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Brief communication: A first hydrological investigation of extreme August 2023 floods in Slovenia, Europe

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Abstract Extreme floods occurred from 4th to 6th of August 2023 in Slovenia claiming 3 casualties and causing economic damage of a few billions EUR. The weather situation not typical for summer period in combination with high temperatures of the Mediterranean Sea and high antecedent soil moisture lead to the most extreme flood event in the last several decades. The return period of precipitation extremes and peak discharges exceeded 250-500 years return period, and runoff coefficient of typical torrential and mostly forested meso-scale catchments was around 0.5. Additionally, intense soil erosion, mass movements and sediment transport processes caused large damages on housing and infrastructure.

1 Introduction

Slovenia is a relatively small country in Central Europe (approx. 20,000 km^2) that is located in temperate-continental, Mediterranean and Alpine climates, and where mean annual precipitation (1981-2010) ranges from below 900 mm in the eastern part of the country to more than 3,000 mm in western part (Dolšak et al., 2016). In combination with relatively complex topography and in some areas unstable terrain this can generate significant soil erosion and mass movement processes that endanger around 45 % of the entire country (Mikoš et al., 2004). Flood risk is a potential threat for more than 5 % of the total surface. Hence, extreme floods and mass movements are occurring relatively frequently, causing large economic damage and human fatalities (Bezak et al., 2016; Mikoš, 2021; Mikoš et al., 2004; Špitalar et al., 2020). Due to climate change, the extreme rainfall evens become more frequent and extreme leading to more severe floods and mass movements. The main objective of this brief communication is to investigate the main drivers, mechanisms and impacts of recent extreme flood event that occurred in August 2023 in Slovenia. We also conduct the preliminary hydrological investigation of the main characteristics of this event in order to provide basics for effective remediation measures that will follow the concept of building-back-better and provide useful examples of lessons learned that could benefit other countries and will increase flood resilience in Slovenia.

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2.1 Drivers and triggering mechanisms

First half of year 2023 was relatively wetter in Slovenia compared to past years as almost all parts of country have recorded more than 50% of the total annual rainfall by the end of July. In Slovenia, the autumn period is usually the wettest period of the year and main flood events and big mass movements occurred in the period from September to December (Bezak et al., 2016; Mikoš et al., 2004; Špitalar et al., 2020). Summer (June to August) is usually the period with smaller rainfall amount but with thunderstorms that can yield high rainfall erosivity (Panagos et al., 2016). Until endo of July 2023, the western part of the country recorded around 50 % of the mean annual precipitation; this number was close to 80 % for some locations in the eastern part of the country and close to 70 % in the central part of the country. In July 2023 in many parts of the country the monthly precipitation sum was 2-3 times higher than the long-term average (ARSO, 2023a). Additionally, several extreme storms occurred in May, June and July (ARSO, 2023b). More specifically, in those three months the Slovenian Environment Agency (ARSO) prepared 11 reports about extreme weather events. Several times the orange or red severe weather alarms were issued on the meteoalarm.org. Consequently, also soil moisture was relatively high before the August 2023 flood event (Figure 1). Summer thunderstorms that occurred in May-July also triggered smaller landslides and soil slips, and damaged forest cover by local windthrows that could not be cleaned before the August 2023 extreme event (Figure 1).

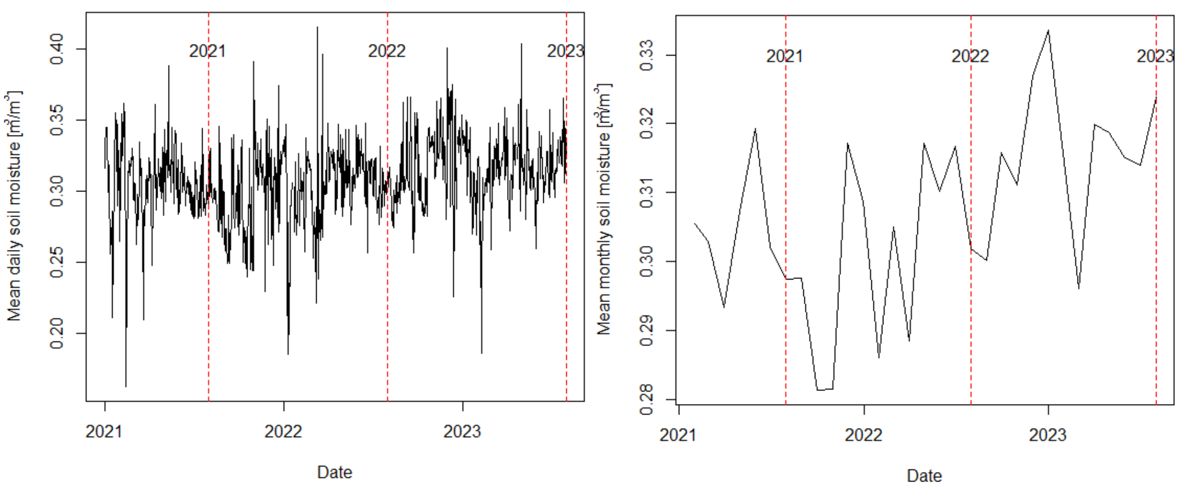

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Figure 1: Upper two figures show mean daily and monthly soil moisture for the Sava River catchment in Slovenia according to the satellite-based soil moisture climate data following the ESA Climate Change Initiative soil moisture version 03.3 (CDS Climate Copernicus, 2023). Lower photos show situation in the Brezovški graben torrent (Bezak et al., 2020) at the end of July 2023.

An additional important driver that caused this extreme event was the relatively high temperature of the Mediterranean and Adriatic Sea as at the beginning of August it was recorded more than 2°C above the long-term average (see Figure 6 shwon in ARSO, 2023a). The same applied for some other regions around the globe (Climate Copernicus, 2023). On the 3rd of August, cold Atlantic air moved across the Alps to the western Mediterranean. At the same time a low pressure cyclonic area was formed over the northern Mediterranean and the weather front stayed over the area of Slovenia from Friday night (4.8.2023) until Saturday morning (5.8.2023) (ARSO, 2023a). Those weather conditions are highly unusual for summer and is more typical for autumn or winter period when the sea temperature is lower (ARSO, 2023a). The first storms occurred in Slovenia already on Thursday (3.8.2023) evening while on the night from Thursday to Friday extreme storms and heavy rainfall hit large areas of the western and northern part of the country (ARSO, 2023a). Rainfall (a bit less intense) continued through Friday and Saturday and slowly moved from the central and northern part of the country to the eastern and south-eastern parts (ARSO, 2023a). In most parts of the country rain stopped on Sunday 6th of August (ARSO, 2023a). Therefore, those extreme rainfalls, mainly during the night from Thursday 3rd of August to Friday when 12-hour rainfall amounts were really extreme for many locations in Slovenia (Table 1, maximum during the event are shown), triggered mass movements (i.e., shallow landslides, deep-seated landslides, soil slips, debris flows), erosion and sediment transport processes and also floods.

For the 12 out of 26 locations (i.e., Kamniška Bistrica, Šmartno pri Slovenj Gradcu, Žiri, Pasja Ravan, Letališče Jožeta Pučnika Ljubljana, Krvavec, Luče, Gornji Grad, Radegunda, Mežica, Ravne na Koroškem, Uršlja Gora) shown in Table 1, the rainfall return period exceeded 250 years according to the intensity-duration-frequency curves for Slovenia (https://crossrisk.eu/sl/climate). Additionally, the Pasja Ravan station recorded 217 mm of rain in 12 hours, which is more than 50 mm above the rainfall amount associated with the return period of 250 years (determined using historical rainfall data). It should be noted that rainfall amounts for the return periods up to 250 years are calculated in Slovenia. For 24-hour rainfall

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amounts (maximum during the event is shown), for 7 out of 26 stations (i.e., Kamniška Bistrica, Pasja Ravan, Žiri, Letališče Jožeta Pučnika Ljubljana, Krvavec, Luče, Radegunda) shown in Table 1, the return period was over 250 years. Hence, it is clear that rainfall amounts were really extreme. However, for some of the stations shown in Table 1 we also managed to calculate the 24-hour probable maximum precipitation (PMP) (World Meteorological Organization (WMO), 2009) which was as 670 mm, 410 mm, 890 mm and 340 mm for the Kamniška Bistrica, Slovenj Gradec, Bovec and Sevno stations respectively. Moreover, it can be seen that theoretically the 24-hour rainfall can be even higher in the future compared to the August 2023 extreme event which caused extensive flooding.

We also calculated the rainfall erosivity (R) of the August 2023 event (i.e., from 3rd to 6th of August) based on the same methodology as was used by Panagos et al. (2023) (Table 1). For stations that were included in the study by Panagos et al. (2023), we also calculated the ratio between the rainfall erosivity R of this extreme event and the mean annual R (Table 1). It can be seen that this ratio is higher than 100 % for 14 stations and even higher than 150 % for seven stations (Table 1; Figure 2). This confirms previous studies that showed that temporal distribution of R can be highly uneven and a few extreme events can generate the major part of the annual rainfall erosivity (Bezak et al., 2021). In nine stations, the 4-days (i.e., from 3rd to 6th of August) rainfall erosivity of this extreme event was higher than 2,300 MJ mm ha^{-1} h^{-1}, yr^{-1} which is the mean annual erosivity in Slovenia (Panagos et al., 2015). The areas with the highest rainfall intensity (and erosivity) were the most affected ones regarding floods.

Table 1: Main characteristics of the extreme August 2023 rainfall event for selected stations in Slovenia. For the calculation of rainfall erosivity the same methodology was used as by Panagos et al. (2023). NA indicated that the percentage could not be calculated because the specific station was not included in the study by Panagos et al. (2023).

Station No	Station	Longitude	Latitude	24h rainfall [mm]	12h rainfall [mm]	30min rainfall [mm]	3.8.-6.8.2023 R [MJ*mm*ha^{-1}*h^{-1}]	% of annual R [MJ*mm*ha^{-1}*h^{-1}*year^{-1}]
1	BOVEC	13.5538	46.3317	94.4	75.8	21.8	920	12%
2	KAMNIŠKA BISTRICA	14.6034	46.3087	242.5	201.7	29	5402	187%
3	ŠMARTNO PRI SLOVENJ GRADCU	15.1112	46.4896	145.8	112.6	14.6	2190	113%
4	POSTOJNA	14.1973	45.7722	64.5	4.7	9.4	2271	74%
5	LJUBLJANA - BEŽIGRAD	14.5124	46.0655	61.3	22.1	8.6	681	30%
6	ČRNOMELJ - DOBLIČE	15.1462	45.56	21.2	0	7.5	944	47%
7	MARIBOR	15.626	46.5678	73.7	50.9	8.6	439	29%
8	SEVNO	14.9236	45.9821	48.9	1.9	6.9	964	44%

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9	MURSKA SOBOTA	16.1913	46.6521	36.6	24.9	7	668	34%
10	ŽIRI	14.1197	46.05	235.8	183.9	31.3	682	19%
11	PASJA RAVAN	14.2282	46.0979	254.4	217	29.8	3121	106%
12	TOPOL	14.3713	46.0941	138.4	93.7	17.2	1053	47%
13	LETALIŠČE JOŽETA PUČNIKA LJUBLJANA	14.4784	46.2114	227.7	198.8	26.6	2041	112%
14	KRVAVEC	14.5333	46.2973	196.1	165.1	30	1527	43%
15	LOGARSKA DOLINA	14.6311	46.3936	142.4	138.2	24.3	4078	166%
16	LUČE	14.7488	46.355	218.9	189.8	28.3	2027	87%
17	GORNJI GRAD	14.8063	46.2987	174.7	122.6	18.7	1335	57%
18	RADEGUNDA	14.933	46.3661	189.9	145.7	18	3673	172%
19	MEŽICA	14.8596	46.5296	150	124.8	12.6	3403	170%
20	RAVNE NA KOROŠKEM	14.94	46.5477	157.3	127.2	16	1915	119%
21	URŠLJA GORA	14.9634	46.4849	183.1	146.8	18	2379	128%
22	VELENJE	15.1119	46.3603	108	66.8	12.3	3053	155%
23	CELJE	15.2259	46.2366	54.8	10.7	9.8	3907	208%
24	ROGLA	15.3315	46.453	98.4	61.4	11.9	3128	159%
25	HOČKO POHORJE	15.5875	46.4919	54.3	31.7	11.7	2192	133%
26	GAČNIK	15.6838	46.6178	74.1	55.5	12.1	1647	107%

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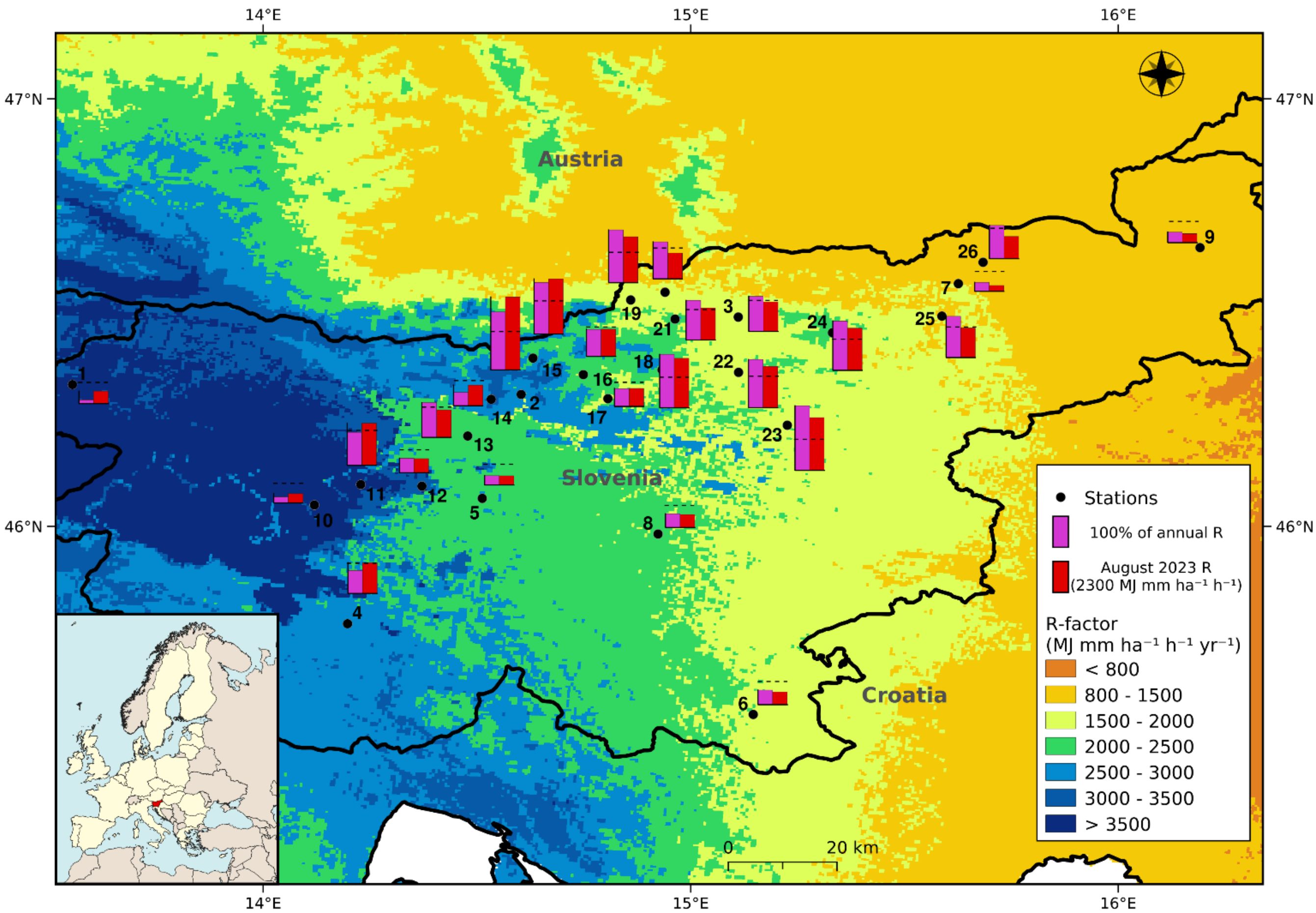

Figure 2. Rainfall erosivity (R-factor) in August 2023 in Slovenia. Red bar represent the Rainfall erosivity in August 2023 for 26 stations (as numbered in Table 1). Fuxia bars represent the % of the August 2023 erosivity compared to the mean annual one. For both bars the dotted line, represents the 100% of annual R (Fuxia) and the 2,300 MJ mm ha-1 h-1 (Red). Background is the mean annual erosivity in Slovenia taken from the European erosivity dataset (Panagos et al., 2015).

2.2 Hydrological conditions in the floods 2023 in Slovenia

The weather situation described in section 2.1 generated extreme local floods that according to the satellite-based data flooded more than 7.5 km^2 (Figure S1) - the preliminary data collected in the field shows that this estimation is severely underestimated because of the potential limitations of remote sensing data (e.g., not all flooded areas could be identified) and torrential characteristics of this August 2023 flood event. For example, a first estimate is that more than 160 km^2 of only agricultural areas were flooded. Additionally, close to 90% of all municipalities in Slovenia (i.e., only 30 out of 212 municipalities did not reported damages) reported some kind of damage due to extreme rainfall, floods and mass movements (ARSO, 2023a). Hence, the hydrological situation was bad and for quite many gauging stations the preliminary data shows that the return period of the event was more than 500 years (Figure 3). Significant morphological changes can also be observed from the orthophoto images taken directly after the August flood event in the most endangered areas (Figure S2). Based on the preliminary data that is available by the Slovenian Environment Agency (ARSO), we also calculated runoff coefficients during the event. For example, for the Kamniška Bistrica River that was one of the most affected areas, the runoff coefficient up to the Kamnik gauging station was around 50% (i.e., the outflow volume equal around ½ of total precipitation during the event), while more than 300 mm of rain fall in this catchment during the entire event (i.e., the runoff during the event probably exceeded 150 mm in a few days). Additionally, the peak discharge (i.e., 4th of August at 5:30) occurred only a few hours after a first important rainfall intensity increase (from 3rd of August 20:00 until 4th of August 3:30 the rainfall sum exceeded 130 mm). For many locations around the country the peak discharges recorded during the extreme August 2023 event were above the average empirical curves derived for specific discharges by Mikoš (2020) for both 100- and 500-year return periods, respectively (Figure 3). However, the August 2023 event was lower than the maximum envelope curves derived by Mikoš (2020) based on the results of the flood frequency analysis for all discharge gauging stations in Slovenia. Additionally, we also derived an empirical threshold curve for the August 2023 event (i.e., $q_{2023}=28*A^{-0.45}$ where q_{2023} is the specific discharge in $m^3/s/km^2$ and A is catchment area in km^2) that could be used in future for the design of some mitigation measures in order to protect specific areas for similar type of hydrological extremes. We also made a comparison between the recorded peak discharges (please note that discharge data has not yet been verified by ARSO) and the envelope of maximum floods in Europe (Herschy, 2002). It can be seen that although the August 2023 floods in Slovenia were extreme, the measured peak discharge values were not even close to the empirical envelope for largest floods in Europe. Therefore, this confirms the comparison of measured 24-hour rainfall values with PMP which indicated that theoretically more rainfall could generate even more extreme floods, especially due to increasing air and sea temperatures. Hence, in future, more extreme floods can be expected in Slovenia.

Following the GCM/RCM climate project models prepared by Slovenian Environment Agency (ARSO) (Bertalanič et al., 2018) and using the calibrated rainfall-runoff model for the Sava River catchment in Slovenia (up to the Čatež gauging station) it can be estimated that the daily rainfall (average values for the entire Sava River catchment in Slovenia) could increase approximately 5-14 mm per 100 years taking into account RCP2.6, RCP4.5 and RCP8.5 scenarios. In terms of discharge this implies a potential rainfall increase up to 3 mm per 100 years, which for the Sava River catchment in Slovenia (catchment area over 10,000 km^2) yields an increase of runoff volume of 30 million m^3 per event (e.g., one day). If this event (i.e., flood wave) lasts in 24h, discharges will be higher for around 350 m^3/s, which represents around 40-60 cm higher water levels according to rating curve of this station. Therefore, more extreme events like in August 2023 can be expected in future. Additionally, we also estimated the travel times of flood waves for Savinja and Sava Rivers that had relatively good coverage of data during the floods. For both rivers the travel time of the flood wave estimated based on the peak discharge values was between 5 and 6 km/h. Also, in Slovenia the rainfall erosivity is expected to increase by 33-42% (depending on the RCP scenario) by 2050 and even at 52% by 2070 based on the future projections of 19 climatic models (Panagos et al., 2022).

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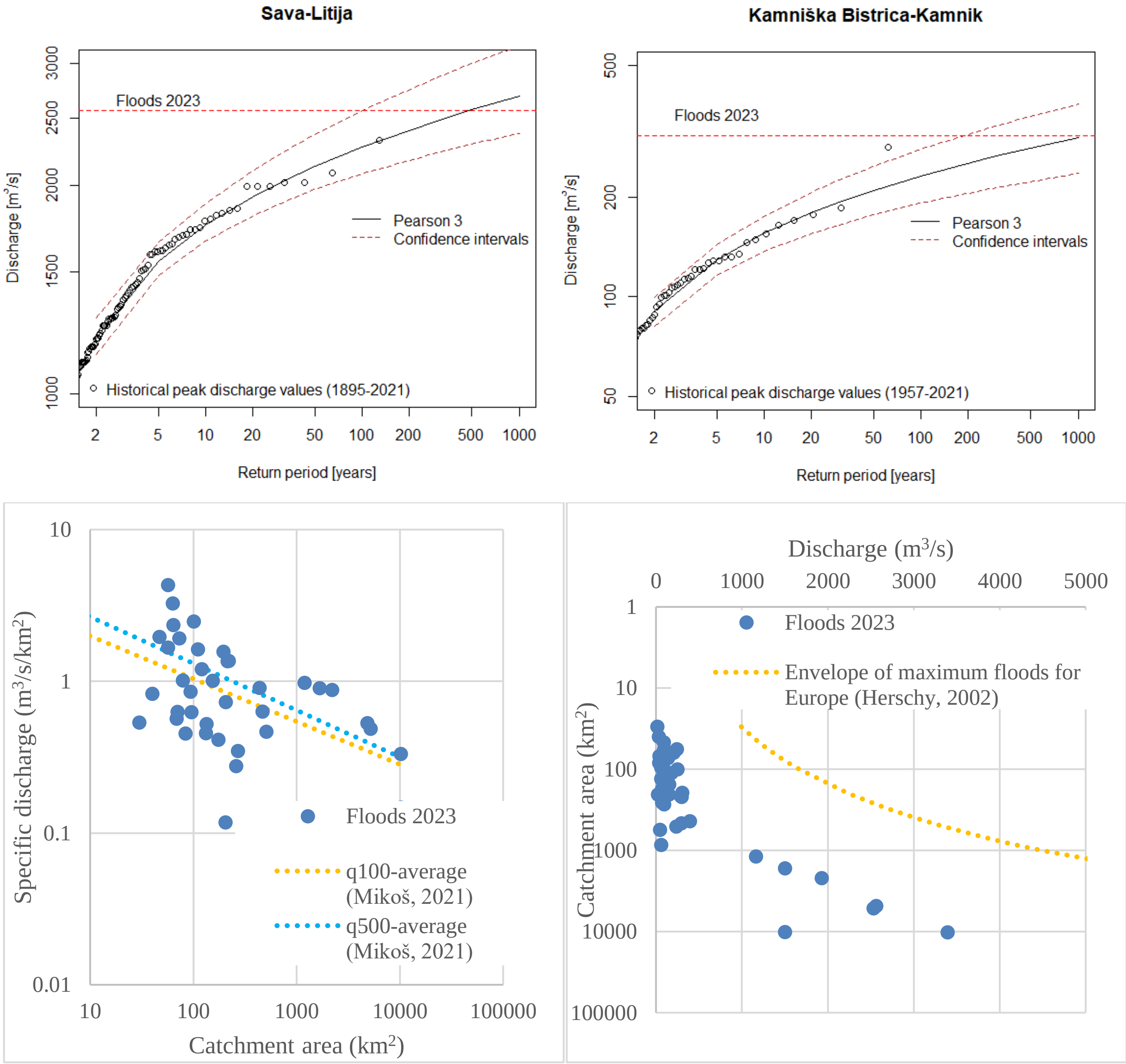

Figure 3: Upper two figures show flood frequency analysis of two gauging stations in Slovenia with confidence intervals derived using the parametric bootstrap approach. Lower two figures show comparison of specific discharge values for multiple gauging stations in relation to average specific discharge values derived by Mikoš (2020) (i.e., $q_{100}=3.81*A^{-0.282}$ and $q_{500}=5.407*A^{-0.308}$, where A is catchment area in km²) and a comparison of peak discharge values for several gauging stations during the August 2023 floods with the envelope of maximum floods for Europe as shown by Herschy (2002) ($Q=230*A^{0.43}$, where A is catchment area in km²; the equation is only valid for catchments larger than 20 km²).

2.3 Torrential processes

The extreme rainfall event during the start of August in Slovenia also triggered numerous shallow landslides (slumps, slips) that are to be mapped and their volume estimated, and local debris flows, debris floods and hyperconcentrated flows with coarse debris transported large amounts of sediments and woody debris, causing significant damage at road infrastructure such

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as clogging of culverts and collapse of bridges - and locally causing even more severe problems with flooding due to sudden geomorphological changes such as bank erosion and lateral course shifting (Figure 4). A detailed analysis of local scenarios that lead to flooding and overtopping of stream banks is needed to better understand slope and fluvial processes during the August 2023 floods.

The rainfall erosivity and intensity was extreme as in most of the locations exceeded the 100% of the annual (Table 1; Figure 3). Additionally, the maximum 12-hour rainfall intensity was for 15 out of 26 stations shown in Table 1 larger than the one predicted by the empirical rainfall threshold curve for shallow landslides and debris flows developed by Caine in 1980 (Bezak et al., 2016). Hence, it is clear that the rainfall event triggered many landslides across the country that should be surveyed using field work and remote sensing techniques. As autumn is normally a rainier season, new landslides are expected to be triggered during late-summer thunderstorms and prolonged autumn rainfall.

Figure 4: Some photos of erosion and mass movements processes across the Slovenia during the extreme August 2023 floods with focus on the upper Savinja River catchment (some by courtesy of Igor Benko).

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2.4 Impacts

According to the satellite-based data, more than 30 km of roads were damaged and more than 700 inhabitants were affected (Copernicus Emergency Management Service, 2023). These numbers are significantly underestimated and collected field data will give more precise information about the direct damage of floods and mass movements such as landslides. The preliminary data, published in media by different sources such as Civil Protection, municipalities, or agencies in charge for road network or water infrastructure, reported much higher numbers. An official report on damages to be submitted to the Government of Slovenia is still due and will give a much better insight into the extent of this natural disaster. A preliminary review of consequences known in the first two weeks (mid-August 2023) after the disaster can be summarised as follows:

- 10,000 to 15,000 affected households, out of them 1,000 households lost everything – on-site reconstruction or rebuilding as well as off-site reconstruction (relocation) of damaged and demolished buildings are planned to lower vulnerability and not to rebuild affected residential buildings in flood prone areas anymore – a new spatial planning paradigm in flood prone areas is needed;
- floods have taken 3 lives and affected several 10,000s residents and quite some tourists;
- damages for business and industry were estimated to 400 million EUR – final estimates are due;
- the area of flooded agricultural land was estimated to 16,000 ha;
- reports from municipalities on landslides gave their number in 10os, and their total number may well exceed 1000;
- only 30 municipalities out of 212 in Slovenia did not report any flood damage;
- flooded waters caused severe damages to local and regional road network and to supply networks (drinking water, electricity, gas)
- floods also polluted the topsoil and agricultural products with a variety of toxic substances that makes monitoring and reclamation very hard;
- the initial estimated of damages immediately after the end of the events of a half a billion EUR were soon replaced by much higher estimates of a total damages in the excess of a several billion EUR, which makes this August 2023 floods the economically most extreme natural disaster in Slovenia since it become independent from Yugoslavia in 1991.

3 Conclusions

The August 2023 flood disaster can be regarded as relatively extreme and it was probably the most extreme flood event in Slovenia in the last several decades (since 1980s). The economic damage was large (still not fully estimated), and could reach well over 5 % of the annual Slovenia Gross Domestic Product (GDP around 61 billion Euros) - the event caused also three fatalities. Due to effective and timely organization of Civil Protection Units and volunteer firefighter brigades, the intervention (protection, evacuation, and rescue) activities were generally adequate regarding in some local rather overwhelming situation, and the number of fatalities stayed relatively low. Initially, the ARSO provided rather accurate short-term severe weather

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forecast (on the 3rd of August in the morning) announcing extreme weather potentially causing large flooding, and issued firstly an orange alarm that was soon replaced during the day by a red alarm advising not just precautionary behaviour but also possible evacuation. The Geological Survey of Slovenia issued warning about potential landslides on the 3rd of August in the morning. This enabled relatively good preparedness of local firefighters and civil protection units.

In a network of 26 meteorological stations, we noticed that the 12h rainfall intensity was higher than 100 mm in 13 stations and the measured rainfall erosivity has exceed the total mean annual erosivity in 14 stations. Also measured peak discharge values for more than 20 gauging stations exceeded mean specific discharge curves with 100 years return period (Figure 3). The return period of the event was in many locations in Slovenia over 250 or even over 500 years – in a way not expected by the population and civil protection regardless the red alarm. It should be noted that all meteorological predictions underestimated the actual situation and consequently also the flood warning system by ARSO (Petan et al., 2015) did not predict such extreme peak discharge values. However, comparison of measured rainfall events and recorded peak discharges indicates that potentially even more extreme events could occur in the future, especially due to warming climate and sea. In Slovenia more than 55,000 buildings is located in floodplain areas (i.e., threatened by extreme floods). As a consequence of this fact, additional focus should be given by stakeholders to redirect classical water management and flood risk management towards intra-sectoral governance for flood resilience taking into account best practices from around the world. The new governance may focus more to incorporate nature-based solutions into structural flood measures (levees, flood control reservoirs, natural areas dedicated to floods without infrastructure and extensive agriculture, green and blue infrastructure in urban areas) however structural flood measures provided good protection in some areas during this event. In addition, the maintenance of existing water infrastructure should be upgraded, especially the investments in torrential areas should be increased. Slovenia is investing several times less money for water infrastructure per river kilometre or per capita (Sodnik et al., 2015) compared to neighbouring countries (e.g., Austria). Protection measures against natural disasters is well invested money with high return rates.

Code and data availability

The precipitation and discharge data can be obtained from the archives of the Slovenian Environment Agency (ARSO). The code used to conduct the analysis can be obtained upon request from the corresponding author.

Author contributions

All authors developed the concepts of the study and NB conducted most of the calculations and prepared a first draft. Other authors edited and improved the manuscript and figures.

Competing interests

The contact author has declared that neither they nor their co-authors have any competing interests.

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