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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 4 to 6 August 2023 in Slovenia causing three casualties and causing total direct and indirect damage, including post-disaster needs according to the Post-Disaster Needs Assessment (PDNA), close to EUR 10 billion. The atypical summer weather conditions combined with the high air and sea temperatures in the Mediterranean and the high soil moisture led to the most extreme flood event in Slovenia in recent decades. The return periods of both daily and sub-daily precipitation extremes and peak discharges reached 250–500 years, and the runoff coefficient of a typical torrential and mostly forested mesoscale catchment was around 0.5. In addition, flooding, soil erosion, mass movements and river sediment transport processes caused major damage to buildings (more than 12 000 houses) and diverse 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 3000 mm in the western part (Dolšak et al., 2016). In combination with complex topography and lithological characteristics, extreme rainfall events can generate significant soil erosion and mass movement processes that endanger around 45 % of the 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 occur relatively frequently, causing significant economic damage and human fatalities (Bezak et al., 2016; Mikoš, 2021; Mikoš et al., 2004; Špitalar et al., 2020). Due to climate change (Kaitna et al., 2023; Tarasova et al., 2023), extreme rainfall events will become more frequent and more 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 an extreme flood event that occurred in August 2023 in Slovenia, Europe. We conduct a preliminary hydrological investigation of the main characteristics of this event in order to (i) provide basics for effective remediation measures that will follow the concept of "building back better" and (ii) provide useful examples of lessons learned that could benefit other countries and will increase flood resilience in Slovenia.

2 August 2023 floods in Slovenia

2.1 Drivers and triggering mechanisms

The first half of 2023 was relatively wet in Slovenia compared to previous years, as almost all parts of the country recorded more than 50 % of the total annual rainfall by the end of June. In Slovenia, the autumn period is usually the wettest period of the year and main flood events and big mass movements occur 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 amounts of rainfall but with thunderstorms that can yield high rainfall erosivity (Panagos et al., 2016). By the end of July 2023, the western part of the country recorded around 50 % of 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 Slovenia. In July 2023, the monthly rainfall total in many parts of the country 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, within 3 months the Slovenian Environment Agency (ARSO) prepared 11 web reports about extreme weather events. Orange or red weather alerts were issued several times for parts of Slovenia on meteoalarm.org. For example, in July, eight orange weather alerts (thunderstorms, rain or wind) and three red weather alerts (thunderstorms, rain or wind) were issued by the Slovenian Environment Agency (ARSO) for parts of Slovenia. Consequently, soil moisture was relatively high before the August 2023 flood event (Fig. 1). Summer thunderstorms that occurred in May–July also triggered smaller landslides and soil slips, and they damaged forest cover by local windthrows. The damaged wood could not be cleared away before the extreme event in August 2023 (Fig. 1).

An additional important driver that caused the August extreme event was the relatively high temperature of the Mediterranean Sea and Adriatic Sea as at the beginning of August. The average sea temperature in July 2023 was more than 2 °C above the long-term average (see Fig. 6 shown in ARSO, 2023a). The same applied for some other regions around the globe (Climate Copernicus, 2023). On 3 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 August 2023) until Saturday morning (5 August 2023) (ARSO, 2023a). A synoptic chart was provided by the Slovenian Environment Agency (ARSO, 2023a). Those weather conditions are highly unusual for summer and are more typical for autumn or winter, when the sea temperature is lower (ARSO, 2023a). The first storms occurred in Slovenia on Thursday (3 August 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). Flooding started early on 4 August. 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 southeastern parts (ARSO, 2023a) (Supplement Fig. S1). In most parts of the country rain stopped on Sunday 6 August (ARSO, 2023a). Therefore, extreme rainfall triggered numerous local mass movements (i.e., shallow landslides, deep-seated landslides, soil slips, debris flows), surface soil erosion and intense fluvial sediment transport processes including extensive flooding. Rainfall maps showing accumulated rainfall for different durations were prepared by the Slovenian Environment Agency (ARSO, 2023a) (Fig. S1).

Rainfall characteristics for specific locations shown in Fig. 2 are also presented in Table 1. For 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 latest intensity–duration–frequency curves for Slovenia (https://crossrisk.eu/sl/climate, last access: 15 November 2023). It should be noted that rainfall numbers were calculated for return periods of only up to 250 years in Slovenia. For 24 h rainfall numbers (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 numbers were very extreme. However, for some of the stations shown in Table 1 we also managed to calculate the 24 h probable maximum precipitation (PMP) (World Meteorological Organization (WMO), 2009), which was 670, 410, 890 and 340 mm for the Kamniška Bistrica, Slovenj Gradec, Bovec and Sevno stations, respectively. Thus, it can be seen that theoretically 24 h rainfall can be even higher in the future compared to the August 2023 extreme event, which caused such extensive flooding. Additionally, the Pasja Ravan station recorded 217 mm of rain in 12 h, which is more than 50 mm above the rainfall number associated with a return period of 250 years (determined using historical rainfall data). Moreover, from 3 until 6 August this area around Pasja Ravan station received around 320 mm of rain (Fig. S1), which indicates that total quantity of water was around 3200 t ha^{-1}.

We also calculated the rainfall erosivity (R) of the August 2023 event (i.e., from 3 to 6 August) based on the same methodology as used by Panagos et al. (2023) (Table 1). 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; Fig. 2). This confirms previous studies that showed that the 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). For nine stations, the 4 d (i.e., from 3 to 6 August) rainfall erosivity was higher than 2300 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 thus erosivity) were the most affected ones with respect to floods. Moreover, in Slovenia, rainfall erosivity is expected to increase by 33 %–42 % (depending on the RCP scenario) by 2050 and even 52 % by 2070 based on the projections of 19 climatic models (Panagos et al., 2022).

2.2 Hydrological conditions of the August 2023 floods in Slovenia

The weather situation described in Sect. 2.1 generated extreme local floods that according to the satellite-based data (Copernicus Emergency Management Service, 2023) covered more than 7.5 km^2 (Fig. S2) – the preliminary data collected in the field show that this estimation is severely un-

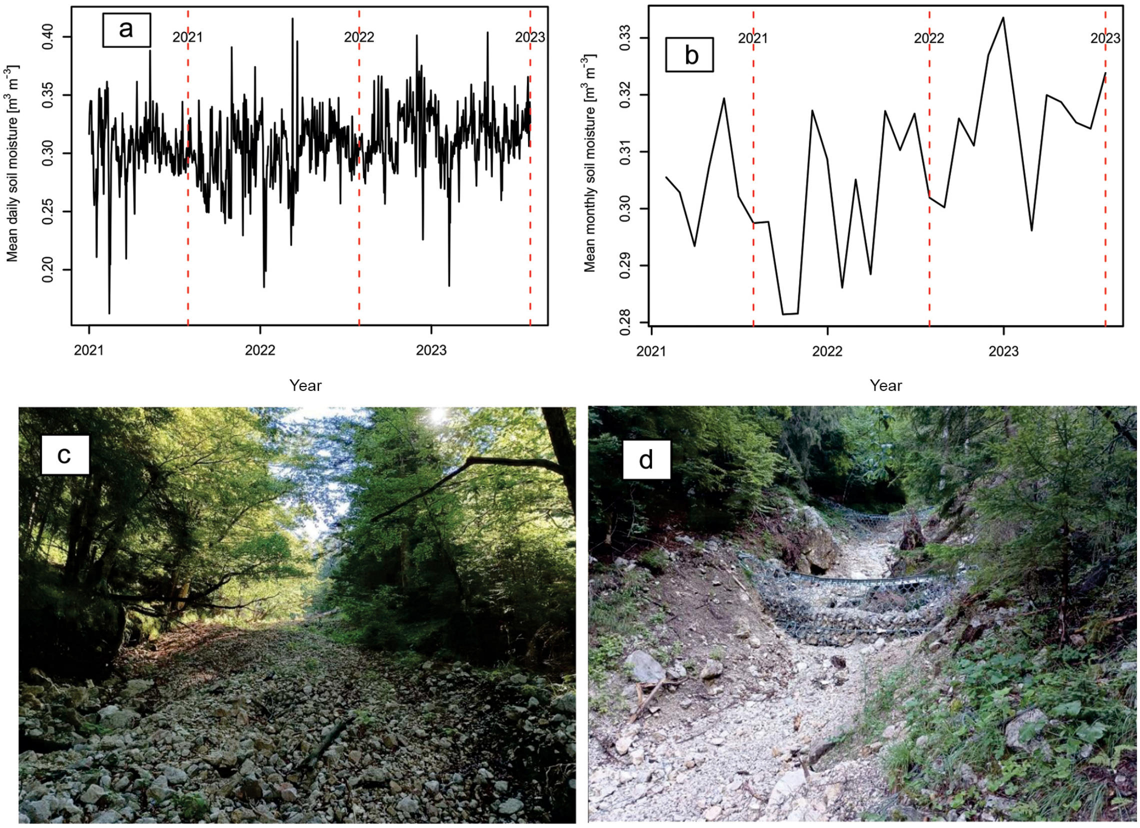

Figure 1. Panels **(a)** and **(b)** respectively show mean daily and monthly soil moisture for the Sava River catchment in Slovenia according to the satellite-based soil moisture climate data following the ESA Climate Change Initiative soil moisture version 03.3 (CDS Climate Copernicus, 2023). The vertical dotted red lines indicate 31 July 2021, 31 July 2022 and 31 July 2023. Panels **(c)** and **(d)** show the situation in the Brezovški graben torrent (Bezak et al., 2020) at the end of July 2023 (Sodnik et al., 2023).

derestimated because of the potential limitations of remote sensing data (e.g., not all flooded areas could be identified) and torrential characteristics of the flood event. For example, a first estimate was that more than 160 km^2 only of agricultural areas were flooded. Additionally, close to 90 % of all municipalities in Slovenia reported some kind of damage (i.e., only 30 out of 212 municipalities did not reported damage) due to extreme rainfall, floods and mass movements (ARSO, 2023a). Hence, the hydrological situation was severe and for numerous gauging stations the preliminary data show that the return period of the event was more than 500 years (Fig. 3). Significant morphological changes can also be observed from the orthophoto images taken directly after the August 2023 flood event in the most endangered areas (Fig. S3). Based on the preliminary data that are available from the Slovenian Environment Agency (ARSO), we also calculated runoff coefficients during the event. For example, for the Kamniška Bistrica River, which was one of the most affected areas, the runoff coefficient up to the Kamnik gauging station was around 50 % (i.e., the outflow volume equalled around 1/2 of total precipitation during the event), while more than 300 mm of rainfall fell 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., 4 August at 05:30 CET; note all times given in CET) occurred only a few hours after a first significant rainfall intensity increase (from 3 August 20:00 until 4 August 03:30, the rainfall sum exceeded 130 mm). For many locations around the country the peak discharges recorded during the extreme August 2023 event were below the maximum curves but above the average empirical curves derived for specific discharges by Mikoš (2020) for both 100- and 500-year return periods, respectively (Fig. 3). However, the August 2023 event was lower than the maximum envelope thresholds derived by Mikoš (2020) based on the results of the flood frequency analyses for all discharge gauging stations in Slovenia (i.e., $q_{100} = 30 \cdot A^{-0.4}$ and $q_{500} = 40 \cdot A^{-0.4}$, where the specific discharge is in m^3 s^{-1} km^{-2} and A is catchment area in km^2). Additionally, we also derived an empirical threshold curve for the August 2023 event (i.e., $q_{2023} = 28 \cdot A^{-0.45}$, where q_{2023} is the specific discharge in m^3 s^{-1} km^{-2} and A is catchment area in km^2) that could be used in the future for the design of some mitigation measures in order to protect spe-

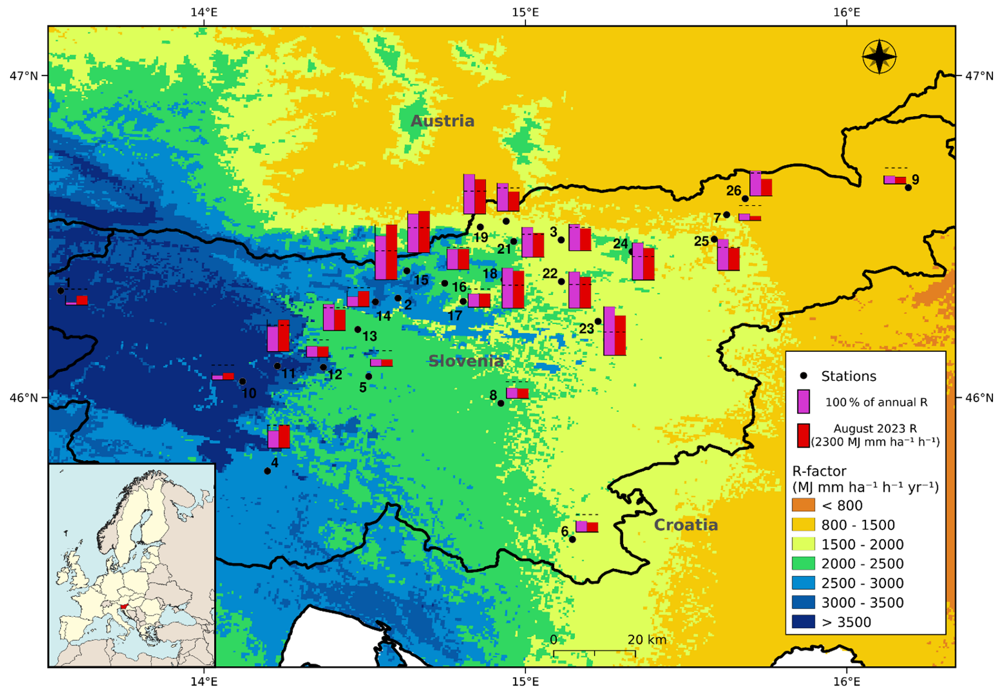

Figure 2. Rainfall erosivity (R factor) from 3 to 6 August 2023 in Slovenia. Red bars represent the rainfall erosivity in August 2023 for 26 stations (as numbered in Table 1). Fuchsia bars represent the proportion (in %) of 3–6 August 2023 erosivity compared to the mean annual erosivity. The dotted line represents 100 % of annual R (fuchsia) and 2300 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).

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 in Panagos et al. (2023).

No.	Station name	Longitude	Latitude	24 h rainfall [mm]	12 h rainfall [mm]	30 min rainfall [mm]	3–6 Aug 2023 R [MJ mm ha^{-1} h^{-1}]	Percent of annual R [MJ mm ha^{-1} h^{-1} yr^{-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	14.5124	46.0655	61.3	22.1	8.6	681	30 %
6	Črnomelj	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 %
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	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 %

cific areas from similar types of hydrological extremes. It should be noted that the derived empirical envelope for the August 2023 event fits well with the maximum unit peak discharges for 2007 flood event (i.e., Marchi, 2023) that occurred in the Selška Sora River catchment and caused six casualties (Marchi et al., 2009). Hence, potentially this empirical threshold curve for the August 2023 flood could be used to design future flood mitigation measures since it is yielding specific peak discharges close to the q_{100} maximum (Mikoš, 2020). We also made a comparison between the recorded peak discharges (please note that discharge data have 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. The same applies when comparing the specific peak discharge values for the flood in August 2023 with the regional envelope curve derived for alpine and alpine–Mediterranean catchments by Amponsah et al. (2018). Therefore, this confirms the comparison of measured 24 h rainfall numbers with PMP, which indicated that theoretically more rainfall could generate even more extreme floods, especially due to increasing air and sea temperatures. Hence, in the future, more extreme floods can be expected in Slovenia.

Following the GCM/RCM climate project models prepared by the 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 from 5 to 14 mm by the year 2100 according to the 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 in runoff volume of 30 million m^3 per event (e.g., 1 day). If this event (i.e., flood wave) lasts 24 h, discharges could be higher, around 350 $m^3\,s^{-1}$, which represents around 40–60 cm higher water levels according to the rating curve of this station. More extreme events like the one in August 2023 are therefore to be expected in the future, partly because this type of late summer weather situation, which occurred in August 2023, could become more frequent in the future due to global warming. Additionally, we also estimated the travel times of flood waves for Savinja and Sava rivers that had relatively good data coverage 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 $km\,h^{-1}$.

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 in the field and their volume estimated (as of early November 2023, close to 5000 landslides were recognised in the field so far). It also caused local debris flows, debris floods and hyper-concentrated flows with coarse debris transporting large amounts of sediments and woody debris, causing significant damage to road infrastructure such as clogging culverts and collapsing 2 bridges. Moreover, this caused even more severe problems with flooding due to sudden geomorphological changes such as bank erosion and lateral course shifting (Fig. 4). A detailed analysis of local conditions 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, in most locations exceeding 100 % of annual erosivity (Table 1; Fig. 3). Additionally, the maximum 12 h rainfall intensity for 15 out of 26 stations (shown in Table 1) was larger than that predicted by the empirical rainfall threshold curve for shallow landslides and debris flows developed by Caine (1980) (see also Bezak et al., 2016). Hence, it is clear that the rainfall event triggered many landslides across the country that should be surveyed using fieldwork and remote sensing techniques. New landslides were triggered during late-summer thunderstorms and prolonged autumn rainfall in September, October and November 2023.

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 the 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 of road networks or water infrastructure, reflected much higher numbers. An official report on damages to be submitted to the Government of Slovenia is still due and will give much better insight into the extent of this disaster. A preliminary review of consequences known in the first 2 weeks (in mid-August 2023) after the disaster can be summarised as follows.

- There were 10 000 to 15 000 households affected. Out of them, 34 houses were demolished and 484 residential buildings were unhabitable. On-site reconstruction and rebuilding as well as off-site reconstruction (relocation) of damaged and demolished buildings are planned. A new Reconstruction Act was approved in December 2023 that sets procedures for relocation of residential buildings in flooded areas.

- The extreme event took three lives, directly related to floods (i.e., drowning) and affected tens of thousands of residents and tourists.

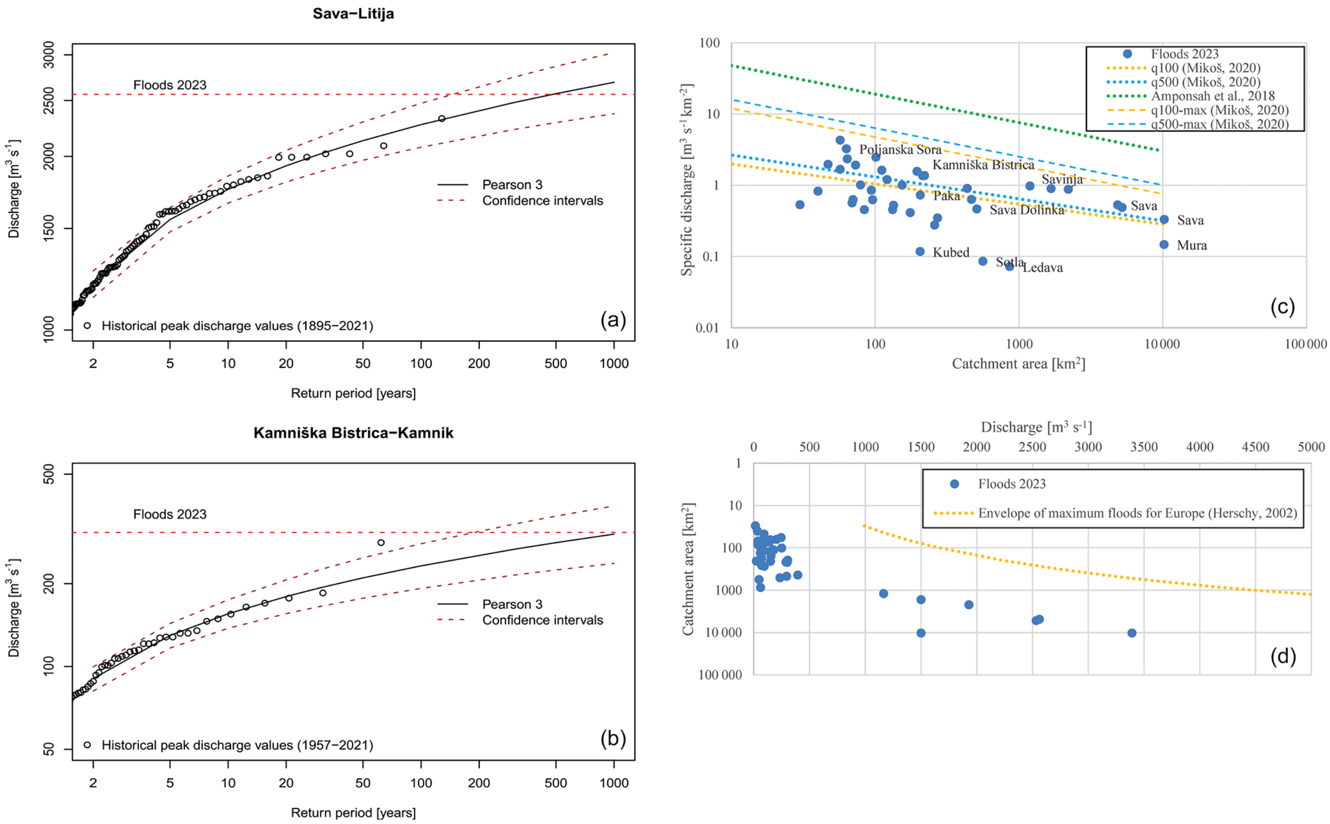

Figure 3. Panels **(a)** and **(b)** show flood frequency analysis of two gauging stations in Slovenia with confidence intervals derived using the parametric bootstrap approach. Panel **(c)** shows a comparison of specific discharge values for multiple gauging stations in relation to average specific discharge values derived by Mikoš (2020) (i.e., $q_{100} = 3.81 \cdot A^{-0.282}$ and $q_{500} = 5.407 \cdot A^{-0.308}$, where A is catchment area in km^2), maximum specific discharge values for Slovenia derived by Mikoš (2020) (i.e., $q_{100-\max} = 30 \cdot A^{-0.4}$ and $q_{500-\max} = 40 \cdot A^{-0.4}$) and a comparison with equation proposed by Amponsah et al. (2018) for alpine and alpine–Mediterranean catchments ($q = 120 \cdot A^{-0.4}$). Panel **(d)** shows 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) ($Q = 230 \cdot A^{0.43}$, where A is catchment area in km^2; the equation is only valid for catchments larger than $20\,\mathrm{km}^2$).

– Damages to business and industry were estimated to be EUR 400 million – final estimates of flood damage in late October checked by the government were close to EUR 5 billion.

– The flooded agricultural land area was estimated to 16 000 ha.

– Reports from municipalities on landslides gave numbers in several hundred; as of November 2023, their number is above 5000.

– Initially, only 30 out of 212 municipalities in Slovenia did not report any flood damage. By September 2023, a total of 173 municipalities reported damage in the AJDA Slovenian damage assessment system.

– Flood waters caused severe damage to local and regional road and 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 difficult.

– The initial estimated damage from immediately after the end of the events of EUR 0.5 billion was soon replaced by much higher estimates totalling in excess of several billion euros (a Reconstruction Act was approved in December 2023, seeks financial resources for the reconstruction and further development of the devastated areas totalling close to EUR 10 billion). This makes the August 2023 floods the most extreme natural event economically in Slovenia since becoming 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

Figure 4. Photographs of bank erosion and infrastructure damage (panels **a**, **c** and **d**) and mass movement processes (landslide in panel **b**) across Slovenia during the extreme August 2023 floods, with focus on the upper Savinja River catchment (some photographs courtesy of Igor Benko).

Slovenia in the last several decades (since the 1980s). The economic damage (i.e., around EUR 10 billion of direct and indirect damage including post-disaster needs, according to the Post-Disaster Needs Assessment (PDNA)) was significant at over 10 % of Slovenia's annual gross domestic product (around EUR 61 billion); the event also took three lives. Due to effective and timely organization of civil protection units and volunteer firefighter brigades, intervention activities (protection, evacuation and rescue) were generally adequate with respect to some locally rather overwhelming situations, and the number of fatalities stayed relatively low. Initially, ARSO provided rather accurate short-term severe weather forecast (on 3 August in the morning) announcing extreme weather potentially causing significant flooding, and issued an orange alert (flood alert for majority of country) advising not just precautionary behaviour but also possible evacuation. Moreover, on 3 August at 13:00 a press-conference was organized in order to warn people and activate all emergency services (e.g., civil protection, firefighters). On 4 August at around 04:00, this was replaced by a red alert (firstly for some sub-catchments). On 4 August at around 09:00 a red flood alert was issued for majority of country. The Geological Survey of Slovenia issued a warning about potential landslides on 3 August in the morning and also attended a press conference where they warned people about potential hazards. This led tot the relatively good preparedness of local firefighters and civil protection units.

In a network of 26 meteorological stations, we noticed that 12 h rainfall intensity was higher than 100 mm at 13 stations and the measured rainfall erosivity exceed the total mean annual erosivity at 14 stations. Also, measured peak discharge values for more than 20 gauging stations exceeded mean specific discharge curves with a 100-year return period (Fig. 3). The derived specific discharge envelope for the August 2023 event was similar to the one from the 2007 flood in the Selška Sora River catchment (Marchi et al., 2009). The return period of the event (both rainfall and peak discharge values) was in many locations in Slovenia over 250 or even over 500 years – in a way not expected by the population and civil protection despite the red alert. It should be noted that all meteorological predictions underestimated the actual situation and consequently the flood warning system by ARSO (Petan et al., 2015) did not predict such extreme peak discharge values. However, ARSO was able to issue timely warnings and organize a press conference before the event. Moreover, comparison of measured rainfall events and PMP and recorded peak discharges and historical European and regional envelope curves 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 are located in floodplain areas (i.e., threatened by extreme floods). As a consequence, stakeholders and decision makers should focus on redirecting classical water management and flood risk management towards intra-sectoral governance of flood resilience, taking into account best practices from around the world. New governance may focus more on incorporating nature-based solutions into structural flood measures (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 (e.g., Sodnik et al., 2023) during this event. In addition, the maintenance of existing water infrastructure should be increased. In particular, financial investment in torrential areas should be increased. Slovenia invests several times less in water infrastructure per river kilometre or per capita (Sodnik et al., 2015) than neighbouring countries (e.g., Austria). Disaster risk reduction measures are 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) (https://www.arso.gov.si/vode/podatki, ARSO, 2023c). The code used to conduct the analysis can be obtained upon request from the corresponding author.

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/nhess-23-3885-2023-supplement.

Author contributions. All authors developed the concepts of the study and NB conducted most of the calculations and prepared a first draft. MM, PP and LL edited and improved the article and figures.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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References

Amponsah, W., Ayral, P.-A., Boudevillain, B., Bouvier, C., Braud, I., Brunet, P., Delrieu, G., Didon-Lescot, J.-F., Gaume, E., Lebouc, L., Marchi, L., Marra, F., Morin, E., Nord, G., Payrastre, O., Zoccatelli, D., and Borga, M.: Integrated high-resolution dataset of high-intensity European and Mediterranean flash floods, Earth Syst. Sci. Data, 10, 1783–1794, https://doi.org/10.5194/essd-10-1783-2018, 2018.

ARSO: Report about the extreme rainfall between 3rd and 6th of August 2023, https://meteo.arso.gov.si/uploads/probase/www/climate/text/sl/weather_events/padavine_3-6avg2023-preliminarno.pdf (last access: 7 November 2023), 2023a.

ARSO: Reports about natural hazards, https://meteo.arso.gov.si/met/sl/climate/natural-hazards/ (last access: 7 November 2023), 2023b.

Slovenian Environment Agency (ARSO): Hydrological data archive, https://www.arso.gov.si/vode/podatki, last access: 18 December 2023c.

Bertalanič, R., Mojca, D., Andrej, D., Honzak, L., Kobold, M., Kozjek, K., Lokošek, N., Medved, A., Vertačnik, G., Vlahović, Ž., and Žust, A.: Ocena podnebnih sprememb v Sloveniji do konca 21. stoletja, 1st ed., edited by M. Dolinar, Slovenian Environment Agency, Ljubljana, http://www.meteo.si/uploads/probase/www/climate/text/sl/publications/OPS21_Porocilo.pdf (last access: 7 November 2023), 2018.

Bezak, N., Šraj, M., and Mikoš, M.: Copula-based IDF curves and empirical rainfall thresholds for flash floods and rainfall-induced landslides, J. Hydrol., 541, 272–284, https://doi.org/10.1016/j.jhydrol.2016.02.058, 2016.

Bezak, N., Jež, J., Sodnik, J., Jemec Auflič, M., and Mikoš, M.: An extreme May 2018 debris flood case study in northern Slovenia: analysis, modelling, and mitigation, Landslides, 17, 2373–2383, https://doi.org/10.1007/s10346-019-01325-1, 2020.

Bezak, N., Mikoš, M., Borrelli, P., Liakos, L., and Panagos, P.: An in-depth statistical analysis of the rainstorms erosivity in Europe, Catena, 206, 105577, https://doi.org/10.1016/j.catena.2021.105577, 2021.

Caine, N.: The Rainfall Intensity-Duration Control of Shallow Landslides and Debris Flows, Soc. Swedish Ann. Geogr. Geogr. Phys., 62, 23–27, 1980.

CDS Climate Copernicus: Soil moisture gridded data from 1978 to present, Copernicus Climate Change Service (C3S) Climate Data Store (CDS) [data set], https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-soil-moisture?tab=overview (last access: 7 November 2023), 2023.

Climate Copernicus: Global sea surface temperature reaches a record high, Copernicus Climate Change Service (C3S) Climate Data Store (CDS), https://climate.copernicus.eu/global-sea-surface-temperature-reaches-record-high (last access: 7 November 2023), 2023.

Copernicus Emergency Management Service: Floods in Slovenia: EMSR680 – Situational reporting, https://rapidmapping.emergency.copernicus.eu/EMSR680/reporting (last access: 7 November 2023), 2023.

Dolšak, D., Bezak, N., Šraj, M., Dolsak, D., Bezak, N., and Sraj, M.: Temporal characteristics of rainfall events under three climate types in Slovenia, J. Hydrol., 541, 1395–1405, https://doi.org/10.1016/j.jhydrol.2016.08.047, 2016.

Herschy, R. W.: The world's maximum observed floods, Flow Meas. Instrum., 13, 231–235, https://doi.org/10.1016/S0955-5986(02)00054-7, 2002.

Kaitna, R., Prenner, D., Switanek, M., Maraun, D., Stoffel, M., and Hrachowitz, M.: Changes of hydro-meteorological trigger conditions for debris flows in a future alpine climate, Sci. Total Environ., 872, 162227, https://doi.org/10.1016/j.scitotenv.2023.162227, 2023.

Marchi, L.: Community Comment 1, https://doi.org/10.5194/egusphere-2023-1979-CC1, 2023.

Marchi, L., Borga, M., Preciso, E., Sangati, M., Gaume, E., Bain, V., Delrieu, G., Bonnifait, L., and Pogacnik, N.: Comprehensive post-event survey of a flash flood in Western Slovenia: observation strategy and lessons learned, Hydrol. Process., 23, 3761–3770, https://doi.org/10.1002/hyp.7542, 2009.

Mikoš, M.: Flood hazard in Slovenia and assessment of extreme design floods – Poplavna nevarnost v sloveniji in ocena ekstremnih projektnih poplavnih pretokov, Acta Hydrotechnica, 33, 43–59, https://doi.org/10.15292/acta.hydro.2020.04, 2020.

Mikoš, M.: After 2000 Stože landslide: Part II – Development in landslide disaster risk reduction policy in Slovenia – Po zemeljskem plazu Stože leta 2000: Del II – razvoj politike zmanjševanja tveganja nesreč zaradi zemeljskih plazov v Sloveniji, Acta Hydrotechnica, 34, 39–59, https://doi.org/10.15292/acta.hydro.2021.04, 2021.

Mikoš, M., Brilly, M., and Ribičič, M.: Floods and Landslides in Slovenia, Acta hydrotechnica, 22, 113–131 https://actahydrotechnica.fgg.uni-lj.si/paper/a37mm.pdf (last access: 7 November 2023), 2004.

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Tadić, M. P., Michaelides, S., Hrabalíková, M., Olsen, P., Beguería, S., and Alewell, C.: Rainfall erosivity in Europe, Sci. Total Environ., 511, 801–814, https://doi.org/10.1016/j.scitotenv.2015.01.008, 2015.

Panagos, P., Borrelli, P., Spinoni, J., Ballabio, C., Meusburger, K., Beguería, S., Klik, A., Michaelides, S., Petan, S., Hrabalíková, M., Banasik, K., and Alewell, C.: Monthly rainfall erosivity: Conversion factors for different time resolutions and regional assessments, Water (Switzerland), 8, 119, https://doi.org/10.3390/w8040119, 2016.

Panagos, P., Borrelli, P., Matthews, F., Liakos, L., Bezak, N., Diodato, N., and Ballabio, C.: Global rainfall erosivity projections for 2050 and 2070, J. Hydrol., 610, 127865, https://doi.org/10.1016/j.jhydrol.2022.127865, 2022.

Panagos, P., Hengl, T., Wheeler, I., Marcinkowski, P., Rukeza, M. B., Yu, B., Yang, J. E., Miao, C., Chattopadhyay, N., Sadeghi, S. H., Levi, Y., Erpul, G., Birkel, C., Hoyos, N., Oliveira, P. T. S., Bonilla, C. A., Nel, W., Al Dashti, H., Bezak, N., Van Oost, K., Petan, S., Fenta, A. A., Haregeweyn, N., Pérez-Bidegain, M., Liakos, L., Ballabio, C., and Borrelli, P.: Global rainfall erosivity database (GloREDa) and monthly R-factor data at 1 km spatial resolution, Data Br., 50, 109482, https://doi.org/10.1016/j.dib.2023.109482, 2023.

Petan, S., Golob, A., and Moderc, M.: Hydrological forecasting system of the Slovenian Environment Agency, Acta Hydrotechnica, 28, 119–131, https://actahydrotechnica.fgg.uni-lj.si/si/paper/a49sp (last access: 7 November 2023), 2015.

Sodnik, J., Kogovšek, B., and Mikoš, M.: Investments into water infrastrucutre in Slovenia and in Austria, Gradb. Vestn., 64, 1–28, https://www.dlib.si/details/URN:NBN:SI:doc-YN57CQGX (last access: 18 December 2023), 2015.

Sodnik, J., Mikoš, M., and Bezak, N.: Torrential Hazards' Mitigation Measures in a Typical Alpine Catchment in Slovenia, Appl. Sci., 13, 11136, https://doi.org/10.3390/app132011136, 2023.

Špitalar, M., Brilly, M., Kos, D., and Žiberna, A.: Analysis of Flood Fatalities–Slovenian Illustration, Water, 12, 64, https://doi.org/10.3390/w12010064, 2020.

Tarasova, L., Lun, D., Merz, R., Blöschl, G., Basso, S., Bertola, M., Miniussi, A., Rakovec, O., Samaniego, L., Thober, S., and Kumar, R.: 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, 2023.

World Meteorological Organization (WMO): Manual on estimation of Probable Maximum Precipitation (PMP), https://library.wmo.int/index.php?lvl=notice_display&id=1302 (last access: 7 November 2023), 2009.