are analysed by the hydro-genetic approach [18]. This method consists of the following steps:

(1) screening of the homogeneity of winter flood records by using the mass curve approach;

(2) estimation of the residual mass curve of winter floods and assessment of stationarity of flood time series;

(3) plotting of fluctuations of winter floods and evaluating synchronicity between different gauges in the homogenous region and between winter floods and selected climate characteristics, i.e., air temperature, precipitation and snow depth.

The residual mass curve and associated fluctuation index $f(t)$ is defined as in [38] according to Equation (1)

$$f(t) = \frac{\sum_{t=1}^{T}(k(t) - 1)}{C_v}, \tag{1}$$

where Cv—the coefficient of variation of annual maximum winter floods; $k(t)$—the modulus coefficients relating individual annual winter flood discharges $Q_{\max}(t)$ in year t to the mean of the annual winter floods Q_{mean} of the time period T (number of years). The modulus coefficient $k(t)$ is defined according to Equation (2):

$$k(t) = \mathrm{Q}_{\max}(\mathrm{t})/\mathrm{Q}_{\text{mean}} \tag{2}$$

More details about assumptions and applications of the methodology are presented in [18,25,28,39].

In order to attribute the flood fluctuations to other climate characteristics, the residual mass curve and fluctuation index are also calculated for the observed maximum daily snow depth, maximum seven-day precipitation and a melt index represented by the sum of positive daily air temperatures in the period (November–April).

3.2. Seasonality Assessment

The seasonality analysis examines the timing of selected hydrological and climate characteristics during the winter season (November–April). In this study, the seasonality of winter floods, maximum winter precipitation, snowmelt timing, and maximum snow accumulation time is evaluated. These characteristics have been found to be the most relevant for flood seasonality assessment in Europe [3]. The maximum precipitation is defined by seven-day maximum precipitation in the winter period, estimated for each year and assigned to the midpoint of the seven days. To understand the effect of snow processes on the flood timing, we used a snowmelt-timing index introduced in [3]. Snowmelt timing index shows the first full seven days in a year when surface air temperatures exceed 0 °C. The snowmelt timing index is also assigned to the midpoint of the seven days. The seasonality of maximum snow accumulation is defined by the date of maximum daily snow depth observed at the climate stations.

4. Results

4.1. Fluctuation and Seasonality of Winter Floods

The analysis of the mass curves of the winter floods for all 24 catchments indicates that the series of observations are homogeneous. Two examples of mass curves for the largest catchments are shown in Figure 3. The plots demonstrate that the shape of mass curves does not show any significant unidirectional deviations in the 60 and 70 years.

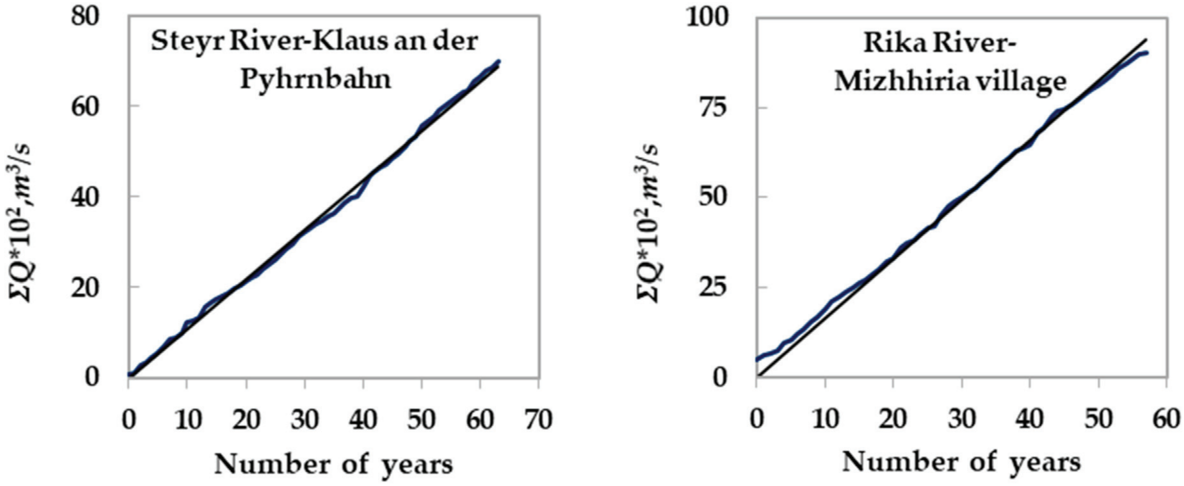
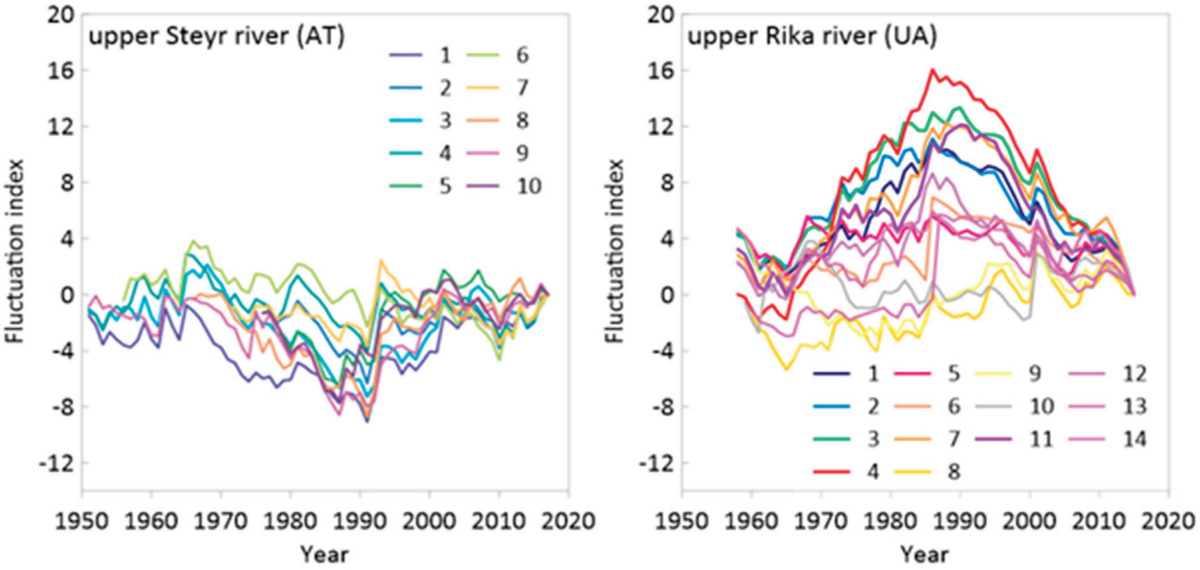


Figure 3. Mass curves of winter floods in the upper Steyr (**left** panel) and upper Rika (**right** panel) River basin.

Figure 4 show the residual mass curves for Austrian (left panel) and Ukrainian (right panel) catchments. The shape of the residual mass curve indicates cyclical and synchronous fluctuations in the winter floods series. The results show a distinct difference between the Austrian and Ukrainian parts of the Danube River basin fluctuations. While the magnitude and length of the cycles in Austrian catchments is smaller, most of the Ukrainian catchments show a distinct fluctuation pattern consisting of an increasing phase of winter flood magnitude from the mid-1960s until the end of the 1980s, followed by a decrease until the recent period (2015). The exceptions are fluctuations in headwater catchments Pylypets River (ID = UA8), Branyshche Stream (ID = UA9), and Pylypetskyi Stream (ID = UA10), which are much smaller and have a significantly increasing phase in the 1980–2000 period. In contrary, most of the Austrian catchments have a decreasing phase between the mid-1960s and 1990s, followed by a sharp increase in winter flood magnitude until 2010.



(**a**) (**b**)

Figure 4. Fluctuations of maximum winter floods in the upper Steyr (**a**) and upper Rika catchments (**b**). Labels of symbols refer to ID number in Table 1 (upper Rika) and Table 2 (upper Steyr).

The seasonality of winter floods of both regions is presented in Figure 5. The left and right panels show the occurrence of winter floods in the upper Steyr and upper Rika catchments, respectively. The green lines indicate the winter flood fluctuations for the largest catchments in both regions (ID = AT1, ID = UA1). The results show that the variability of flood occurrence in individual years is larger in the Austrian than in the Ukrainian catchments. The variability is mainly related to the larger topographical variability of Austrian catchments. The earliest occurrence of winter flood maxima in the upper Steyr catchment is observed mostly at Klaus an der Pyhrnbahn gauge, which is the main outlet. The latest occurrence is typically observed in the highest catchment (Polsterlucke, ID = AT10) and the difference between the occurrence of flood maxima between the catchments in individual years can exceed 3–4 months. The largest floods in Austrian catchments tend to occur in November/December. In the upper Rika River, the inter-annual variability of flood occurrence is also large, but the variability between the catchments is notably smaller than in Austrian catchments. Interestingly, the smallest between-catchment variability is observed between 1985 and 1995, which is the start of the main fluctuation decline. During this period, most of the floods occur in November/December.

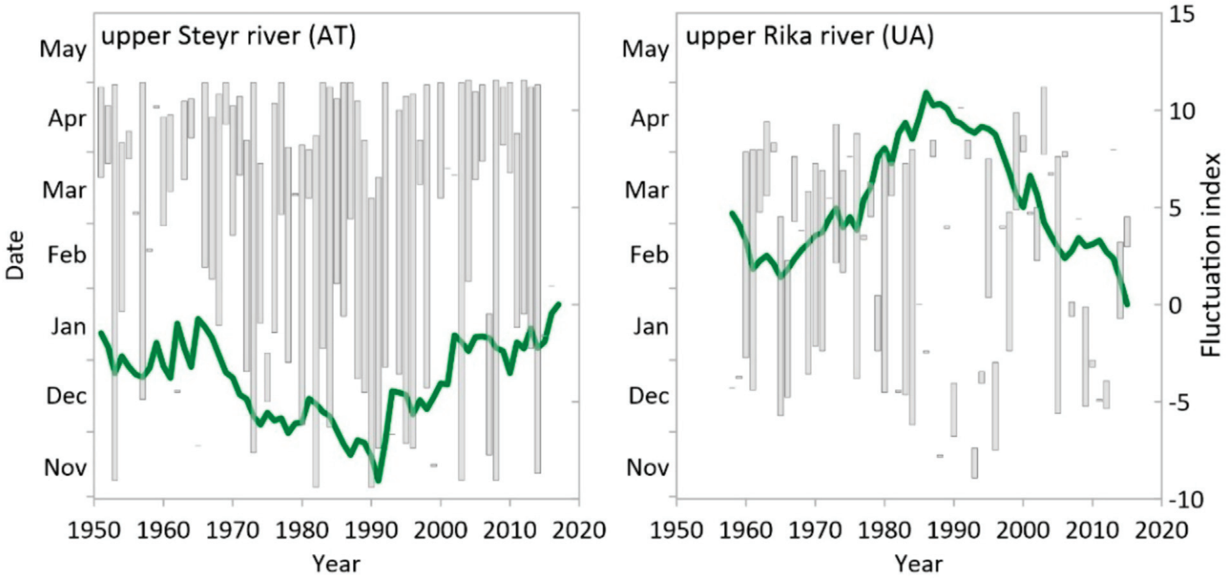


Figure 5. Seasonality of winter floods (grey lines). The grey band represents the variability of flood occurrence between the catchments from the same region. The green line indicates fluctuation index in the Steyr River—Klaus an der Pyhrnbahn (**left**) and Rika River—Mizhhiria village (**right**) catchments.

4.2. Factors Controlling Winter Flood Fluctuations

For a more detailed characterization of the fluctuations of winter floods, Figures 6–8 compare winter flood fluctuations with the fluctuations and seasonality of 7-day sum of precipitation, melt index based on sum of positive air temperature, and maximum snow depth. Pink bands in Figure 6 (top panels) show the fluctuations of winter maximum (seven-day) precipitation in the upper Steyr (left) and upper Rika (right) catchments. The fluctuations in the upper Steyr are synchronous with fluctuations in winter floods (green line). In the upper Rika catchment, the positive phase (i.e., an increase) in flood magnitude until 1990 is not associated with an increase in maximum precipitation, particularly between 1980 and 1990. An increase in maximum precipitation after 2010 also does not correspond with flood fluctuations, which are in this period in a negative phase (decreasing floods).

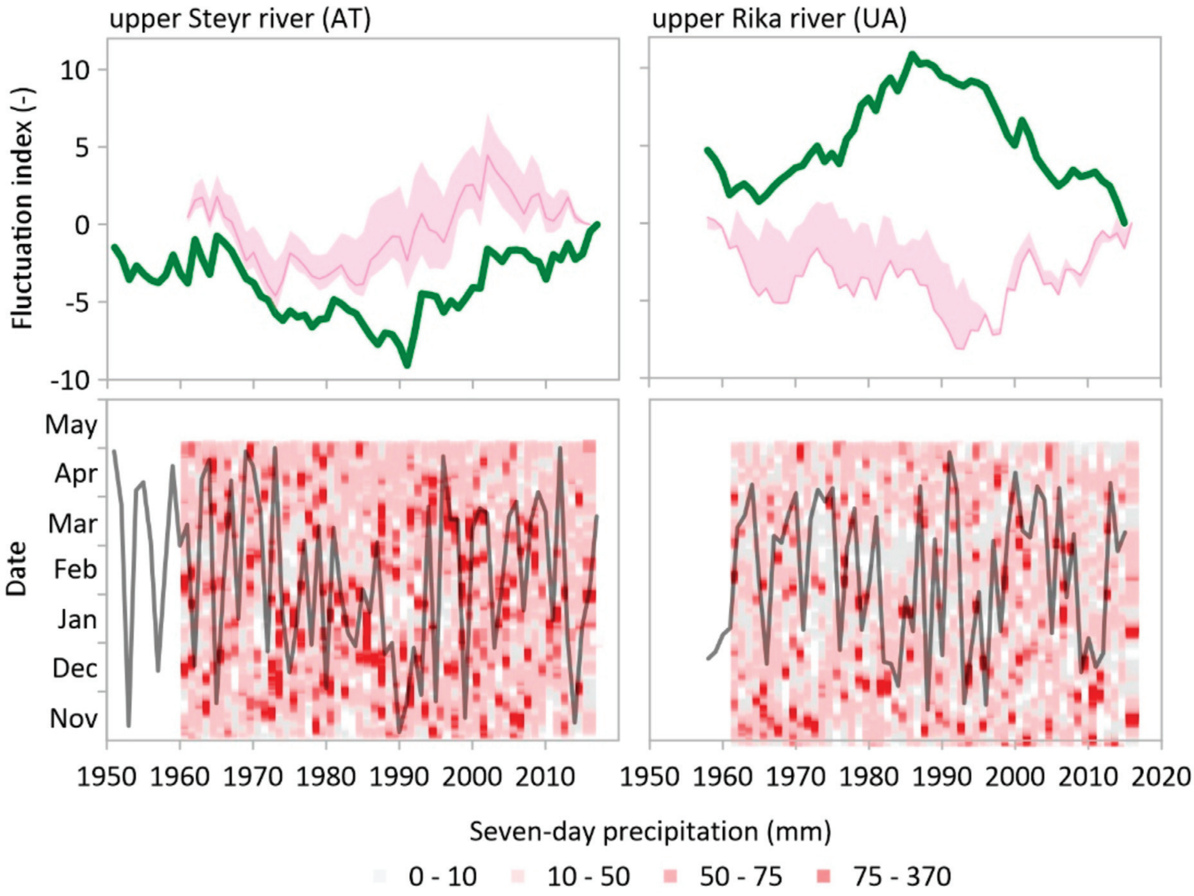


Figure 6. Fluctuations (**top** panels) and seasonality (**bottom** panels) of the winter maximum seven−day precipitation in the upper Steyr and the upper Rika catchments. Variability in maximum precipitation (pink band in **left top** panel) is plotted for all sub-catchments in the upper Steyr catchment. For Mizhhiria station in the upper Rika River (**top right** panel), the pink band indicates the variability between precipitation observations at three (Mizhhiria, Nyzhnii Studenyi, Verkhnii Bystryi) climate stations (Table 4). The green line indicates the fluctuation index of the winter floods (**top** panels). Bold lines (**bottom** panels) represent the season of the maximum precipitation in each year.

The seasonality of maximum precipitation (Figure 6, bottom panels) has a very strong inter-annual variability and the winter maxima tend to occur either in November/December or March/April. In both regions, there are no clear links between flood and precipitation fluctuations and the seasonality of maximum precipitation.

Fluctuations of positive air temperature sums are presented in Figure 7 (top panels). In both regions, they have a similar cycle showing a decreasing phase (cooling) until the 1990s, followed by a continuous increasing phase until recent years. The region's difference is mainly in the declining phase, which is less pronounced in Ukrainian catchments in 1960–1980. On the other hand, the positive increasing phase starts in the upper Rika catchment later than in the Steyr catchment. The seasonality of the melt index does not show a clear pattern related to the fluctuations of floods. There is a strong inter-annual variability, but the differences between the regions cannot explain the difference in the flood fluctuations.

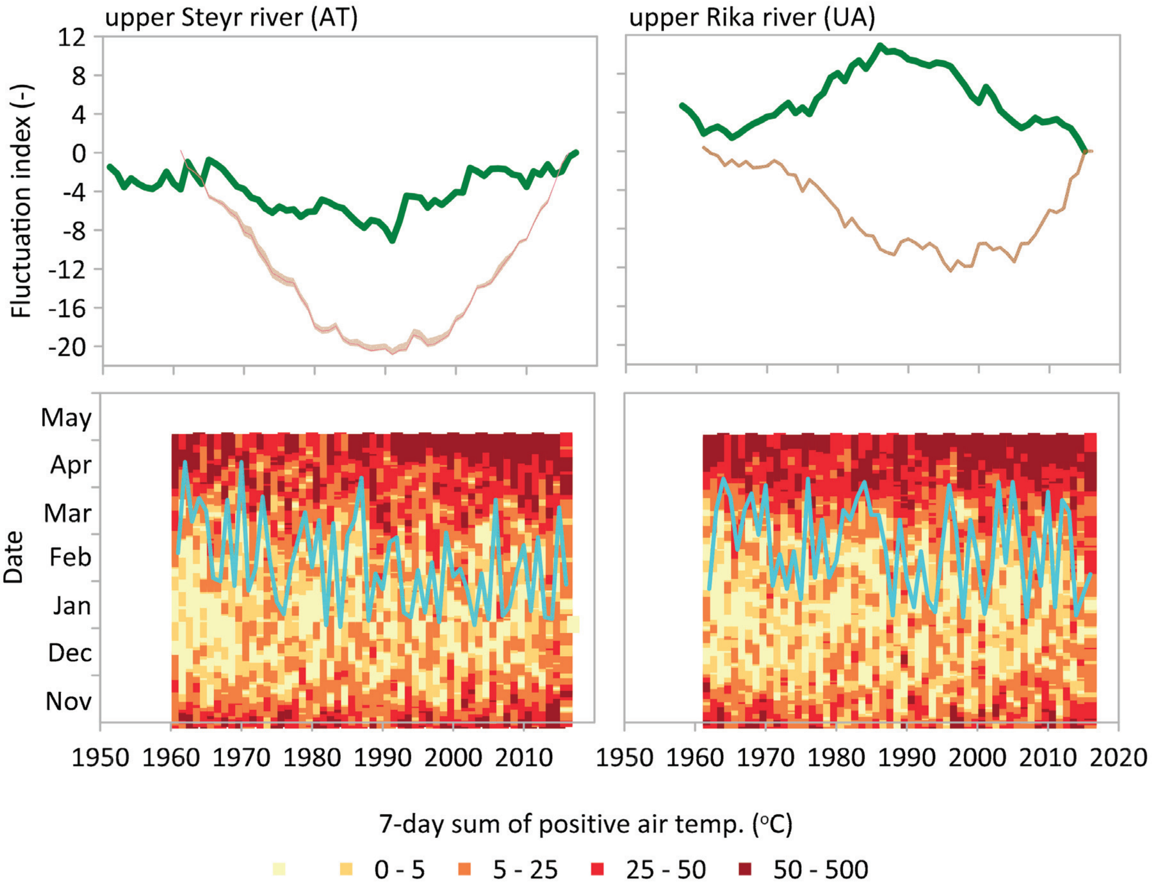


Figure 7. Fluctuations (**top** panels) of the sum of positive air temperature and seasonality (**bottom** panels) of the seven−day melt index in the upper Steyr and the upper Rika catchments. Variability in the sum of positive air temperature (brown band in **left top** panel) is plotted for all sub−catchments in the upper Steyr catchment and Mizhhiria station in the upper Rika River (**top right** panel). The green line indicates the fluctuation index of the winter floods (**top** panels). Bold lines (**bottom** panels) represent the seasonality of the snowmelt index, i.e., the first full seven days in a year when surface air temperatures exceed 0 °C.

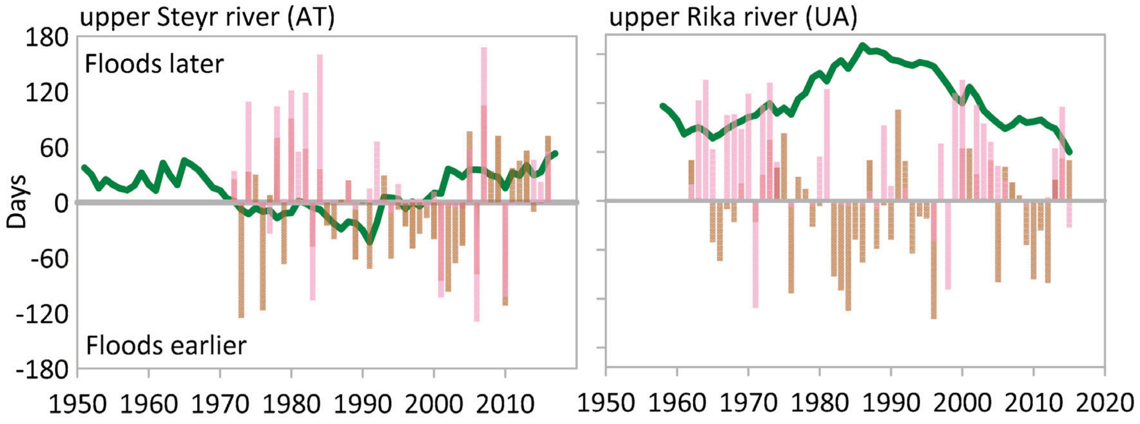


Figure 8. Difference in the occurrence of winter floods and the occurrence of maximum precipitation (pink bars) and melt index (brown bars). Positive difference (days) indicates that floods occur later than maximum (seven−day) precipitation or occurrence of (seven-day) positive air temperatures. The green line indicates the fluctuation index of the winter floods.

The difference between the occurrence of floods and the occurrence of maximum precipitation and start of the melt season is examined in Figure 8. The positive and negative values indicate the later and earlier occurrence of floods than the occurrence of maximum winter precipitation (pink bars) and melt start (brown bars), respectively. Figure 8 shows that in the upper Steyr catchment, the positive phase of flood fluctuations (after 2000) occurs when the flood occurrence coincides with the occurrence of maximum winter precipitation. The stable phase in the 1970s is associated with floods occurring in March and April, but the maximum precipitation occurred in the beginning of winter. The same pattern is observed in the upper Rika catchment. The peak of positive phase (i.e., mid-1980s and 1990s) is characterized by a coincidence of floods and maximum precipitation.

The fluctuations of annual maximum daily snow depth are presented in Figure 9. In the upper Steyr catchment, the maximum snow depth fluctuations follow the fluctuations in winter floods. The periods of increasing or decreasing phases correspond to the phase of flood fluctuations. In the upper Rika catchment, the snow depth fluctuations are very stable in 1950–1980 and do not follow the increasing phase of the winter floods fluctuations. However, the decreasing phase of snow depths from the mid-1980s until the end of the 1990s corresponds with decreasing flood magnitudes in this period. The increase in snow depth from the beginning of the century (2000) is also reflected in a slight rise in winter flood magnitudes. The seasonality of annual snow depth maxima also has a strong inter-annual variability. Earlier snow depth maxima are associated with lower snow depth magnitude and typically smaller winter floods.

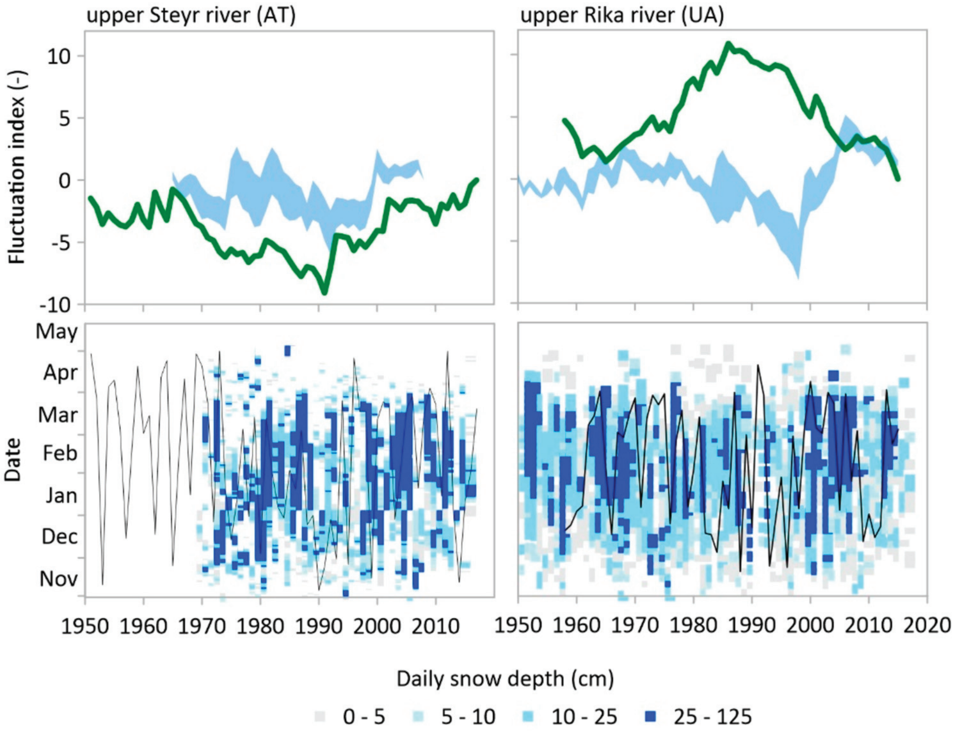


Figure 9. Fluctuations (**top** panels) and seasonality (**bottom** panels) of the winter floods and observed snow depth in the upper Steyr and the upper Rika catchments. Lines show fluctuation and seasonality of winter floods in the Steyr River—Klaus an der Pyhrnbahn (**left**) and Rika River—Mizhhiria village (**right**) catchments. Variability in snow depth fluctuation (blue band in **top** panels) is plotted for climate stations listed in Table 4. The green line indicates the fluctuation index of the winter floods (**top** panels). Daily snow depth seasonality is presented for the Spital am Pyhrn (Austria, 630 m a.s.l.) and Nyzhnii Studenyi (Ukraine, 615 m a.s.l.).

5. Discussion and Conclusions

This study compares the long-term fluctuations of winter floods in two regions in the Danube River basin. Recent studies of changes in flood seasonality and flood magnitude in Europe [2,3] show that floods have changed in the last 50 years and different drivers control these changes. One of the drivers is the change in snowmelt due to increased warming. This study compares the fluctuation of winter flood magnitudes and their seasonality in similarly sized and small catchments in Austria and Ukraine. The results show that the winter floods are synchronous and correspond well with fluctuations of sum (seven-day) of positive air temperature and maximum precipitation and snow depth. In the last decades, the increasing phase in melt temperatures has resulted in decreasing winter floods in Ukrainian catchments, which corresponds well with changes in flood magnitude identified by the author of [2] in Eastern Europe. This study, however, did not find a significant change in flood or snow characteristics as reported in [3] or [40] or North-Eastern Europe [4,5]. The seasonality of winter floods and associated climate characteristics have an extreme inter-annual variability. Even air temperatures have increased continuously in the last decade; the generation of maximum winter floods still tends to vary between the years. The recent increase in the upper Steyr catchment and stabilization of the decreasing phase of flood magnitudes in the upper Rika catchment is associated with the coincidence of floods with the occurrence of maximum precipitation and/or its combination with the snowmelt.

A previous study [28] examined flood fluctuations in many rivers in Ukraine and identified four different types of long-term fluctuations. Our results for the upper Rika catchments mostly belong to the first type characterized only by two simple phases: decreasing and increasing. The fluctuations found for the upper Steyr catchments are close to the fluctuations found for the Tysa River. These fluctuations are characterized by a smaller number of cycles with shorter duration and smaller amplitude than found in the upper Rika catchment. In future studies, it will be interesting to analyze the flood fluctuations across larger geographical transects to examine further factors and drivers controlling their variability.

The comparative assessment of similarities and differences in winter flood fluctuations suggests that the fluctuations are a reflection of the various flood producing processes. The combination of the hydro-genetic approach with the seasonality assessment allowed us to identify drivers controlling flood magnitude fluctuations. The differences in fluctuations are the reflection of the snow accumulation and melt processes and the occurrence of larger precipitation amounts. The findings indicate that the variability in winter floods is also controlled by topographical variability within the study region through the differences in the snowmelt timing. To validate the effects of elevation in the other areas and explore its interplay with the runoff generation processes, we plan to focus our next efforts on evaluating the combination of hydro-genetic method and seasonality assessment in the entire Alps-Carpathian region. The main aim will be to examine the spatio-temporal patterns of flood fluctuations along selected transects in Europe and identify regions with similar fluctuation characteristics.

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