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Climate impact on flood changes – an Austrian-Ukrainian comparison

Sergiy Snizhko[1,2*], Miriam Bertola[2], Valeriya Ovcharuk[3], Olga Shevchenko[1], Iulii Didovets[4], Günter Blöschl[2]

[1] Department of Meteorology and Climatology, Taras Shevchenko National University of Kyiv, Volodymyrska Str. 60, Kyiv, Ukraine.
[2] Institute of Hydraulic Engineering and Water Resources Management, Vienna University of Technology, Karlsplatz 13/222, Vienna, Austria.
[3] Hydrometeorological Institute, Odesa State Environmental University, Lvivska Str. 15, Odesa, Ukraine.
[4] Department of Climate Resilience, Potsdam Institute for Climate Impact Research, Telegrafenberg A 31, Potsdam, Germany.
[*] Corresponding author. Tel.: +38 0674911110. E-mail: snizhko@knu.ua

Abstract: This study compares the flood regime of rivers in Ukraine and Austria over the last decades. We used data from mountain and lowland watersheds, where floods are caused by different processes. In order to identify possible shifts in the day of occurrence of annual flood maxima, we apply the kernel density method to the time series of two subperiods (1960–1987 and 1988–2015). We use the Mann Kendall test at a 5% significance level to identify significant positive or negative trends in the series of annual maximum discharges. In Austria, we observe an increasing trend in summer floods associated with increasing precipitation. In the lowland areas of Ukraine, a clear reduction in spring floods is observed, linked to shallower snow packs in a warming climate. In the Ukrainian Carpathians, on the other hand, where floods occur throughout the year, an increase in the portion of liquid precipitation during the cold period of the year leads to earlier floods and an increase in the probability of flooding in winter.

Keywords: Timing of floods; Seasonality; Circular kernel density histograms; Trends in flood magnitude, Climate change.

1 INTRODUCTION

Weather-related extremes account for 80% of the total economic losses caused by natural hazards in the EEA Member States between 1980 and 2020, amounting to EUR 487 billion (European Environment Agency, 2022a). Floods are the most costly hazard, having caused 43% of economic losses worldwide in the last 30 years (European Environment Agency, 2022b).

Climate change affects the water cycle in complex ways. There are concerns that a warmer climate may shift flood regimes and thus increase potential flood damage and/or reduce the economic efficiency of flood management measures. The IPCC reported that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, increasing at a rate of 0.2°C per decade (IPCC, 2018). Increased heating of the sea and land surface leads to greater evaporation, increasing the amount of water vapor in the atmosphere. According to the Clausius-Clapeyron equation, the water holding capacity of air increases by 7% for every 1 degree Celsius (Karl and Trenberth, 2003). However, this does not necessarily translate into rainfall increases, as atmospheric dynamics are also relevant for extreme rain events along with the atmospheric water content which, in the midlatitudes, is only 15 mm on average (Kalnay et al., 1996). The last IPCC report predicts that climate-related extreme events will become more frequent around the world (IPCC, 2021).

Long series of monthly and annual precipitation data indicate complex trends, depending on the specific region of the world in which the observations are made (Climate Change, 2021). According to recent studies of the European continent, and the Carpathians in particular, annual precipitation patterns are variable across the last three decades showing no significant trends for Central and Eastern Europe (Fleig et al., 2015; Niedźwiedź et al., 2009; Twardosz et al., 2011, 2014, 2016). Blöschl et al. (2013b) suggest that mean annual precipitation is useful as a parameter not only for describing the direct effect on runoff generation at the event scale, but also its indirect effect on longer-term soil moisture availability and also more long-term evolution processes of the landscape, soil and vegetation.

On the other hand, a growing body of research points to significant increasing trends in extreme precipitation across parts of Europe over the past decades, in particular in the north, leading to major flooding (Bürger et al., 2021; Łupikasza et al., 2010; Matygin et al., 2010; Van den Besselaar et al., 2013). Increases in precipitation events with high precipitation quantiles have been observed in regional studies (Dai et al., 1997; Groisman et al., 2004; Hulme et al., 1998) which may increase the frequency of flooding. However, as stated by Beven (1993), flood generation and runoff are a highly nonlinear system, which is exposed to the natural and spatial/temporal variability of meteorology, topography, soil, vegetation, climate, groundwater conditions, and the channel drainage system. Therefore, other factors in addition to rainfall also need to be considered (Beurton and Thieken, 2009; Blöschl et al., 2017; Bronstert, 2003).

Merz et al. (2012) defined three groups of potential drivers of flood regime changes (1-river channel engineering and hydraulic structures, 2-land use change, and 3-climatic change). Climatic factors influence regional precipitation impacts (Blöschl, 2022). They act over large spatial (synoptic) scales, providing a synchronous influence on the variation of amplitudes, frequencies and timing of river floods of different river basins of the region. Exceptions can occur with convective precipitation events, which may increase flood peak discharge in small basins even more (Hall et al., 2014). Local factors acting at the basin scale (topography, soil, vegetation, microclimate, groundwater conditions, channel drainage system, etc.) can significantly transform the influence of climate on flood formation. All of these factors show very significant regional variations related to the flood generation processes.

A spatial comparison between regions or between countries can therefore shed light on flood-change processes. Ukraine and Austria are ideally suited for such a comparison for a number of reasons. In the Ukrainian plains in the northwest of the country, the largest floods tend to occur in spring due to snowmelt. In the south, spring floods have strongly decreased in the past decades in association with higher temperatures, less snow storage and less snowmelt (Blöschl et al., 2019; Ovcharuk et al., 2020; Snizhko et al., 2021). In the west of Ukraine (the river basins of the Ukrainian Carpathians), floods occur during both winter and summer, and so climate effects are more complex (Didovets et al., 2019; Snizhko et al., 2020). For the formation of winter floods in the mountain rivers of the Ukrainian Carpathians, not only are the processes of accumulation, melting of snow and precipitation important, but also is the variability of the relief. This significantly affects the processes of flood generation, resulting in differences in the timing of snow melting (Zabolotnia et al., 2022).

In Austria, similarly, floods are produced by a diversity of processes, mainly depending on climatic, and topographical influences as well as basin sizes. In the highest parts of the country in the west, snow and glacier melt are relevant flood producing processes. In the lowlands of the east, most floods are produced by rainstorms. In the north and south, depending on the local conditions, both snowmelt and rain can be of importance (Blöschl et al., 2019). Merz and Blöschl (2003) in their study of flood seasonality in south-eastern Austria found ample evidence for the role of convective storms in the occurrence of floods in this region. Gaal et al. (2012) also confirmed that climate-related processes, such as convective and synoptic storms, snowmelt and rain, and precipitation type are of great importance in the occurrence of floods in Austria, their magnitude and seasonality. Blöschl et al. (2013a) investigated causal factors of the largest Upper Danube floods in the past two centuries including the atmospheric situation, runoff generation and the propagation of the flood wave. They emphasized that the combination of factors remains an essential concept for understanding the magnitude of large, regional floods. Given these runoff generation mechanisms in Ukraine and Austria, it is of interest to see what can be learned from comparing flood trends in the two countries. The aim of this study is therefore to make a comparative analysis of flood changes in Ukraine and Austria to address the following research questions:

(a) Are climate-induced processes influencing flood formation similar in Ukraine and Austria?

(b) Is there an analogy of process drivers leading to similar changes in flood probabilities?

(c) What trends in flood magnitude occur due to climate change in the two countries?

2 STUDY AREA AND DATA

2.1 Study area

For the comparison, basins with different conditions of runoff formation were selected in Ukraine and Austria. The four basins in Ukraine selected for this study are the Dniester, Tisza, Desna, and the Southern Bug basins (Figure1) and in Austria the selected basins are in the Alpine region, the Northern Lowlands region and the Eastern Lowlands region (Figure 2).

The Dniester River originates in the Ukrainian Carpathians, flows through the territory of Moldova, and flows into the Black Sea. The maximum discharges of the Dniester River are either caused by spring snowmelt or are formed as a result of summer and autumn heavy rains, which cover considerable areas. In the upper reaches of the river, before leaving the mountains, rain-driven peaks usually exceed the peaks of spring floods and sometimes become catastrophic (July 1980, July 2010, June 2020). As the rivers cross the Volyn-Podilsk plain, both snow and rain flood peaks decrease.

The Upper Tisza, a left tributary of the Danube, is formed by the confluence of the White and Black Tisza. Extremely intense downpours and torrential rains form in this area, causing catastrophic floods. Depending on the snowmelt conditions in the winter-spring period and precipitation amounts in spring and summer, some years have mainly spring floods of varying size and, more recently, small rainfed-floods. In other years spring floods are not relevant, and in some years both spring and winter floods can be important (Didovets et al., 2019; Gopchenko et al., 2018). As a result, floods in the Tisza basin occur usually in winter and spring, but not in late autumn.

Fig. 1. Map of Ukrainian river basins (1 - Tisza, 2 - Dniester, 3 - South Bug, 4 - Desna) and stream gauges (points).

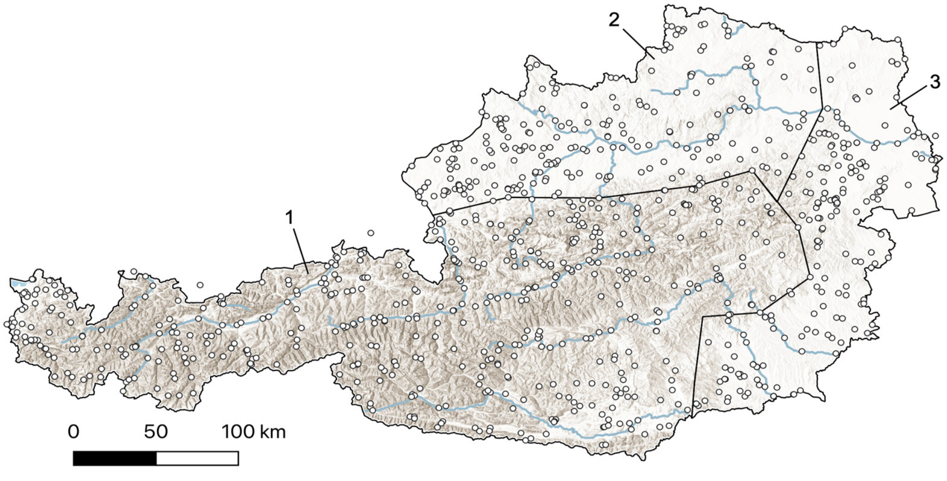

Fig. 2. Map of Austrian regions and gauges: 1 - Alpine region, 2 - Northern Lowlands, 3 - Eastern Lowlands.

The Desna River is the second-longest left tributary of the Dnieper, and contributes up to 20% of its runoff. The streamflow regime is largely determined by spring floods, their duration and the contribution of meltwater to the annual runoff. In the Desna sub-basin, spring flooding begins along its tributaries, which are located in the lower part of the basin. Catastrophically high spring flood levels were last observed in the Desna sub-basin in 1932 and 1970 (Ovcharuk et al., 2019).

The Southern Bug is a river in southwestern Ukraine, the third largest river in Ukraine. The rivers of the upper and middle reaches of the Southern Bug are characterized by pronounced spring floods and low dry-weather runoff, which are to varying degrees disturbed by summer and winter floods due to summer rains and melting snow during thaws. The rivers of the lower Southern Bug flow within the steppe zone. This is characterized by an arid climate, an unstable winter regime with unstable snow cover (due to frequent thaws), which leads to partial or complete melting of snow, and the formation of winter floods of varying intensity and water content. Due to such conditions, floods are often formed in spring, but these tend to be smaller events than the winter floods in January-February.

In Austria, hydroclimatic regions have been defined according to Merz and Blöschl (2009) based on the dominant meteorological and hydrological processes. The spatial variability of hydrological conditions is enormous in terms of altitudinal range (150 m to 3700 m above mean sea-level) and annual rainfall (ranging from 400 mm to more than 3000 mm year^{-1}) and much greater than in Ukrainian basins. For this comparative study, three regions were selected (Figure 2) based on the spatial aggregation of hydroclimatic regions of Merz and Blöschl (2009) which have similar hydro-climatic characteristics.

The **Alpine region (region 1)** covers the Alps in the west and south of Austria with elevations ranging from 1200m to 3700 m above mean sea-level. In this region, snow and glacier melt have a strong influence on runoff variability. This is also the zone with the highest rainfall in the country due to the orographic effect of the Alps, in particular along the northern fringes of the Alps and in southern Carinthia. Depending on the location of the basins, hydrological processes are mainly influenced by north-westerly weather patterns (in the north-western part of region 1) and Mediterranean storm tracks (through the south-eastern part of region 1). When compared to the rest of the country, this region is characterised by high values of mean annual flood discharges. Although the highest discharges occur in the northern parts of the region, the associated annual maximum flood peak values show low variation. The lowest values of flood peak variation occur in the southern part of the region (Lun et al., 2021). Annual maximum floods occur on average during the summer months, when rainfall is most intense and in association with snowmelt.

The Northern Lowlands region (region 2) is located in the north-west of Austria. The topography of this region is rather flat, and the rainfall is lower than over the Alpine region. This region is characterised by values of mean annual flood discharges that are on average lower than those in the Alpine region and higher than those in the Eastern Lowlands. Annual maximum floods occur in all seasons due to a mixture of different flood generating processes (summer floods due to heavy rainfall, winter floods of lower-intensity rain on wet soils, rain-on-snow), with a slightly prevailing summer seasonality.

The Eastern Lowlands region (region 3), located in the east of Austria, is the driest region of the country and is characterised by a continental climate with warm and dry summers, and cold winters without significant snowfall (Pannonian climate). Mean annual flood discharges are the lowest observed in the country, and the coefficients of variation of annual maximum flood series are high (Merz and Blöschl, 2009). This is because of low event runoff coefficients for small and intermediate sized events, while for large events the runoff coefficients can be much larger. Annual maximum floods occur in all seasons due to a mixture of different flood generating processes, with slightly prevailing summer seasonality.

2.2 River flow data

The hydrological data were obtained from daily runoff observations carried out by the Boris Sreznevsky Central Geophysical Observatory in Ukraine and the Hydrographic Service of Austria. Data for the same period 1960–2015 in the two countries were selected for comparability. Annual maximum river flows (Qmax) were extracted from the daily discharge data set, as the maximum value in a year for each of the gauges. A flood time indicator (TQmax) was defined as the number of the day of occurrence of Qmax for each year. In total, series from 273 and 578 gauges in Ukraine and Austria, respectively, were used.

3 METHODOLOGY

3.1 Analysis of timing of annual maximum discharges

We analyze the distribution of the day of occurrence of annual maximum discharges, which is a circular variable represented by a number between 1 (1st of January) and 365 or 366 (31st of December). The distribution of the day of occurrences of annual maximum discharges is estimated as a non-parametric circular kernel density using the R function "density" from the R package "circular", after transforming the circular data to radians (Silverman and Solmon, 1998). More details on circular kernel density and its application are represented in Bai et al. (1989), Klemelä (2000) and Kernel Density Estimation (2022).

To investigate a possible shift in the time of flood occurrence, the distribution of the timing of floods (for pooled flood series within specifically identified regions) is constructed for the entire temporal series length (1960–2015) and two sub-periods of equal length, i.e., 1960–1997 and 1998–2015. The comparison of the distribution of the days of occurrence of floods for these periods aims at identifying changes in flood seasonality, possibly related to changes in flood generation processes due to climate change.

3.2 Analysis of trends in the magnitude of annual maximum discharges

The non-parametric Mann Kendall (MK) test (Kendall, 1975; Mann, 1945) at 5% significance level is used to detect monotonic positive or negative significant trends in the series of annual maximum discharges. This test has been used in previous studies (e.g. Bertola et al., 2020; Blöschl et al., 2017; Blöschl et al., 2019; Ivancic et al., 2015; Mangini, et al., 2018; Mediero et al., 2014; Venegas-Cordero et al., 2022). The test is applied to each series of annual maximum discharges with at least 30 years of data in the period 1960–2015. Currently, the MK test is represented in various statistical software programs and packages. In this study it was performed using the function "Mann Kendall" from the R package "Kendall".

4 RESULTS AND DISCUSSION

4.1 Timing of floods: Ukraine and Austria

Figures 3a and b show the seasonality of floods in all Ukrainian (blue) and Austrian (red) basins in terms of the circular kernel density for the entire period and the two sub periods (1960–1987 and 1988–2015), respectively. There are differences in the seasonality in Ukraine and Austria. In Ukraine the main flood period is in February-May, while in Austria it is in May-October. This is because of the larger frequency of spring floods due to snowmelt in Ukraine as compared to Austria. Flatland rivers dominate in Ukraine, and mountain rivers in at least part of Austria.

4.2 Flood timing of Ukrainian rivers

In order to identify the impact of climate change on the formation of floods in more detail, the kernel density distributions were evaluated for each river basin separately (Figure 4) and for both time subperiods.

Upper Tisza river basin. In this area floods may occur in all seasons of the year but are most likely in December, March, and July in the first subperiod (1960–1987). The comparison of both subperiods shows that the distribution of the timing has changed significantly. Investigations of climate change impact on water resources in Ukraine (Didovets et al., 2019; Gopchenko and Loboda, 2001; Hrebin, 2010; Snizhko et al., 2020) have shown that significant climate change impacts began to manifest themselves around 1989, thus, the second period represents the flood regime under the influence of climate change. In the second period, the number of days with Qmax in January-February decreased to one half of its previous value, the maximum shifted to an earlier date (from March 28 to March 6). The frequency of flooding in November, however, increased twofold. This led to a shift in the average timing of the annual flood peaks from spring to autumn. The results obtained here are in good agreement with previous studies (Blöschl et al., 2017, 2019; Vyshnevskyi and Donich, 2021), which revealed a trend towards an increase in runoff during the cold period of the year and a shift in the timing of the annual maxima to later in the year.

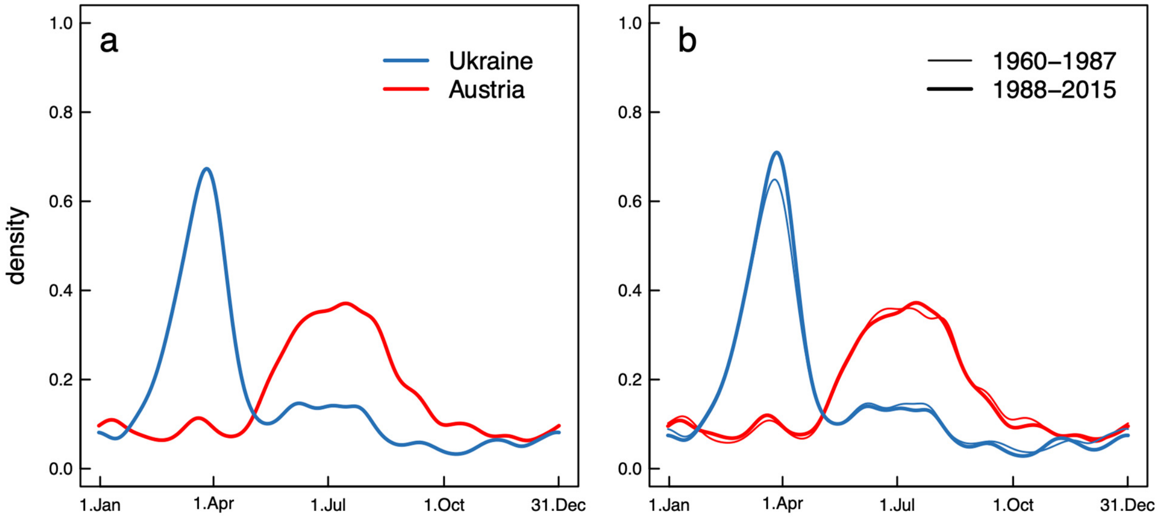

Fig. 3. Seasonality of floods in Ukraine (blue) and Austria (red). The lines in panel a show the distribution (circular kernel density) of the day of occurrence of floods in the two countries for the period 1960–2015. All gauges and all observations have been used (273 gauges in Ukraine and 571 gauges in Austria). Panel b shows the densities of the seasonality of floods in two sub-periods (1960–1987 and 1988–2015).

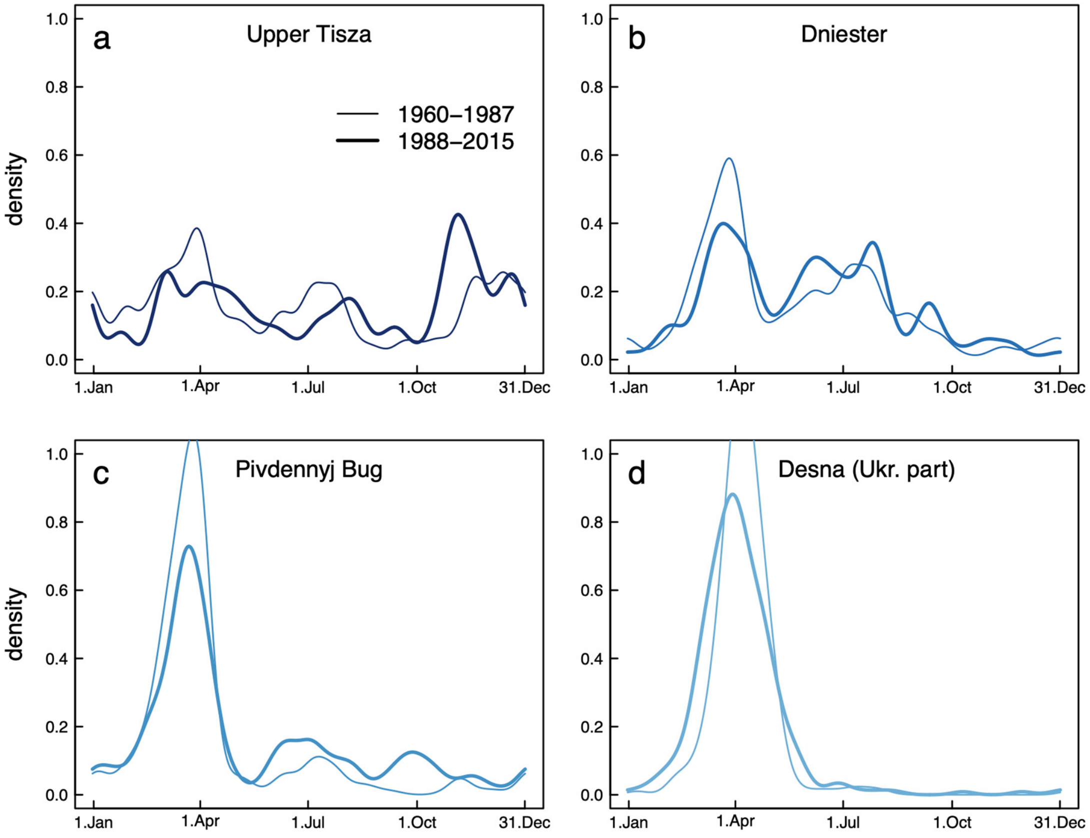

Fig. 4. Seasonality of floods in four Ukrainian river basins. The lines show the distribution (circular kernel density) of the day of occurrence of floods in two subperiods (1960–1987 (thin line) and 1988–2015 (bold line)). The panels refer to the Upper Tisza (a) (24 stream gauges), Dniester (b) (54 stream gauges), Southern Bug (c) (19 stream gauges), Desna (d) (10 stream gauges).

Dniester river basin. Analysis of both temporal subperiods shows that floods tend to be most frequent in spring (March–May), however in the second subperiod the number of spring floods is much lower (by 33%) when compared to the first period, whilst the frequency of summer floods has increased.

Southern Bug basin. In the first subperiod, the Southern Bug basins are characterized by frequent spring flooding, while in the second subperiod spring flooding is 30% less frequent. There are slight increases in the frequency of flooding in June to October. This redistribution of the maximum river runoff in the Southern Bug basin is consistent with the predicted trends toward a decrease in spring flood runoff obtained in Gorbachova et al. (2021) and Ovcharuk and Gopchenko (2022).

Desna river basin. The Desna basins behave similarly to those of the Bug. In the first subperiod, the most frequent floods occur in early April. In the second subperiod flooding begins almost two weeks earlier than in the first subperiod, with floods being most frequent in late March.

4.3 Flood timing of Austrian rivers

River basins of the Alpine region. Floods in the Alpine region occur most frequently in the summer (Figure 5). There is a slight shift towards between the two subperiods, and the floods tend to become somewhat more frequent across the months September to November.

River basins of the Northern Lowlands. In this region, the main flood types are caused by long rain and rain-on-snow events (Merz and Blöschl, 2003). The circular kernel density diagrams of the day of occurrence of floods for the two periods have a multi-peaked distribution (Figure 5). Floods are observed throughout the year with the lowest frequency occurring in autumn. The second subperiod shows a lower frequency of floods in January but a higher frequency in March–April, and a somewhat lower frequency in July. Even though rainstorms tend to occur more frequently in summer, the high soil moisture content in winter is a contributing cause to floods in these months (Sivapalan et al., 2005). Rain-on snow floods tend to be most extreme in late December. These events are triggered by the advection of relatively warm and moist air which produces significant energy input into the snow cover through condensation and long wave radiation (Sui and Koehler, 2001).

River basins of the Eastern Lowlands. In these basins, flash floods caused by convective storms are frequent, in addition to other flood types (Merz and Blöschl, 2003). The highest frequency of floods is in summer (June–August) with 25–30% of all Qmax values occurring in this period of the year. Some flooding occurs also in the other seasons. The flood seasonality of the two subperiods is rather similar.

4.4 Comparative analysis

Many researchers (Blöschl et al., 2019; Hall and Blöschl, 2018; Rottler et al., 2021) confirm that climate change has a complex effect on the water cycle and the flood regime, and this is also the case in Austria and Ukraine. The comparison of mountain and lowland basins reveals significant differences in the seasonality of floods with similarities between the countries.

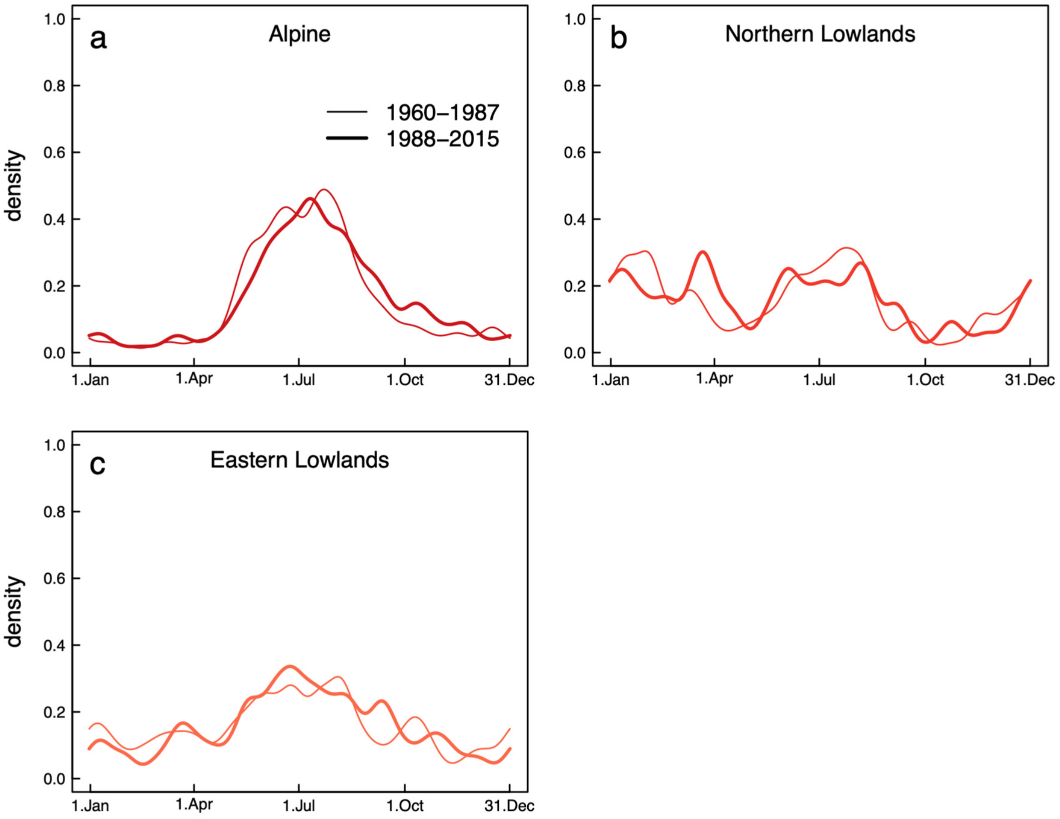

Fig. 5. Seasonality of floods for three Austrian regions. The lines show the distribution (circular kernel density) of the day of occurrence of floods in two periods (1960–1987 and 1988–2015). The panels refer to the Alpine region (a), Northern Lowlands (b) and Eastern Lowlands (c).

Mountain basins such as the Upper Tisza in the Ukrainian Carpathians and the Alpine region in Austria have a very similar flood seasonality. The floods in the Upper Tisza basin occur throughout all seasons of the year with a maximum frequency of occurrence in March-April and in November. The Tisza basin, unlike other river basins of the Carpathian region, is characterized by floods of mixed origin (rain on snow floods and rain-induced flooding, which occur in the cold period of the year. The flood regimes are determined by climate influences that vary across geographies, climate change influences and orographic influences of Transcarpathia.

Snowmelt floods and rain on snow floods are typical for winter and spring. Flash floods and long-rain floods occur in summer and in autumn. The Carpathian Mountains block the path of moist air masses from the Atlantic and the Mediterranean, which leads to a direct dynamic influence of mountain slopes on the air flows.

The two subperiods considered, 1988–2015 and 1960–1987 differ in terms of the flood seasonality for the Tisza basin. The spring flood peak (maximum kernel density) shifts from late to early March and there is an increase in autumn floods. The reason for the latter is an increase in the frequency of heavy precipitation events (250–350 mm) occurring over large areas and over short duration (2–3 days), especially in autumn, that have been related (to some extent) to climate change in the region (Balabukh, 2008; Tatarchuk and Tymofeyev, 2017). The results are in good agreement with previous studies (Blöschl et al., 2017; 2019; Vyshnevskyi and Donich, 2021), which reveal a trend towards an increase in runoff during the cold period of the year and a shift in the flooding to later dates in the year.

In the Alpine region, the period of most frequent floods from April to October is related to the continental climate and, again airflows from the Atlantic and the Mediterranean. High intensity mid-latitude cyclones tend to be more frequent in the summer, which explains the higher frequency of precipitation events and associated floods (Hofstätter et al., 2018). The occurrence of these heavy precipitation events is related to the cyclone track type. In particular, cyclones of type VB according to van Bebber (1891) are particularly relevant for flooding in summer. Additionally, snow and glacier melt can be important for flooding in this region (Merz and Blöschl, 2003). But snowmelt usually plays only a secondary role in flood generation and instead cyclone systems (and associated by thunderstorms) are the main drivers of floods across basin areas. Changes in atmospheric circulations, and associated changes to precipitation patterns across different parts of the year are complex (Haslinger et al., 2021), and so do not manifest clearly in the flood seasonality. Rainfall depths tend to be largest in the north-west of the region, mainly as a result of orographic effects. At the northern fringe of the Alps in the north-west of Austria, rainfall associated with a return period of 100 years is of the order of 150 mm (Breinl et al., 2021). In the basins at the northern fringe of the high Alps, long duration rainfall driven floods are particularly common. The high Alps act as a topographic barrier to north-westerly airflows, and orographic enhancement often produces persistent rainfall which can result in floods.

A comparison of the Alpine region in Austria and the Upper Tisza mountainous region in Ukraine shows that in both regions the dominant factor influencing the formation of maximum floods is the same synoptic process. This synoptic process is associated with the development of cyclones from the Mediterranean Sea and the Atlantic. This explains, why these regions have a similar pattern of flood seasonality. Floods in the Alpine region most often occur in summer. In the Upper Tisza basin, they occur most often in spring, summer and winter. Some of the differences in flood seasonality between the two basins are explained by the significant variability of the relief in the Upper Tisza basin.

In the second sub-period (1988–2015) there was a noticeable increase in the frequency of floods in the autumn period for both basins. In the basin of the Upper Tisza compared to the first period the frequency of floods has in fact doubled. In the Alpine region, the change is not as significant.

The seasonality of floods of lowland rivers, which include the basins of the Dniester, Southern Bug, Desna (Ukraine) and the rivers of the Northern Lowland and the Eastern Lowland (Austria), differs from that of mountain rivers.

In the Dniester basin the maximum number of days with annual Qmax in both comparative periods is observed in spring (March-May). Because of the contributions of mountain and lowland zones, the Dniester River has a flood seasonality with two maxima: in spring (March-May) caused by spring snowmelt and in autumn (September) caused by summer and autumn heavy rains. The frequency of spring floods decreased from 60% in the first period (1960–1987) to 40% in the second period (1988–2015), and it is likely that the trend of these changes will persist in the future. Modelling of the RCP4.5 and RCP8.5 scenarios predicts a 10–30% decrease in spring flood runoff (Ovcharuk, 2020), as well as an increase in summer flood runoff (Didovets et al., 2019). The basins of the Northern Lowlands have a similar multi-peaked seasonality with the highest frequencies of floods occurring in January (associated with snowmelt), March, June and August (rain on snow flood, long-rain flood, flash flood). Following Merz and Blöschl (2003) spring flooding in these regions of Austria is often related to a rapid increase in air temperature as a result of the inflow of warm and moist air. Relatively low rainfall depths on an existing snow cover produce a significant portion of maximum annual floods in these basins and are affected by a warmer climate. Rain-on snow floods tend to be most extreme in late December, partly because of the advection of warm moist air which transfers significant energy inputs to the snow cover through condensation and long wave radiation.

The highest frequency of recurrence of days with annual Qmax is observed in January (about 25%), March-October (about 30%), June (about 25%), August (about 30%) and December (about 20%). Three main changes were found in the timing of the floods in the basins of the Eastern Lowlands rivers during the first observation period (1988–2015) compared to the previous period (1960–1987). First, the probability of a day with annual Qmax in January decreased from 30% to 15–20%. Second, the probability of a day with annual Qmax in March-April increased from 10–20% to 30% and third, for July it decreased from 30% to 20%. In the Northern Lowlands there is a tendency for more frequent floods in spring and in December. In the Eastern Lowlands on the other hand, the changes are small.

The basins of the Eastern Lowlands are the driest part of Austria and therefore are comparable with the South Bug basins in Ukraine, where the lower parts are in the steppe zone characterized by an arid climate, intermittent snow cover and less spring flooding. The most frequent floods occur in the South Bug basins in spring (April) and in the Austrian Eastern Lowlands in the summer (June–August). Indeed, the upper and middle reaches of the Southern Bug are characterized by pronounced spring floods (70–80% of annual river flow) and low dry-weather runoff with a flood seasonality typical of most of the lowland rivers of Ukraine.

Three main changes were found in the timing of the floods in the basins of the Eastern Lowlands rivers during the first observation period (1988–2015) as compared to the previous period (1960–1987). First, the peak of the histogram with the highest frequency of annual Qmax cases shifted from August to June. Second, the frequency of days with an annual Qmax increased for June by about 40% and third, this also increased for September by about 25%.

In the basin of South Bug in the second period of observation, the probability of a day with annual Qmax decreased for April from 90% to 70% and increased for June from 10% to 20%.

The changes in flood timing in the Desna basin is similar to those of basins discussed above with the difference being that the shift towards earlier spring floods is clearer, related to warmer winters with associated thaws (Gorbachova and Koshkina, 2013). The frequency of winter floods in the Desna river basin is increasing and frequency of spring floods is decreasing (Snizhko et al., 2022). In the second period of observations (1988–2015) the process of flood formation began almost two weeks earlier than in the first period (1960–1987). A comparison of histograms of the distribution of annual Qmax dates of both periods shows an increase in the recurrence of annual Qmax cases in the second period from May 8 to June 12. This is explained, first of all, by the intensification of the warming of the underlying surface, which affects the formation of powerful convective air currents, thunderstorms and showers (Balabuh, 2008, 2011).

In the Dniester basin the frequency of spring floods decreased and it is likely that these changes will persist in the future. Modeling of the RCP4.5 and RCP8.5 scenarios predicts a 10-30% decrease in spring flood runoff (Ovcharuk, 2020), as well as an increase in summer flood runoff (Didovets et al., 2019). Similar changes in the timing of floods can be seen in the Southern Bug which is consistent with the predicted trends toward a decrease in spring flood runoff (Gorbachova et al, 2021; Ovcharuk and Gopchenko, 2022; Ovcharuk et al., 2017).

The changes in flood timing in the Desna basins is similar to those of basins discussed above with the difference being that the shift towards earlier spring floods is clearer, related to warmer winters and associated thaws (Gorbachova and Koshkina, 2013). Balabuh (2008; 2011) found significant increases in the average summer temperature and moisture content of the troposphere in Ukraine since the 90s, which has led to an increase in convective potential energy of the atmosphere (increasing instability of the atmosphere). As a result of such changes, the number and intensity of heavy rains, hail, squalls, tornadoes and the number of days with thunderstorms have increased (Balabuh, 2008; 2011).

4.5 Trends in flood magnitude

During the study period (1960–2015) a negative (decreasing) trend in flood magnitude was found for most (85.7%) of the gauges of the Ukrainian rivers (Table 1), i.e. 234 gauges out of 273. For 109 gauges (39.9%) of these 234 gauges the negative trends are statistically significant at the 5% significance level. Positive (increasing) trends in flood magnitude were found only for 39 Ukrainian river gauges, of which only 5 (1.8%) were statistically significant. The positive trends occur mainly in the mountain rivers of Ukraine. For example, in the Upper Tisza basin, positive trends were found for 34.3% of the stations, but the trends are statistically significant for only 2.9% of the gauges. In the Dniester Basin, the percentage of positive trends is even lower, i.e. 27.3% (only 3.6% are statistically significant). For the lowland rivers of Ukraine, positive trends in flood magnitude for the study period were not detected. For both lowland basins

(South Bug and Desna), a slight decrease in flood magnitude is observed. The observed trends are negative at all gauges of these basins. However, statistically significant trends were confirmed in the South Bug basin only in 14.3% of the stations, and in the Desna Basin in 50% of the stations.

In Austria, on the other hand, most river gauges (75.3%) show an increase of the flood magnitude during the study period, and 20.3% show a significant positive trend (Table 2). Negative trends were detected only in 24.2% of the gauges, and 2.5% were statistically significant. A large number of positive trends are found in the Alpine region (at 71.2% of the gauges) and 17.3% show statistically significant positive trends. In the river basins of the Northern Lowlands positive trends were detected at 80.9% of the gauges (with 22.3% of gauges showing significant positive trends). In the Eastern Lowlands positive trends at 80.9% of the gauges were detected (with 22.3% of gauges showing significant trends). No statistically significant negative trends of flood magnitudes were found in the Eastern Lowlands.

In order to identify the spatial differentiation of flood formation processes under climate change, two maps with time trends of flood magnitude were constructed (Figure 6). These maps clearly demonstrate a largely coherent negative trend across Ukraine (red downward triangles) in the formation of the magnitude of floods due to climate change. The areas where there is an increase in the magnitude of floods (blue upward triangles) in the Ukraine are very localized. They are limited to the mountainous regions of Ukraine, such as the Crimean and the Carpathian Mountains (Figure 6). In Austria, on the other hand, tendencies towards an increase in magnitude prevail, in particular in the north of the country. The warming of the climate is aligned with increases in summer rainfall, in particular north of the Alps (Blöschl et al., 2018). Fig. 6. Trend in annual maximum discharges in the period 1960–2015. Blue upward triangles indicate positive trends. Red downward triangles indicate negative trends. Stations with significant trends at 5% significance level are indicated with darker black bordered triangles. Trends are calculated only for series with at least 30 years for data in 1960–2015.

Table 1. Number and percentage of stations exhibiting trends in the magnitude of annual maximum discharges for Ukraine and four Ukrainian regions.

		Positive trend	Negative trend	All	Positive trend (%)	Negative trend (%)	All (%)
Ukraine All gauges	Significant	5	109	114	1.83	39.93	41.76
	Not significant	34	125	159	12.45	45.79	58.24
	All	39	234	273	14.29	85.71	100
Ukraine Upper Tisza	Significant	1	10	11	2.86	28.57	31.43
	Not significant	11	13	24	31.43	37.14	68.57
	All	12	23	35	34.29	65.71	100
Ukraine Dniestr	Significant	2	14	16	3.64	25.45	29.09
	Not significant	13	26	39	23.64	47.27	70.91
	All	15	40	55	27.27	72.73	100
Ukraine Pivdennyj Bug	Significant	0	3	3	0	14.29	14.29
	Not significant	0	18	18	0	85.71	85.71
	All	0	21	21	0	100	100
Ukraine Desna	Significant	0	5	5	0	50	50
	Not significant	0	5	5	0	50	50
	All	0	10	10	0	100	100

Table 2. Number and percentage of stations exhibiting trends in the magnitude of annual maximum discharges for Austria and three Austrian regions.

		Positive trend	Negative trend	All	Positive trend (%)	Negative trend (%)	All (%)
Austria All gauges	Significant	120	18	138	20.62	3.09	23.71
	Not significant	315	125	440	54.3	21.48	76.29
	All	435	143	578	74.91	24.57	100
Alpine	Significant	53	13	66	17.26	4.23	21.5
	Not significant	166	74	241	54.07	24.1	78.5
	All	219	87	307	71.34	28.34	100
Northern Lowlands	Significant	36	2	38	22.78	1.27	24.05
	Not significant	92	28	120	58.23	17.72	75.95
	All	128	30	158	81.01	18.99	100
Eastern Lowlands	Significant	30	3	33	26.55	2.65	29.2
	Not significant	57	21	80	50.44	18.58	70.8
	All	87	24	113	76.99	21.24	100

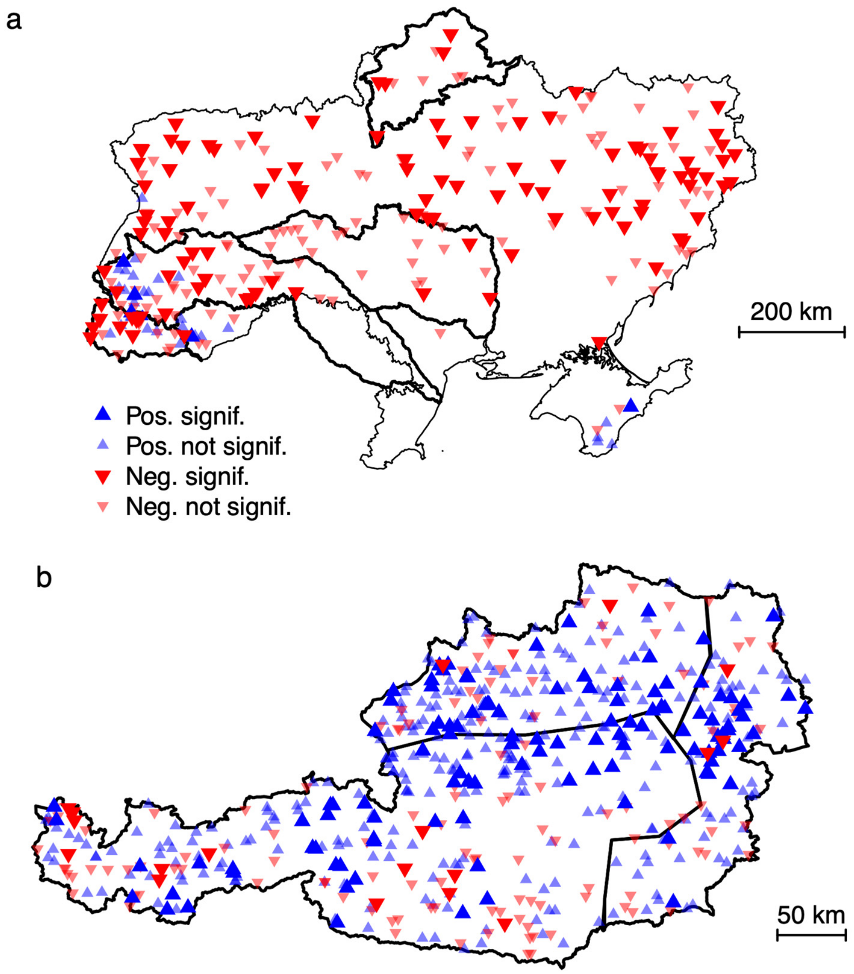

Fig. 6. Trend in annual maximum discharges in the period 1960–2015. Blue upward triangles indicate positive trends. Red downward triangles indicate negative trends. Trends are calculated only for time series with at least 30 years of data in the period 1960–2015.

4.6 The effect of seasonality on the formation of the flood magnitude trends

The shift in flood seasonality, which has occurred with climate change, has significantly impacted the formation of trends in flood magnitude for both plain and mountain river basins. Floods on the mountain rivers of Ukraine are formed as a result of melting snow cover and rain on snow (in winter and spring) and under the influence of rain runoff (during summer and autumn). Hrebin (2010) states that in the modern period under climate change the average monthly rainfall in December and January in the Carpathian region decreased by 8–19%. In winter, under conditions of warming, snowfall is partially or completely replaced by rain, and snowmelt increases, which leads to a decrease in snow cover. Zabolotnia et al. (2021) indicates that the average annual maximum snow depth observed at Ukrainian stations for the period 1935–2016 is 38 cm, which is significantly less than that at Austrian stations for the period 1970–2016 (68 cm). A decrease in snow accumulation and water yield from the snowpack leads to a decrease in the frequency and amplitude of floods in February and March compared to the first observation subperiod (1960–1987). This factor not only strongly weakens the formation of positive trends in the magnitude of floods on the mountain rivers of the Carpathians, but also changes them to negative ones (65.7% in the Tisza basin and 72.7% in the Dniester basin).

At the same time, an increase in the amount of precipitation in the autumn months by 38–44% (Hrebin, 2010) leads to the formation of a significant peak of the frequency of Qmax annual in November for the Upper Tisza region (Figure 4a). This process contributes to the formation of a positive trend between the first and second subperiods. However, clear positive amplitude trends were found only on small watercourses and streams, where rapid melting of the winter snowpack or the rain runoff affected water flows.

The Dnister basin is characterized by maximum runoffs from different source regions - the mountains and the plains. In the mountains, Q max annual values are observed mainly during rain floods, and on the plains mainly during spring. Melnyk and Loboda (2018) show that the ongoing climate change in the Upper Dniester basin may cause both an increase and a decrease in the maximum river runoff. The major role in trends in the maximum runoff is played by precipitation. The role of thaws increases in the cold season, especially in the lowlands, where most of the annual runoff is formed by snow melt.

The value of the density distribution of Q max annual for plain rivers of Ukraine (Southern Bug and Desna) in the spring flood peak area decreased significantly between the two analysis periods. As a result of climate change (significant warming in the cold period of the year), winter thaws led to a decrease in water reserves in the snow and resulted in an early onset of the spring flood and a decrease in its magnitude. Therefore, trends in flood magnitude for these rivers have a clearly expressed negative trend.

In contrast to the Ukrainian rivers, the flood magnitude of the Austrian rivers has increased in 75.3% of the gauges. These increases are mainly related to changes in the weather patterns such as high intensity mid-latitude cyclones with heavy precipitation in the summer. Blöschl et al. (2019) analysed records from a pan-European flood database and revealed consistent spatial patterns of trends in the magnitude of the annual maximum flood, with clear positive trends in north-western Europe and decreasing trends in southern and eastern Europe.

The increasing winter runoff in the UK is typically explained in the literature by increasing winter precipitation and soil moisture (Wilby et al., 2008). Recent studies show that extreme winter precipitation and flooding events in northwestern Europe are positively correlated with the North Atlantic Oscillation and the east Atlantic pattern (Brady et al., 2019; Hannaford and Marsh, 2006; Steirou et al., 2019; Zanardo et al., 2019). Furthermore, the largest winter floods in Britain occur simultaneously with atmospheric rivers (Lavers et al., 2011), which are expected to become more frequent in a warmer climate (Lavers and Villarini, 2013).

5 CONCLUSIONS

a). The comparative study of flood formation under climate change in the period from 1960 to 2015 shows differences in the seasonality of floods in Ukraine and Austria. In Ukraine most floods occur in February-May while in Austria they occur in May-October. This is because spring floods of most Ukrainian lowland rivers are caused by snowmelt and summer floods in Austria are mostly caused by heavy precipitation.

b). The timing of flooding is not a stable characteristic but changes under the influence of increased air temperature and differing precipitation regimes. Spring floods now tend to occur earlier than in the past and with lower frequency, which is related to warmer winters with earlier thaw periods and lower values of snow pack depths. On the other hand, the warming has increased the frequency of floods in autumn and winter, especially in the mountain basins.

c). The trend analysis shows that during the study period (1960–2015) most Ukrainian rivers (85.7% of gauges) show decreasing trends in flood magnitude, and about 40% show significantly decreasing trends. These decreases are mainly related to smaller snow pack depths and less intense snow melt. In contrast, the flood magnitude of the Austrian rivers has increased in 75.3% of the gauges, where 20.3% show statistically significant positive trends. These increases are mainly related to modifications in the weather patterns.

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