Present Environment and Sustainable Development
Volume 17, number 2, 2023
DOI: https://doi.org/10.47743/pesd2023172001

Increasing flood magnitude, an effect of climate change or natural climate variability?

Dan DUMITRIU[1]

[1]Alexandru Ioan Cuza University of Iași, Faculty of Geography and Geology

*****Correspondence: dumitriu.dan@uaic.ro

Keywords: maximum peak discharge; flood magnitude ratio; mean annual flood; flood-rich period.

Abstract: The last two decades have seen a number of changes in the magnitude of flood events. In general, the causes of these changes have been attributed to either climate change or natural climate variability. The aim of this paper is to identify changes in the magnitude of flood events recorded in recent decades on the Trotuș River and to attempt to determine the underlying causes. The identification of changes in flood magnitude was based either on the analysis of annual and monthly peak flows or on the analysis of flows above a certain threshold. Based on these data sets, two important parameters characterizing the magnitude of a flood event were quantified: the flood magnitude ratio and the mean annual flood. The analysis of the values of the two parameters revealed that there has been a clear increase in flood magnitude since 2004. At all stations analysed, there were at least 5 flood events with a magnitude at least twice the maximum magnitude of the pre-2004 period between 2004 and 2020. As the changes in magnitude occurred quite rapidly, we believe that they are largely due to natural climatic variability and that the period after 2004 can be considered a flood-rich period.

1. Introduction

The characteristics of flood events (magnitude, frequency, intensity, duration, etc.) have undergone a number of important changes in recent decades (Pinskwar et al., 2012; Kundzewicz et al., 2013; Hall et al., 2014; Mangini et al., 2018; Blöschl et al., 2020). Variations in flood magnitude can be caused by three main groups of potential factors, located at catchments, river channels and within the atmosphere. These factors include: land use change (urbanization, deforestation, wildfires, agricultural management practices, drainage of wetlands and agricultural areas, construction of flood retention basins); river channel engineering and hydraulic structures (river training, reduction in river length, construction of dikes, groynes and weirs, operation of hydropower plants and reservoirs) and climatic change (natural climate variability at different time scales, anthropogenic climate change) (Merz et al., 2012; Kundzewicz, 2015; Blöschl, 2022). The effects of the three categories of factors on the flood regime have different degrees of understanding. While at the scale of a watershed the effect of hydropower structures seems to be fairly well understood, with regard to the effect of land use/management and climate variability on the flood regime things are a bit more complicated (Hall et al., 2014; Rogger et al., 2017; Xu et al., 2019).

As global warming intensifies, more extreme precipitation is expected for much of the globe. This would be due to the Clausius-Clapeyron thermodynamic relationship, whereby the concentration of water vapour in the atmosphere, which provides water for precipitation, will increase by about 6-7% for every one degree increase in temperature. As a result, global average precipitation is expected to increase by 1-3% per degree of warming, and extreme precipitation is expected to increase at a much faster rate of about 5-10% per degree, with much larger increases in some regions (Swain et al., 2020). Climate change is therefore expected to alter hydrological regimes around the world, with major implications for extreme hydrological events (floods and droughts) (Blöschl et al., 2019; Eccles et al., 2021). These changes are not spatially uniform but vary from region to region (Hirabayashi et al., 2013; Cao et al., 2021), as water availability plays an important role in the moisture-temperature relationship. Amplification of extreme precipitation can lead to changes in flood characteristics, primarily magnitude (Thober et al., 2018; Tabari, 2020). Despite this evidence, there is still much uncertainty about the correlation between intensification of extreme precipitation and increased flood magnitude (Knox, 2000; Rojas et al., 2012; Wasko and Sharma, 2017; Sharma et al., 2018; Wasko et al., 2020; Blenkinsop et al., 2021). Changes in flood magnitude, intensity and frequency depend not only on extreme precipitation but also on antecedent soil moisture conditions. However, as a result of rising temperatures, intense evaporation of soil water also occurs, which will lead to a decrease in soil moisture (Ficklin et al., 2019; Brêda et al., 2023).

Data on floods on the European continent over the last 50 years highlight that for some regions there has been an increase in their frequency and magnitude (Kundzewicz, 2015; Pińskwar et al., 2019). The causes of these changes are not fully understood and it is not clear whether they are due to climate change or to natural climate variability at different timescales, which would favour a flood-rich period. The difficulty in establishing the causes of the increase in the frequency and magnitude of floods in recent decades is closely linked to the irregular nature of such events. A large flood event does not necessarily indicate an increasing flood trend (Hall et al., 2014). Many papers suggest that analysis of flood frequency and magnitude trends is not always conclusive, as floods are complex phenomena influenced by a multitude of local, regional or hemispheric controlling factors (Kundzewicz et al., 2005).

A number of studies have identified clustering or flood-rich/flood-poor periods in historical streamflow data (Jacobeit et al., 2003; Glaser et al., 2010; Kundzewicz, 2015; Markonis et al., 2018; Lun et al, 2020; Brönnimann et al., 2022). In the context of natural climate variability, the existence of flood-rich periods alternating with flood-poor periods is attributed to the Hurst effect (Blöschl and Montanari, 2010). It is assumed that this clustering pattern of flood events is related to climate-ocean oscillations or persistent long-term memory of hydrological processes (Hall et al., 2014; Tarasova et al., 2023). For several European river basins, it has been demonstrated (based on historical records, lake sediments, etc.) that there have been flood-rich periods over the last 1000 years. In relation to this, most authors, point out that the frequency and magnitude of flooding during the Little Ice Age (1300-1870) and in particular the Late Maunder Solar Minimum (1675-1725) have been correlated with lower temperatures (Hall et al., 2014), whereas nowadays these changes occur against a background of higher temperatures. However, to date, no clear relationship between air temperature and periods of high precipitation has been identified. Blöschl et al. (2020) identified nine flood-rich periods on the European continent over the last 500 years. The last period, 1990-2016, probably continues today.

Studies on floods in recent decades for rivers in Eastern and Central Europe (which have a connectivity with the Romanian territory) show either a decrease in their magnitude, attributed to decreasing snow cover and snowmelt, resulting from warmer temperatures (Blöschl et al., 2019; Gudmundsson et al., 2019) or a certain increase (Markonis et al., 2018; Kemter et al., 2020). As regards projections for the next 100 years, a generally decreasing trend in flood magnitude is expected (Bertola et al., 2020; Kundzewicz and Pińskwar, 2022). However, all these general trends are highly sensitive depending on the size of the basins, local conditions, methodologies and statistical approaches used, type of databases (Lun et al., 2021; Brêda et al., 2023).

It has been found that the vast majority of studies have used annual or seasonal mean flows in relation to climate change, and less so maximum flows (Arheimer and

Lindström, 2015). For this reason, the present study attempted an analysis of changes in streamflow of the Trotuș River over the last half century using maximum monthly and annual discharge.

The aim of the study is to identify, using different methodologies, changes in the magnitude of flood events over the last 50 years. The objectives were: (i) to quantify the flood magnitude ratio and the mean annual flood; (ii) to analyse the correlations between peak flows and other hydrological parameters; (iii) to establish the trend in flood magnitude over the last 20 years and the conditions that contributed to its change.

2. Materials and Methods

2.1. Study area

The analysis of the variation in the magnitude of flood events was based on data from four gauging stations along the Trotuș River. The Trotuș river basin, with an area of about 4500 km2, is located in the central-eastern part of the Eastern Carpathians and Subcarpathians of Moldova (Figure 1).

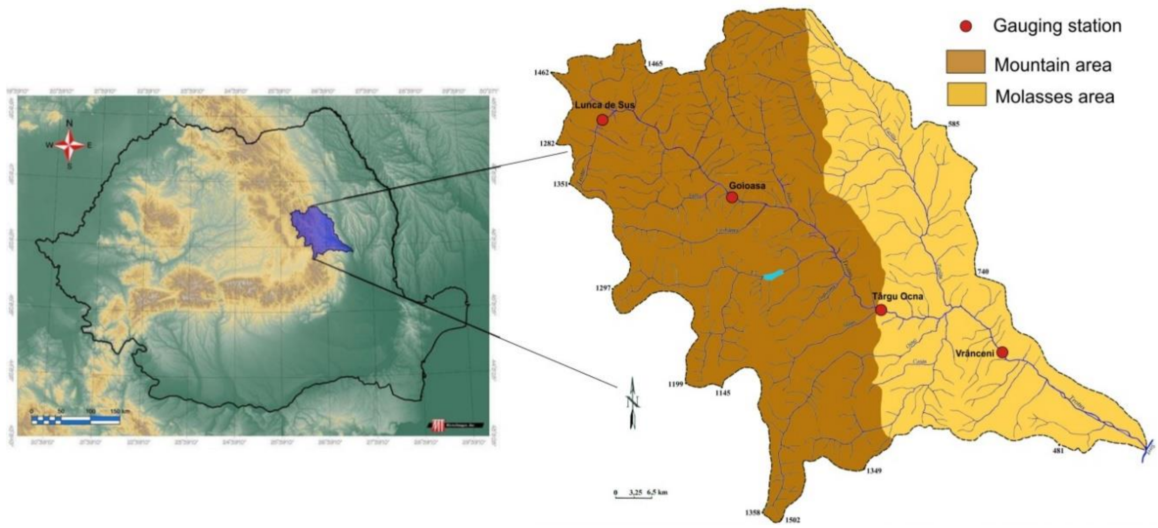

Figure 1. Location of the study area in Romania and location of gauging stations.

The climate is typical of Carpathian mountainous areas with mean annual precipitation of 720 mm, ranging from 580 in the lowlands to 1150 mm at high altitudes. The share of the precipitation related to the total sum of maximum amounts recorded in 24 hours above 100 l/m^2 has been rising continually: 8.3% between 1941 and 1960; 30.8% between 1961 and 1980; 47.5% between 1980 and 2000; and 67.7% after 2000 (Dumitriu, 2014, 2018). As regards the land cover/land use, forests, pasturelands and meadows are prevalent in the higher regions of the upper and mid courses, whereas in the lowlands corresponding to the lower course agricultural lands and pastures are dominant (Dumitriu, 2016, 2018). The multi-year average flow (reported to 2020) was 0.88 m^3/s at the Lunca de Sus station (in the upper course); 17 m^3 /s at the Târgu Ocna station (in the middle course, at the contact between the Carpathian and subcarpathian areas) and 35 m^3/s at the Vrânceni station (in the lower course, located at the contact between the subcarpathian and plateau areas). The maximum flow (2845 m^3/s) was recorded at the Vrânceni station in July 2005 (Dumitriu, 2020a).

2.2. Data sources

In this study, data on monthly and annual maximum peak discharges have been used, from the establishment of the four gauging stations (Lunca de Sus - 1976; Goioasa - 1952; Târgu Ocna - 1955; Vrânceni - 1963) until 2020. For some comparisons, average daily discharges from 1994-2020 have also been used. The data are provided by the

"Romanian Waters" National Administration - Siret Water Branch, which manages the gauging stations included in this study.

2.3. Methods

In a first step, for the long-term analysis of the variability of the magnitude of flood events, the flood magnitude ratio (FMR) was calculated using the following formula (Bhattacharya et al., 2019):

$$FMR = \frac{Qp}{Q_a} \quad (1)$$

where Q_p represents the annual maximum peak discharges and Q_a represents the average discharge for the period under review.

Conceptually, FMR defines the severity of a flood event by considering only the peak flood discharge. The higher the magnitude of the flood event, the higher the FMR. Unfortunately, FMR does not take into account the dynamic aspects of flood propagation (Bhattacharya et al., 2019).

The mean annual flood (MAF) was defined as either the arithmetic average of all annual floods for the recorded gage period (or other specified time interval) (Dumitriu, 2016). This parameter was calculated for two specific periods: 1994-2004 and 2005-2020.

Flood-rich and flood-poor periods can be analysed either on the basis of annual maximum peak discharges (AMP) or peak over threshold series (POT) (Karim et al., 2017; Mangini et al., 2018; Fischer et al., 2023). The AMP series include peak flows for each year. The advantage of using AMP series is that flood events can be considered independent. The main disadvantage of the AMP method would be that it neglects flood events that had peak flows lower than the annual peak (Mangini et al., 2018). The POT series comprises the peak flows of flood events that exceed a predefined threshold. The analysis of the two distinct data sets to define flood-rich and flood-poor periods on a per-basin basis is performed using complex statistical methods. In this study a simple analysis of the AMP data series was used. From the AMP series, flood events with a recurrence interval of 10, 50, and 100 years, respectively, were used for comparison. The characteristic flows for the three recurrence periods were determined by the Gumbel method using the (free trial) HYFRAN 1.2 software (HYdrological FRequency ANalysis).

3. Results and discussion

3.1. Flood magnitude ratio

In the upper reaches (Lunca de Sus), the FMR shows values close to those of the annual peak flows, with the largest differences (positive for FMR) observed in years with significant flood events (1984, 2005, 2014, 2016 and 2018) (Figure 2). The differences between the two parameters increase downstream (FMR values are lower), indicating that peak flows are much higher than the multi-year averages. Related to this, the literature appreciates that the range of FMR values is primarily influenced by the geomorphological characteristics of the catchment (Bhattacharya et al., 2019).

At all four stations there is a noticeable change after 2004 in the magnitude of flood events. At the Lunca de Sus station, in the period 1976-2004, the recurrence interval or return period flood of 10 years (10-year flood) occurred only once, namely in 1984. After 2004, the 10-year flood was reported in 2005, 2010, 2014, 2016 and 2018. Also at Lunca de Sus, the 50-year flood was recorded only in 2016. At the next station, Goioasa, the 10-year flood had 5 occurrences between 1952-2004 (1971, 1975, 1978, 1984 and 2002) and 5 between 2004-2020 (2004, 2005, 2010, 2016, 2018) (Figure 2).

The difference is that the first interval spans 52 years and the second only 17 years. The situation is totally different in the case of the 100-year flood which was reported only in the interval 2004-2020 (2004, 2005, 2010 and 2016). At Târgu Ocna, the station located at the contact of the mountainous and subcarpathian area, the 10-year flood occurred 5 times in the period 1955-2004 (1969, 1971, 1975, 1984 and 1991), as well as in the interval 2004-2020 (2004, 2005, 2010, 2016 and 2018). In contrast, the 100-year flood was reported only twice, in the second interval analysed (2005, 2018). At Vrânceni, in the lower course, the number of 10-year floods is clearly in favour of the first interval (1963-2004), with 7 occurrences (1969, 1971, 1975, 1979, 1984, 1988, 1991). Also at this station, 100-year floods were recorded only after 2004 (2005, 2016, 2018).

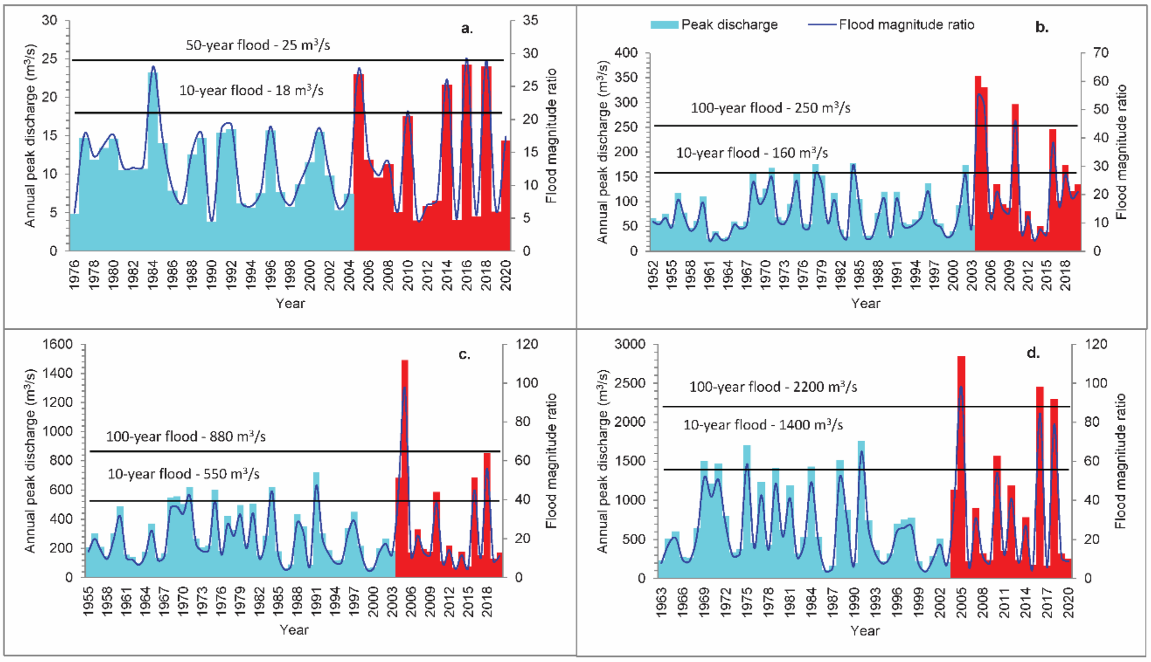

Figure 2. Flood magnitude ratio: (**a**) Lunca de Sus; (**b**) Goioasa; (**c**) Târgu Ocna; (**d**) Vrânceni. The flood-rich period after 2004 is shown in red.

These data seem to confirm those presented by Blöschl et al. (2020), i.e. that central Europe (the Trotuș river basin being located, according to these authors, at the interface of the central and eastern European zones) is currently experiencing a period of high flooding. The authors point out that this situation seems to be caused by a persistent anomalous circulation regime of frequent low-pressure systems over the east Atlantic and western Europe. Although the temperature is slightly higher, the current conditions in this part of Europe seem to be similar to those of the period of high flooding between 1760 and 1800. According to these data, natural climate variability appears to be behind the increase in the magnitude of flood events over the last 20 years. It appears that at the eastern edge of central Europe the onset of this flood-rich period had a time lag of more than 10 years. Previous studies of the study area (Rădoane et al., 2013; Dumitriu, 2020b) have highlighted a trend of decreasing multiannual mean liquid flows, amidst stagnating or decreasing precipitation amounts, concomitant with increasing evapotranspiration (Prăvălie et al., 2019). However, an increase in the magnitude and frequency of extreme precipitation (Croitoru et al., 2016) and peak discharge has been observed (Dumitriu, 2020b). In this context, in the study area, the link between climate change - temperature increase - precipitation and discharge increase is poorly supported by hard data. Thus, the increase in the magnitude of flood events in the last 20 years seems to be a consequence of natural climate variability rather than a direct consequence of anthropogenic climate change.

3.2. Mean annual flood

The mean annual flood has values much closer to the mean daily flows than the instantaneous peak flows. For this reason, a graphical representation of the mean annual flood values in two time periods (1994-2004 and 2005-2020) in terms of mean daily flows was chosen (Figure 3). As in the case of FMR and MAF, it highlights the increase in the magnitude of flood events after 2004. The MAF values corresponding to the second interval are visibly higher compared to those of the first interval: 1.3 times at Lunca de Sus; 1.8 times at Goioasa; and about 1.4 times at Târgu Ocna and Vrânceni. It can be observed here too that in the upper reaches the changes are smaller than in the middle reaches. This situation can be explained by the fact that in this sector, the Trotuș receives most of the tributaries. Each of these basins is characterized by different hydro-geomorphological conditions. As a consequence, the range of variation of influences on the main river is much more complex.

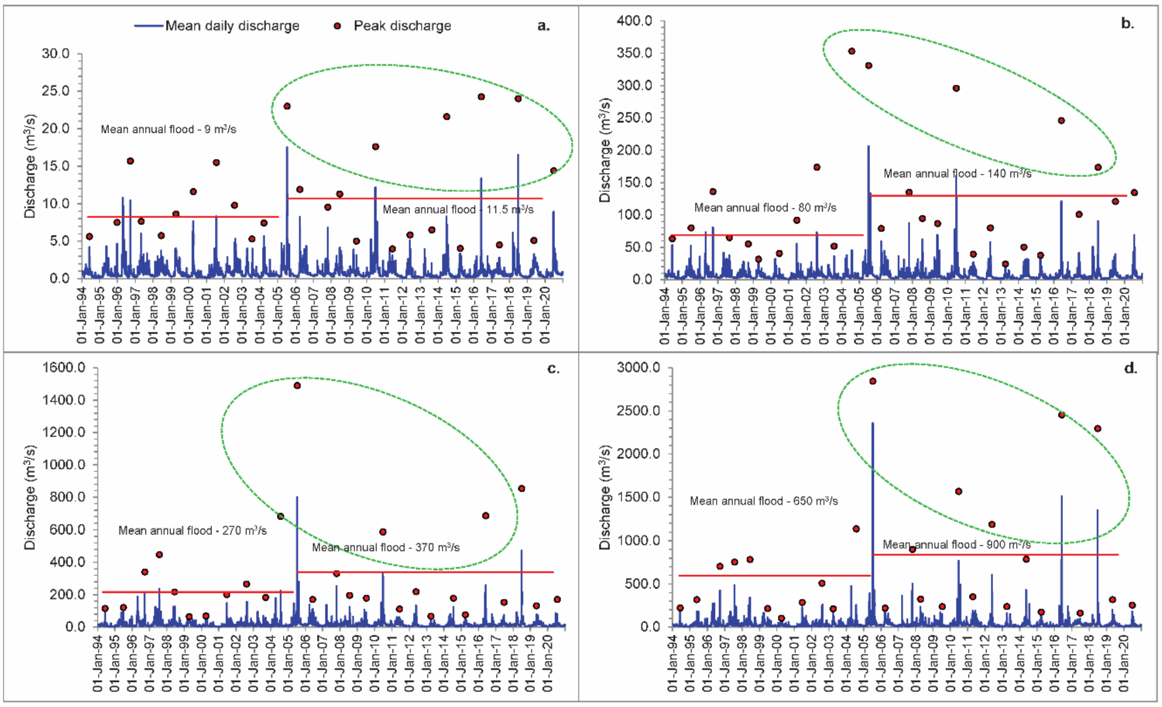

Figure 3. Time series of the mean daily discharge data (1994-2020) and the instantaneous peak discharge: (**a**) Lunca de Sus; (**b**) Goioasa; (**c**) Târgu Ocna; (**d**) Vrânceni.

This dependence of MAF values on the physical-geographical conditions of a river basin is recognized in the literature (Mimikou and Gordios, 1989). In the second range analysed, a much greater degree of dispersion of maximum flow values is observed, which can be attributed to the increased role of extreme rainfall in the formation of flood events. If in the first interval the maximum discharge values are positioned close to the MAF line, in the second interval the differences are quite significant. For example, at the Vrânceni station, in the period 1994-2004, the maximum flow was 1.75 times higher than the MAF, while in the interval 2005-2020 it was 3.2 times higher.

In general, MAF is regarded as a potential index of the magnitude of a flood event. This parameter facilitates the standardization of flood event data from different river basins (Mimikou and Gordios, 1989). At the four stations along the Trotuș River, an increase in the magnitude of flood events after 2004 is observed based on the MAF analysis.

3.3. Annual peak discharge vs. mean annual discharge

The correlation between mean and maximum annual flows was used to highlight the role of changing control factors on streamflow characteristics. The time period analysed (1994-2020) was divided into two intervals: 1994-2004 and 2005-2020. While for the first interval a certain homogeneity of the correlation between these parameters can be observed, in the second interval the degree of spreading is accentuated downstream (Figure 4).

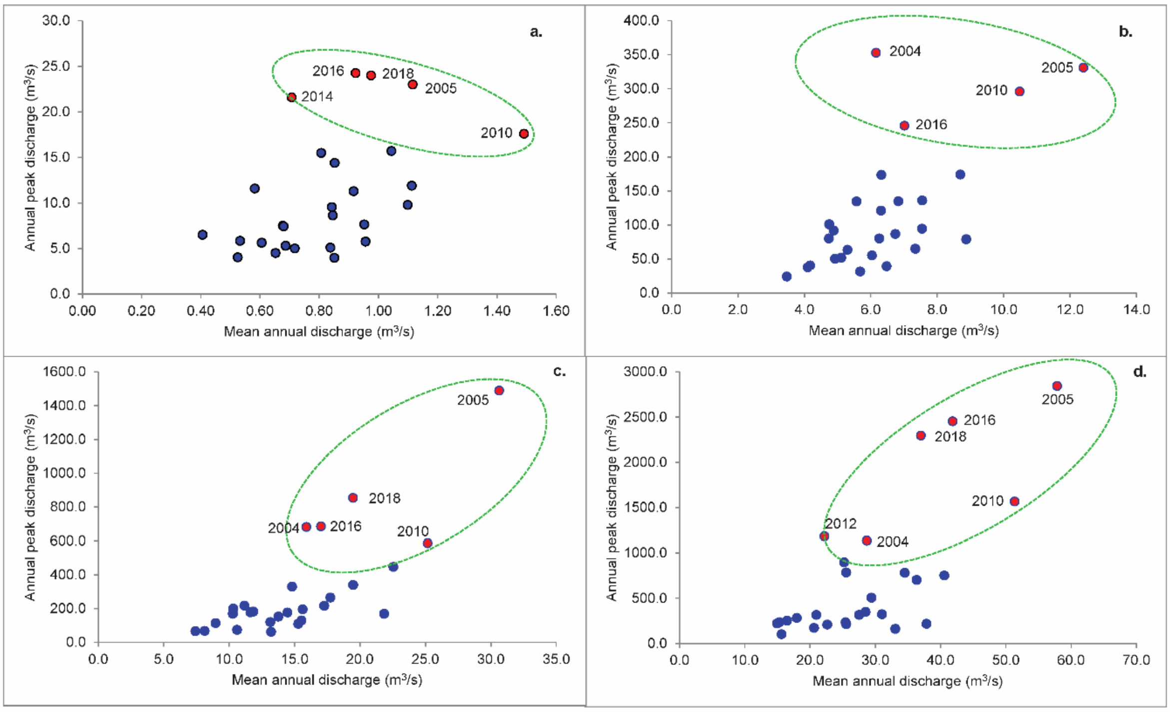

Figure 4. Annual peak discharge vs. mean annual discharge: (**a**) Lunca de Sus; (**b**) Goioasa; (**c**) Târgu Ocna; (**d**) Vrânceni.

Flood events in 2005, 2010, 2012, 2014, 2016, 2018, especially in the lower reaches, exceeded 40-50 times the mean annual flows. In the first interval, peak flows were on average 10-14 times higher than the annual average, and in the second interval 20-25 times higher. It can be seen that after 2004, the magnitude of flood events almost doubled compared to the previous interval. Hall et al. (2014) concluded that a high magnitude flood event does not necessarily indicate a trend of increasing flood event (magnitude). However, in the situation of the Trotuș river basin these events were not isolated. From 2004 to 2020 there have been at least 5 flood events with a magnitude at least 2 times the maximum magnitude of the previous period.

3.4. Modification of maximum monthly discharge

The maximum flows in May, June and July recorded since the establishment of the hydrometric stations and up to 2020 were selected for comparison. These months were chosen because more than 90% of the annual maximum flows were recorded in the May-July period (Figure 5). At all stations it can be seen that until the 1990s most of the highest flows were recorded in May. For the stations with longer observation periods (Goioasa, Târgu Ocna) a period rich in floods is observed from the end of the 1960s to the beginning of the 1980s (but with lower magnitudes than the current one), during which the maximum flows of May had the main share. Gradually, these are replaced by the July and June flows. July peak flows are predominant in the period 2000-2010, while June peak flows are particularly important after 2010. The mechanisms of flood generation in a given catchment can change over time under the influence of climate variability or climate change (Jiang et al., 2022).

The observed changes in the Trotuș River are consistent with those stated by Blöschl et al. (2020) that major flood events in this part of Europe tend to be concentrated in the summer season. Kemter et al. (2020) observed that after 1960 the role of snowmelt in flood events in Eastern Europe has continuously decreased. Increasingly reduced snow cover will contribute to the decreasing role of this type of precipitation in flood formation.

As a result, spring flood events will be increasingly attenuated compared to summer flood events.

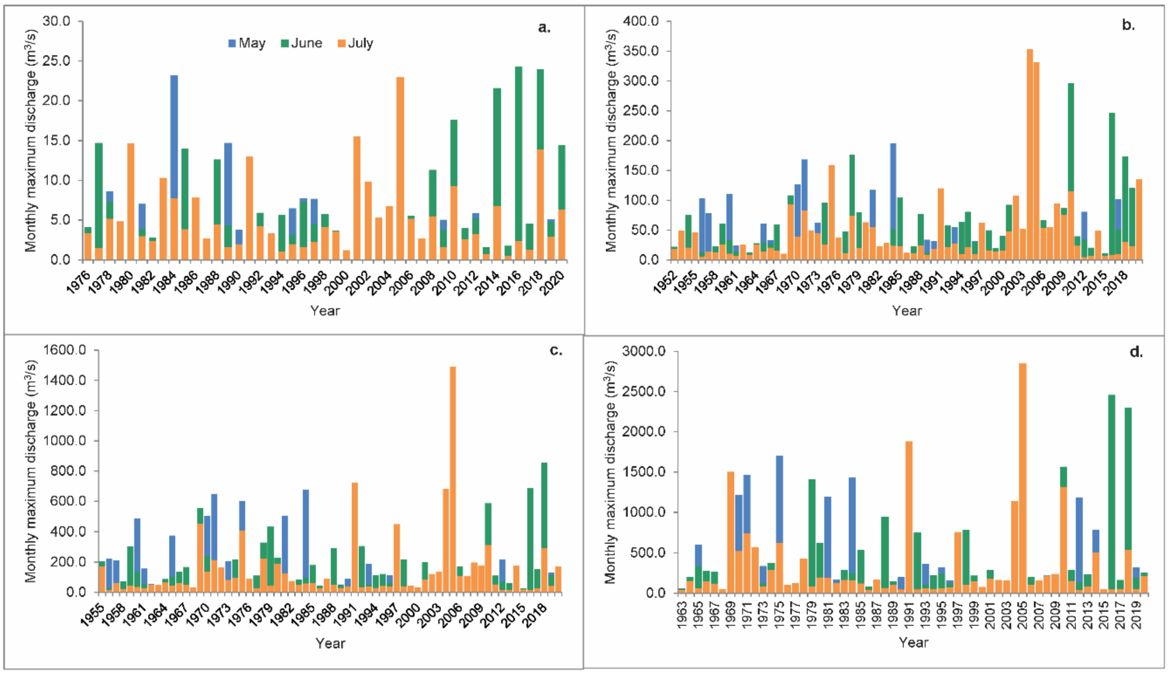

Figure 5. Maximum monthly discharge for May, June and July: (**a**) Lunca de Sus; (**b**) Goioasa; (**c**) Târgu Ocna; (**d**) Vrânceni.

4. Conclusions

Changes in the characteristics of flood events (including their magnitude) in recent decades and their future trends are topics of real scientific and practical interest. In the case of the Trotuș River, based on the analysis of two hydro-geomorphological parameters (flood magnitude ratio and mean annual flood), a clear trend of increasing magnitude of flood events has been observed after 2004. These changes are well exemplified by floods with certain recurrence intervals (10-year flood and 100-year flood). In the data series on maximum annual flows from all gauging stations, floods with a recurrence interval of 100 years were not recorded until after 2004. This indicates a significant increase in the magnitude of flood events. This increase is also highlighted by the second parameter analysed, namely the average annual flood. At all the stations analysed, the MAF specific to the 2004-2020 period was 1.3-1.8 times higher than that characteristic of the periods prior to 2004. The same conclusion, of an increase in the magnitude of flood events, is reached by the comparative analysis of the maximum flows in relation to the daily or annual average flows. At all four stations analysed it was observed that from 2004 to 2020 there were at least 5 flood events with a magnitude at least 2 times higher than the pre-2004 maximum magnitude. The analysis of the monthly peak flows showed a decrease in the May-specific peak flows and a considerable increase in the June and especially July peak flows. This argues for an increased role of extreme precipitation in the formation of flood events.

The cause of these types of changes is quite difficult to determine precisely. As Kundzewicz (2015) also pointed out, recording the climate signal for these categories of changes is quite difficult and complex and requires long and good quality recordings. In this context, Fischer et al. (2023) stated that explaining flood-rich periods is a challenge and has been called one of the Unsolved Problems in Hydrology. Although our analysis is more empirical, considering that these changes were quite rapid in the case of the Trotuș (2004-2005), we conclude that the main role is played by natural climatic variability. In this sense, after 2004 we entered a flood-rich period, as evidenced by rapid changes in the magnitude of flood events. This period would correspond to period IX described by

Blöschl et al. (2020). It is our opinion that anthropogenically influenced climate change alone cannot produce such dramatic changes in the magnitude of flood events as in the present case.

References

1. Arheimer, B.; Lindström, G. (2015) Climate impact on floods: changes in high flows in Sweden in the past and the future (1911–2100). *Hydrol. Earth Syst. Sci.*, *19*, 771–784. https://doi.org/10.5194/hess-19-771-2015
2. Bertola, M.; Viglione, A.; Lun, D.; Hall, J.; Blöschl, G. (2020) Flood trends in Europe: are changes in small and big floods different?. *Hydrol. Earth Syst. Sci.*, *24*, 1805–1822. https://doi.org/10.5194/hess-24-1805-2020
3. Bhattacharya, B.; Suman, A.; Solomatine, D. (2019) Developing flood index from past flood hydrographs and using it as a tool to characterize flood severity. *Environ Eng Manag J*, *18*(5), 1013-1028. http://89.44.47.69/index.php/EEMJ/article/view/3864
4. Blenkinsop, S.; Muniz Alves, L.; Smith, A.J.P. (2021) Climate change increases extreme rainfall and the chance of floods ScienceBrief Review. In: *Critical Issues in Climate Change Science*, Edited by: Le Quéré C., Liss P. & Forster P. https://doi.org/10.5281/zenodo.4779119
5. Blöschl, G. (2022) Three hypotheses on changing river flood hazards. *Hydrol. Earth Syst. Sci.*, *26*, 5015–5033. https://doi.org/10.5194/hess-26-5015-2022
6. Blöschl, G.; Montanari, A. (2010) Climate change impacts – throwing the dice? *Hydrol. Process* *24*(3),374-381. https://doi.org/10.1002/hyp.7574
7. Blöschl, G.; Hall, J.; Viglione, A., et al. (2019) Changing climate both increases and decreases European river floods. *Nature* 573, 108–111. https://doi.org/10.1038/s41586-019-1495-6
8. Blöschl, G.; Kiss, A.; Viglione, A. et al. (2020) Current European flood-rich period exceptional compared with past 500 years. *Nature*, 583, 560–566. https://doi.org/10.1038/s41586-020-2478-3
9. Brêda, J.P.L.F.; de Paiva, R.C.D.; Siqueira, V.A.; Collischonna, W. (2023) Assessing climate change impact on flood discharge in South America and the influence of its main drivers. *J Hydrol, 619*, 129284. https://doi.org/10.1016/j.jhydrol.2023.129284
10. Brönnimann, S.; Stucki, P.; Franke, J.; Valler, V.; Brugnara, Y.; Hand, R.; Slivinski, L.; Compo, G.; Sardeshmukh, P.; Lang, M.; Schaefli, B. (2022) Influence of warming and atmospheric circulation changes on multidecadal European flood variability. *Clim Past*, *18*, 919–933. https://doi.org/10.5194/cp-18-919-2022
11. Cao, W.; Zhang, Z.; Liu, Y.; Band, L.E.; Wang, S.; Xu, H. (2021) Seasonal differences in future climate and streamflow variation in a watershed of Northern China. *J Hydrol: Reg Stud, 38*, 100959. https://doi.org/10.1016/j.ejrh.2021.100959
12. Croitoru, A.E.; Piticar, A.; Burada, D.C. (2016) Changes in precipitation extremes in Romania. *Quatern Int*, *415*, 325-335. http://dx.doi.org/10.1016/j.quaint.2015.07.028
13. Dumitriu, D. (2014) Source area lithological control on sediment delivery ratio in Trotuş drainage basin (Eastern Carpathians). *Geogr Fis Din Quat*, 37, 91-100. https://doi.org/10.4461/GFDQ.2014.37.08
14. Dumitriu, D. (2016) Geomorphic effectiveness of floods on Trotuş River channel (Romania) between 2000 and 2012. Carpath. *J Earth Env*, *11*, 181-196.
15. Dumitriu, D. (2018) Sub-bankfull flow frequency versus magnitude of flood events in outlining effective discharges. Case Study: Trotuș River (Romania). *Water*, *10*, 1292. https://doi.org/10.3390/w10101292

16. Dumitriu, D. (2020a) Sediment flux during flood events along the Trotuș River channel: hydrogeomorphological approach. *J Soils Sediments*, *20*, 4083–4100. https://doi.org/10.1007/s11368-020-02763-4

17. Dumitriu, D. (2020b) Streamflow and suspended sediment load trends in Trotuș drainage basin: geomorphic implications. *Present Environment and Sustainable Development*, *14*(2), 67-87. https://doi.org/10.15551/pesd2020142005

18. Eccles, R.; Zhang, H.; Hamilton, D.; Trancoso, R.; Syktus, J. (2021) Impacts of climate change on streamflow and floodplain inundation in a coastal subtropical catchment. *Adv Water Resour*, *147*, 103825. https://doi.org/10.1016/j.advwatres.2020.103825

19. Ficklin, D.L.; Abatzoglou, J.T.; Novick, K.A. (2019) A new perspective on terrestrial hydrologic intensity that incorporates atmospheric water demand. *Geophys Res Lett*., 46, 8114–8124. https://doi.org/10.1029/2019GL084015

20. Fischer, S.; Lun, D.; Schumann, A.H.; Blöschl, G. (2023) Detecting flood-type-specific flood-rich and flood-poor periods in peaks-over-threshold series with application to Bavaria (Germany). *Stoch Env Res Risk A*, *37*(4), 1395-1413. https://doi.org/10.1007/s00477-022-02350-8

21. Glaser, R.; Riemann, D.; Schönbein, J. et al. (2010) The variability of European floods since AD 1500. *Climatic Change*, 101, 235-256. https://doi.org/10.1007/s10584-010-9816-7

22. Gudmundsson, L.; Leonard, M.; Do, H.X.; Westra, S.; Seneviratne, S.I. (2019) Observed trends in global indicators of mean and extreme streamflow. *Geophys Res Lett*, *46*, 756–766. https://doi.org/10.1029/2018GL079725

23. Hall, J.; Arheimer, B.; Borga, M.; et al. (2014) Understanding flood regime changes in Europe: a state-of-the-art assessment. *Hydrol Earth Syst Sci*, *18*, 2735–2772. https://doi.org/10.5194/hess-18-2735-2014

24. Hirabayashi, Y.; Mahendran, R.; Koirala, S.; Konoshima, L.; Yamazaki, D.; Watanabe, S.; Kim, H.; Kanae, S. (2013) Global flood risk under climate change. *Nat Clim Change*, *3*, 816–821. https://doi.org/10.1038/nclimate1911

25. Jacobeit, J.; Glaser, R.; Luterbacher, J.; Wanner, H. (2003) Links between flood events in central Europe since AD 1500 and large-scale atmospheric circulation modes. *Geophys Res Lett*, *30*, 1172. https://doi.org/10.1029/2002GL016433

26. Jiang, S.; Bevacqua, E.; Zscheischler, J. (2022) River flooding mechanisms and their changes in Europe revealed by explainable machine learning. *Hydrol Earth Syst Sci*, *26*, 6339–6359, https://doi.org/10.5194/hess-26-6339-2022

27. Karim, F.; Hasan, M.; Marvanek, S. (2017) Evaluating annual maximum and partial duration series for estimating frequency of small magnitude floods. *Water*, *9*(7), 481. https://doi.org/10.3390/w9070481

28. Kemter, M.; Merz, B.; Marwan, N.; Vorogushyn, S.; Blöschl, G. (2020) Joint trends in flood magnitudes and spatial extents across Europe. *Geophys Res Lett*, *47*, 1–8. https://doi.org/10.1029/2020GL087464

29. Knox, J.C. (2000) Sensitivity of modern and Holocene floods to climate change. *Quat Sci Rev*, *19*(1-5), 439–457. https://doi.org/10.1016/S0277-3791(99)00074-8

30. Kundzewicz, Z.W. (2015) Climate change track in river floods in Europe. *Proc IAHS*, 369, 189–194. https://doi.org/10.5194/piahs-369-189-2015

31. Kundzewicz, Z.; Graczyk, D.; Maurer, T.; Pinskwar, I.; Radziejewski, M.; Svensson, C.; Szwed, M. (2005) Trend detection in river flow series: 1. Annual maximum flow. *Hydrolog Sci J*, *50*(5), 810. https://doi.org/10.1623/hysj.2005.50.5.797

32. Kundzewicz, Z.W.; Pinskwar, I.; Brakenridge, G.R. (2013) Large floods in Europe, 1985–2009. *Hydrolog Sci J*, *58*, 1-7. http://dx.doi.org/10.1080/02626667.2012.745082.

33. Kundzewicz, Z.W.; Pińskwar, I. (2022) Are pluvial and fluvial floods on the rise? *Water*, *14*(17), 2612. https://doi.org/10.3390/w14172612

34. Lun, D.; Fischer, S.; Viglione, A.; Blöschl, G. (2020) Detecting flood-rich and flood-poor periods in annual peak discharges across Europe. *Water Resour Res*, *56*, e2019WR026575. https://doi.org/10.1029/2019WR026575

35. Lun, D.; Viglione, A.; Bertola, M.; Komma, J.; Parajka, J.; Valent, P.; Blöschl, G. (2021) Characteristics and process controls of statistical flood moments in Europe – a data-based analysis. *Hydrol Earth Syst Sci*, *25*, 5535–5560. https://doi.org/10.5194/hess-25-5535-2021

36. Mangini, W.; Viglione, A.; Hall, J.; Hundecha, Y.; Ceola, S.; Montanari, A.; Rogger, M.; Salinas, J. L.; Borzì, I.; Parajka, J. (2018) Detection of trends in magnitude and frequency of flood peaks across Europe. *Hydrolog Sci J*, *63*, 1–20. https://doi.org/10.1080/02626667.2018.1444766

37. Markonis, Y.; Hanel, M.; Maca, P.; Kysely, J.; Cook, E.R. (2018) Persistent multi-scale fluctuations shift European hydro-climate to its millennial boundaries. *Nat Commun*, *9*, 1767, https://doi.org/10.1038/s41467-018-04207-7

38. Merz, B.; Vorogushyn, S.; Uhlemann, S.; Delgado, J.; Hundecha, Y. (2012) HESS Opinions "More efforts and scientific rigour are needed to attribute trends in flood time series". *Hydrol Earth Syst Sci*, *16*, 1379–1387, https://doi.org/10.5194/hess-16-1379-2012

39. Mimikou M.; Gordios J. (1989) Predicting the mean annual flood and flood quantiles for ungauged catchments in Greece. *Hydrolog Sci J*, *34*(2), 169-184. https://doi.org/10.1080/02626668909491322

40. Pinskwar, I.; Kundzewicz, Z.W.; Peduzzi, P.; Brakenbridge, G.R.; Stahl, K.; Hannaford, J. (2012) Changing floods in Europe. In: *Changes in Flood Risk in Europe*; Eds: Kundzewicz, Z.W.; IAHS Press: Wallingford, UK, pp. 83–96.

41. Pińskwar, I.; Choryński, A.; Graczyk, D. et al. (2019) Observed changes in extreme precipitation in Poland: 1991–2015 versus 1961–1990. *Theor Appl Climatol*, *135*, 773–787. https://doi.org/10.1007/s00704-018-2372-1

42. Prăvălie, R.; Piticar, A.; Roșca, B.; Sfîcă, L.; Bandoc, G.; Tiscovschi, A.; Patriche, C. (2019) Spatio-temporal changes of the climatic water balance in Romania as a response to precipitation and reference evapotranspiration trends during 1961–2013. *Catena*, *172*, 295-312. https://doi.org/10.1016/j.catena.2018.08.028

43. Rădoane, M.; Obreja, F.; Cristea, I.; Mihailă D. (2013) Changes in the channel-bed level of the eastern Carpathian rivers: climatic vs. human control over the last 50 years. *Geomorphology*, *193*, 91-111. https://doi.org/10.1016/j.geomorph.2013.04.008

44. Rogger, M.; Agnoletti, M.; Alaoui, A.; Bathurst, J.C.; Bodner, G.; Borga, M. et al. (2017) Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water Resour Res*, *53*, 5209–5219. https://doi.org/10.1002/2017WR020723

45. Rojas, R.; Feyen, L.; Bianchi, A.; Dosio A. (2012) Assessment of future flood hazard in Europe using a large ensemble of bias-corrected regional climate simulations. *J Geophys Res*, *117*, D17109. https://doi.org/10.1029/2012JD017461

46. Sharma, A.; Wasko, C.; Lettenmaier, D.P. (2018) If precipitation extremes are increasing, why aren't floods? *Water Resour Res*, *54*, 8545–8551. https://doi.org/10.1029/2018WR023749

47. Swain, D.L.; Wing, O.E.J.; Bates, P.D.; Done, J.M.; Johnson, K.A.; Cameron, D.R. (2020) Increased flood exposure due to climate change and population growth in the United States. *Earth's Future*, *8*, e2020EF001778. https://doi.org/10.1029/2020EF001778

48. Tabari, H. (2020) Climate change impact on flood and extreme precipitation increases with water availability. *Sci Rep, 10*, 13768. https://doi.org/10.1038/s41598-020-70816-2

49. Tarasova, L.; Lun, D.; Merz, R.; Blöschl, G.; Basso, S.; Bertola, M.; Miniussi, A.; Rakovec, O.; Samaniego, L.; Thober, S.; Kumar, R. (2023) Shifts in flood generation processes exacerbate regional flood anomalies in Europe. *Commun Earth Environ*, *4*, 49. https://doi.org/10.1038/s43247-023-00714-8

50. Thober, S.; Kumar, R.; Wanders, N.; Marx, A.; Pan, M.; Rakovec, O.; Samaniego, L.; Sheffield, J.; Wood, E.F.; Zink, M. (2018) Multi-model ensemble projections of European river floods and high flows at 1.5, 2, and 3 degrees global warming, *Environ Res Lett, 13*, 014003. https://doi.org/10.1088/1748-9326/aa9e35

51. Wasko, C.; Sharma, A. (2017) Global assessment of flood and storm extremes with increased temperatures. *Scient Rep, 7*, 7945. https://doi.org/10.1038/s41598-017-08481-1

52. Wasko, C.; Nathan, R.; Peel, M.C. (2020). Trends in global flood and streamflow timing based on local water year. *Water Resour Res*, *56*(8), e2020WR027233. https://doi.org/10.1029/2020WR0272

53. Xu, S.; Qin, M.; Ding, S.; Zhao, Q.; Liu, H.; Li, C.; Yang, X.; Li, Y.; Yang, J.; Ji, X. (2019) The impacts of climate variation and land use changes on streamflow in the Yihe River, China. *Water*, *11*, 887. https://doi.org/10.3390/w11050887