X-RISK-CC pilot areas (top) and the pilot area of Gorenjska – Sora catchment – two sub-basins: Selška Sora in the northern part and Poljanska Sora in the southern part (bottom)

FLASH FLOODS IN GORENJSKA – SORA CATCHMENT

Slovenia

Interreg
Co-funded by the European Union
Alpine Space

X-RISK-CC

Pilot report prepared by Slovenian Environment Agency, GeoSphere Austria and EURAC Research with the support of the X-RISK-CC partnership

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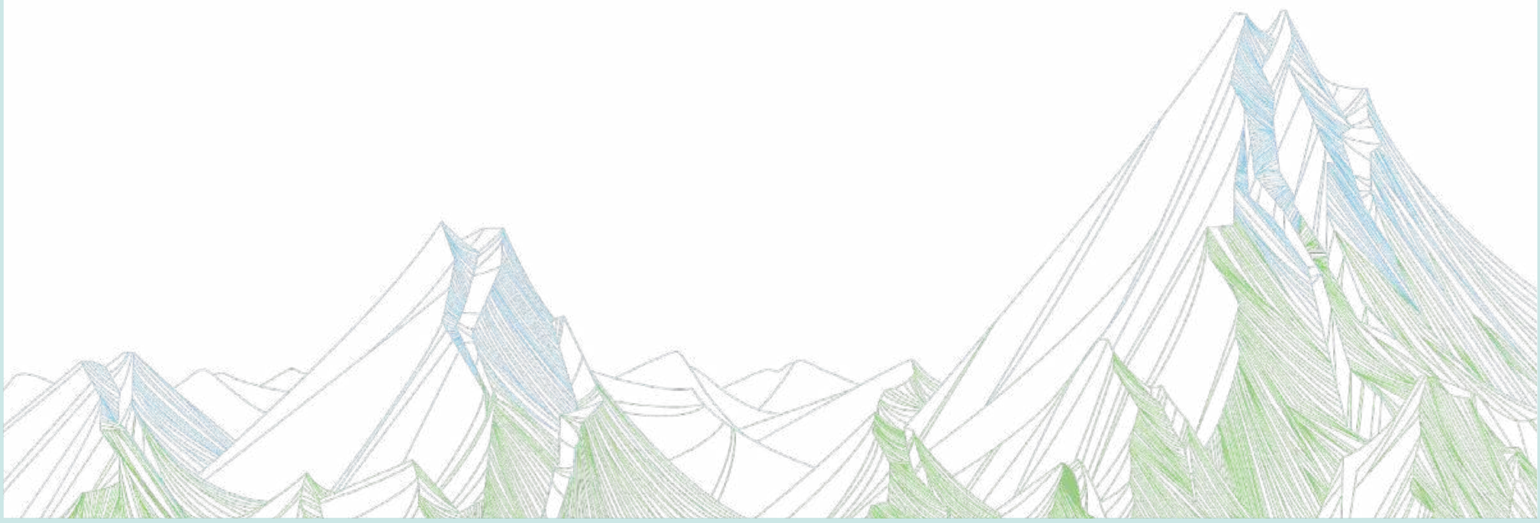


KEY MESSAGES

- The relevant weather extremes that lead to flash floods, river floods and landslides in the Sora catchment are extreme 1- to 7-day precipitation, especially in summer and autumn months.

- In the past, the two most pronounced flood events in the Sora catchment occurred in September 2007 and August 2023. They were the result of record 1- to 3-day extreme precipitation with return periods of at least 200 years (locally exceeding 500 years). The main difference between the 2007 and 2023 floods were the timescale and the area affected.

- Since 1950, there has been an increasing trend of extreme 2- to 3-day precipitation intensity on an annual level, especially in the northern parts of the Sora catchment, while a decrease can be observed in summer. Extreme 1-day precipitation does not show a trend.

- While precipitation is the major meteorological driver for flooding events, the occurrence of flooding also depends on the maximum hourly precipitation intensity, the actual soil moisture, season, soil infiltration capacity, topography, river management and flood protection infrastructure. A rough estimate of 2-day precipitation threshold for the flood events (2nd and 3rd warning level) is at least 80 mm, considering the whole catchment.

- In the future, the greatest changes in 1- to 3-day extreme precipitation with respect to current conditions (1991–2020) are expected under a global warming level of 4 °C in spring (increase in intensity by more than 20 %), while changes of up to 15 % are expected in other seasons. In terms of frequency of 1- to 3-day extreme precipitation, the number of heavy precipitation days will increase slightly in all seasons (the most in spring and winter and the least in summer). Maximum 1-day precipitation in autumn that is as extreme as the 1-in-50-year event in 1991–2020 is projected to become up to 2.4 times as likely under global warming levels of 3 and 4 °C.

PAST EXTREME EVENTS IN FOCUS

EXTREME RAINFALL IN SLOVENIA FROM 3RD TO 6TH AUGUST 2023 LEADING TO DEVASTATING FLOODS AND LANDSLIDES

The most extensive and destructive floods in Slovenia were the result of the interaction of several different predisposing factors, including the atypical synoptic situation for summer, warm sea surface and saturated soil conditions. These factors were favourable for the onset of the flood event between 3rd and 6th August 2023, when a weather front persisted over Slovenia for almost 36 hours, bringing the normal amount of precipitation for August in some areas in just a few hours. Severe storms with heavy rainfall, hail and strong winds caused several landslides and the strong winds knocked down a considerable number of trees. Record or near-record daily precipitation amounts were measured at several stations in the area of heaviest rainfall on 4th August, including in the southeastern part of the Sora catchment. The amount of precipitation at several stations in the region was estimated at a 200-year return period or higher. From a hydrological perspective, high water

FIGURE 1: *Škofja Loka during the flood in August 2023 (Author: Mitja Legat).*

FIGURE 2: *Flash flood in the Selška Sora river catchment (Source: https://www.poplavna-varnost.si/zelezniki/).*

thresholds were exceeded at 122 gauging stations on 74 rivers in Slovenia, including the Sora river and its tributaries (***FIGURE 1***). The unique characteristic of this flood event was that the three largest Slovenian rivers, Sava, Drava and Mura, were all flooding at the same time. Record discharges were measured at 31 gauging stations (3 in the Sora catchment), most of which had a return period of 100 years or more. Numerous roads, water supply, and electrical installations were damaged. Several buildings were flooded or damaged, and 265 landslides were triggered in the municipalities of Škofja Loka, Gorenja vas - Poljane, Žiri and Železniki. The final estimate of direct material damage caused by the August floods in Slovenia was 2.98 billion euros.

EXTREME RAINFALL AND FLASH FLOODS IN SLOVENIA ON 18TH SEPTEMBER 2007

On 18th September 2007, the western, north-western and northern parts of Slovenia experienced heavy and abundant precipitation. It led to a rapid increase in river discharges, especially in the Baška grapa area and the wider Cerkno and Škofja Loka hills area. Flash floods of the Selška Sora, Davča and Kroparica rivers caused severe damage in the area (***FIGURE 2***). The torrents and rivers in the Karavanke region, the foothills of the Kamnik-Savinja Alps, Kranj and Domžale fields, the Tuhinj Valley, and in the wider Celje region, flooded as well. In the areas with the greatest damage, the discharges exceeded the 100-year return periods. Out of 210 municipalities in Slovenia, 60 reported flood damages, and the total economic flood damage was estimated at 223.7 million euros; highest damage was reported by the municipality of Železniki in north-west Slovenia. There were six fatalities as a result of the event.

DEFINITION OF METEOROLOGICAL AND HYDROLOGICAL EXTREMES

EXTREME PRECIPITATION

Rx1d, Rx2d, Rx3d, Rx7d, Rx30d, Rx60d, Rx90d: annual and seasonal precipitation maxima over 1, 2, 3, 7, 30, 60 and 90 days.

R97pN: annual and seasonal number of days with daily to multi-daily precipitation exceeding the 97th percentile of the reference period 1991–2020 (percentile from wet days with 1 mm or more precipitation).

FLOODS

The **discharge of the river** exceeds a threshold value, which is determined based on the observed magnitude of flooding: overflowing/minor flooding (1st level warning), flood (2nd level warning) and major flood (3rd level warning). In the Sora river catchment there are 6 gauging stations with their corresponding thresholds (***FIGURE 3***, ***TABLE 1***). The extent to which the threshold value is exceeded depends on many factors (precipitation, soil moisture, catchment characteristics). For the case study, the probability of exceedance of the flood threshold was analysed in connection to the extreme precipitation events in the Sora river catchment.

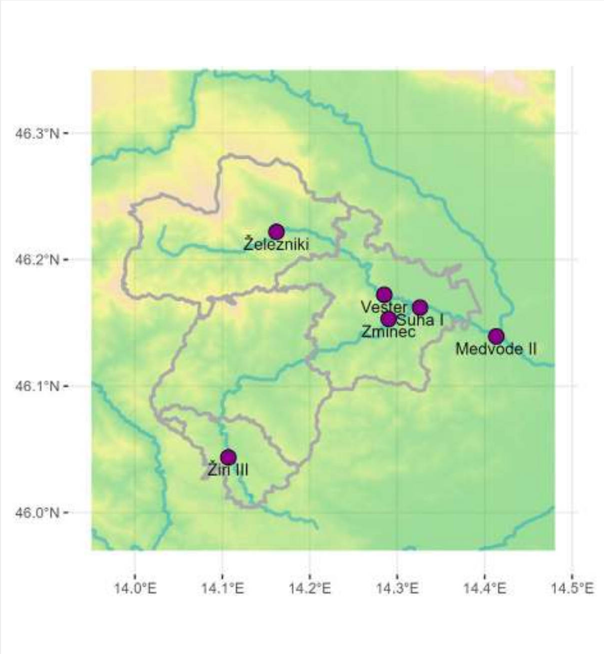


FIGURE 3: *Hydrological stations in the Sora catchment. The borders of municipalities of the Sora catchment are marked with a grey line.*

TABLE 1: *Hydrological stations in Sora catchment and their corresponding warning level thresholds.*

Station	**River discharge** [m³/s]		
Name	**1st warning level - overflowing**	**2nd warning level - flood**	**3rd warning level - major flood**
Suha	320	489	557
Medvode	370	540	650
Žiri	98	130	162
Zminec	140	190	260
Železniki	82	120	220
Vešter	140	220	335

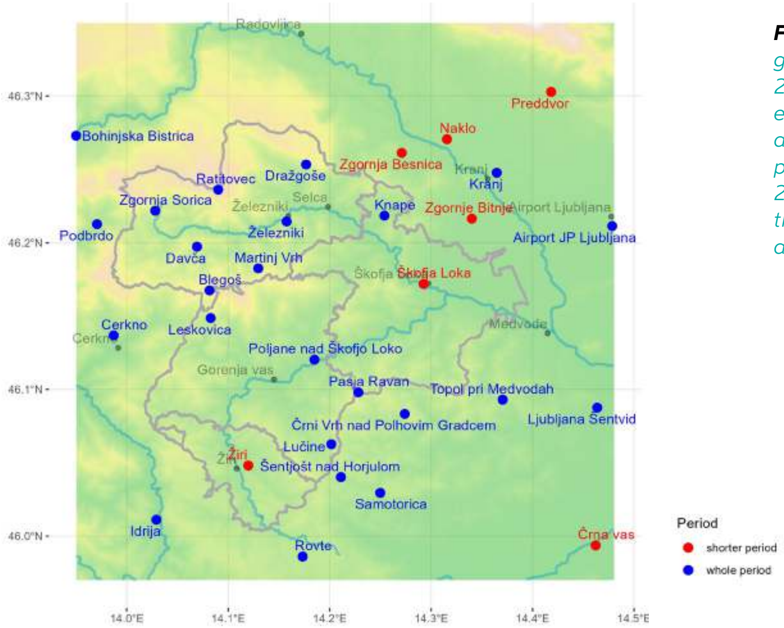


FIGURE 4: *Precipitation stations in the greater Sora catchment area. Blue denotes 24 precipitation stations with data over the entire period 1950–August 2023 and red denotes 7 precipitation stations with shorter period of data (mostly in the periods 1950–2022 or 1950–July 2023). The borders of the municipalities of the Sora catchment are marked with a grey line.*

DATA

For the case study area of the Sora catchment in Gorenjska, observations of daily precipitation at 31 gauging stations (part of ARSO station network) were used for the analysis of extreme precipitation in the period from 1950 to August 2023 (***FIGURE 4***). The daily precipitation measurements at ARSO cover time period from 7:00 CET (6:00 UTC) of the previous day to 7:00 CET (6:00 UTC) of the day of the measurement. All datasets have undergone homogenization and missing data were interpolated using data from neighbouring stations. Not all datasets however span the whole period from 1950 to the end of August 2023 (there are two stations with data up to July 2023 and five stations with data up to the end of the year 2022). The data from all stations were used to assess the statistics (frequency, trends etc.) but only the data from 24 stations, covering the entire period, were used to describe the floods in August 2023. For the analysis of events in focus, we have chosen 1- to 90-day precipitation accumulations from the day of the event to the day after the event.

When analysing station observations, it is important to consider that these can be affected by uncertainties, especially in areas characterised by complex orography. In particular, precipitation amounts at high-elevation sites can be underestimated, especially during episodes of high wind speeds and snowfall.

In addition to the precipitation data, records of peak discharges per flood event at 3 hydrological gauging stations (part of ARSO station network, ***FIGURE 3***) in the Sora river catchment were used for the analysis of flood events in relation to extreme precipitation in the period from 1961 to August 2023.

The analysis of future changes in the frequency and intensity of extreme precipitation is based on national projections of daily precipitation with a resolution of 12 km, which were bias-adjusted from EURO-CORDEX model simulations (***TABLE 2***) according to observations in the period 1981–2010 (Bertalanič et al., 2018). The changes are examined for four global warming levels relative to the pre-industrial period (1850–1900), namely 1.5 °C (representing very near future conditions), 2 °C, 3 °C and 4 °C and shown as deviations from the reference period 1991–2020.

It is important to note that station observations and model simulations are not directly comparable, even after the bias-adjustment procedure, which increases the overall accuracy of the model fields but does not increase the spatial scales resolved. The coarser spatial resolution of the model simulations therefore limits the representation of features at the local scale, especially in orographically-complex regions.

TABLE 2: *List of bias-adjusted EURO-CORDEX models simulations used for evaluation of projected changes in extreme precipitation in the Sora catchment.*

	Global Climate Model	**Regional Climate Model** (Institute)
1	EC-EARTH	HIRHAM5 (DMI)
2	HadGEM2-ES	RACMO22E (KNMI)
3	CNRM-CM5-LR	CCLM4-8-17 (CLMcom)
4	IPSL-CM5A-MR	WRF331F (IPSL)
5	MPI-ESM-LR	CCLM4-8-17 (CLMcom)
6	MPI-ESM-LR	RCA4 (SMHI)

TYPICAL SYNOPTIC SITUATION LEADING TO THE EXTREME EVENT

SYNOPTIC SITUATION: FLOOD 2023

On 3rd August 2023, a trough of cold Atlantic air, which had formed over Western Europe, moved south over the western Mediterranean, as a weather front moved across the Alps. The trough reached the northern and central Mediterranean the day after. Meanwhile, a shallow cyclonic area formed over the northern Mediterranean. The abovementioned weather front persisted over Slovenia for almost 36 hours, from the night of 3rd August until the morning of 5th August. The synoptic situation was rather unusual for summer and more typical for autumn or winter, when sea surface temperature in the Mediterranean is no longer as high as in August. This time, the surface of the Mediterranean Sea over which the air mass passed, was mostly warmer than the long-term average. Furthermore, in July, the month prior to the event, Slovenia received above-average amount of precipitation, up to three times the normal July precipitation, indicating that the soil was already saturated.

SYNOPTIC SITUATION: FLOOD 2007

The centre of a cyclone was situated over northern Europe on 18th September 2007. A cold front was approaching the Alpine region from the north-west, passing western and central Europe. At the same time, upper air trough was moving across Western Europe towards the east. This situation resulted in increased southwesterly wind over Slovenia. The main reasons for extreme precipitation were the orography of western Slovenia, strong inflow of warm and moist air from the southwest, huge potential instability of airmass, as well as a significant wind shear in the lower part of the atmosphere (below 6 km). The orographic triggering of the potential instability caused stationary thunderstorm activity with extreme convective rainfall.

The prevailing circulation type for the flash flood case in Sora catchment on 18th September 2007 is GWT 3 ('Gross-Wetter-Type'; a circulation type classification).

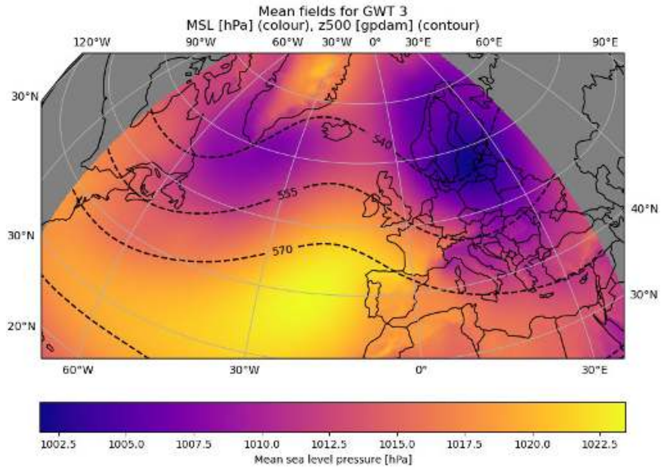


FIGURE 5: *Prevailing GWT for Gorenjska – Sora catchment (flash flood): GWT 3. Mean sea level pressure is shown in colours, 500 hPa geopotential as contours.*

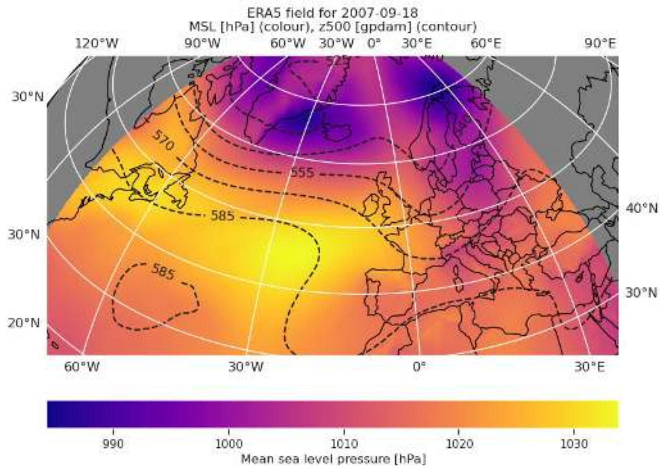


FIGURE 6: *Mean sea level pressure and geopotential height in 500 hPa for Gorenjska – Sora catchment in the case of flash flood on 18th September 2007 based on ERA5 reanalysis data. Mean sea level pressure is shown in colours, 500 hPa geopotential as contours.*

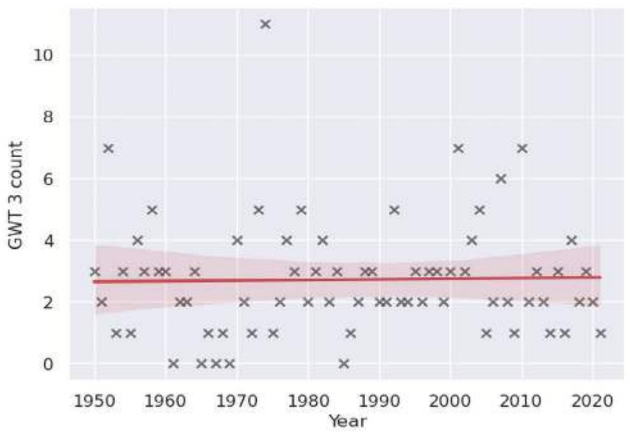


FIGURE 7: *GWT 3 counts per meteorological autumn for each year. No significant trend can be seen from historical data. Note that this only depicts the dynamic component, i.e. circulation that is associated with that event.*

This circulation pattern is shown in ***FIGURE 5***. GWT 3 is characterised by a trough over Central Europe with corresponding low pressure across Central Europe. Precipitation for this circulation pattern can be wide ranged in the front of the through axis, due to lifting. The specific ERA5 field for the day when the event took place is shown in ***FIGURE 6***. The trough axis is located west of the Alps, which leads to a southerly flow and hence precipitation south of the Alpine ridge. ***FIGURE 7*** shows the count of GWT 3 per year (only during meteorological autumn – from September to November). No significant trend is visible over the historical observational period. For meteorological summer (June to August) there is a tendency to slightly less GWT 3 events over the last 70 years. Note that this only depicts the circulation and hence the dynamic factor for frequency and says nothing about possible magnitude changes of such events.

Note that GWTs only capture the large-scale circulation of the weather situation and serve as preconditioning for extreme weather events. However, the existence of a specific GWT class alone does not entail extreme weather events all the time. There are more fine-grained details and thermodynamic components that also play a role in any specific weather situations. Nevertheless, the GWT analysis allows to estimate large-scale circulation changes and therefore changes to the preconditioning relevant for extreme weather events.

CHARACTERISTICS OF EXTREME EVENTS IN THE PAST

EXTREME PRECIPITATION AND DISCHARGE DURING FLOODS IN AUGUST 2023

The **maximum measured values** for 1-, 2-, 3- and 7-day precipitation during floods in August 2023 are depicted in ***FIGURE 8***. The values denoted only in red at a specific location mean that the historical record value was measured during this event. Both the relative and absolute highest values for 1-, 2- and 3-day precipitation were measured south of Škofja Loka, over the Poljanska Sora river (southern tributary of the Sora river). The record values for 1- to 3-day precipitation were measured at many precipitation stations in the abovementioned area, in Kranj and Airport JP Ljubljana on the eastern edge of the Sora catchment, and the record values for 7-day precipitation were also measured. The majority of precipitation was recorded in the first day of the event, from 3rd to 4th August. The highest values for precipitation accumulations of different length are shown in ***TABLE 3***. Before the 2023 floods took place, the soil was already very wet, as indicated by large values of 30- to 90-day precipitation.

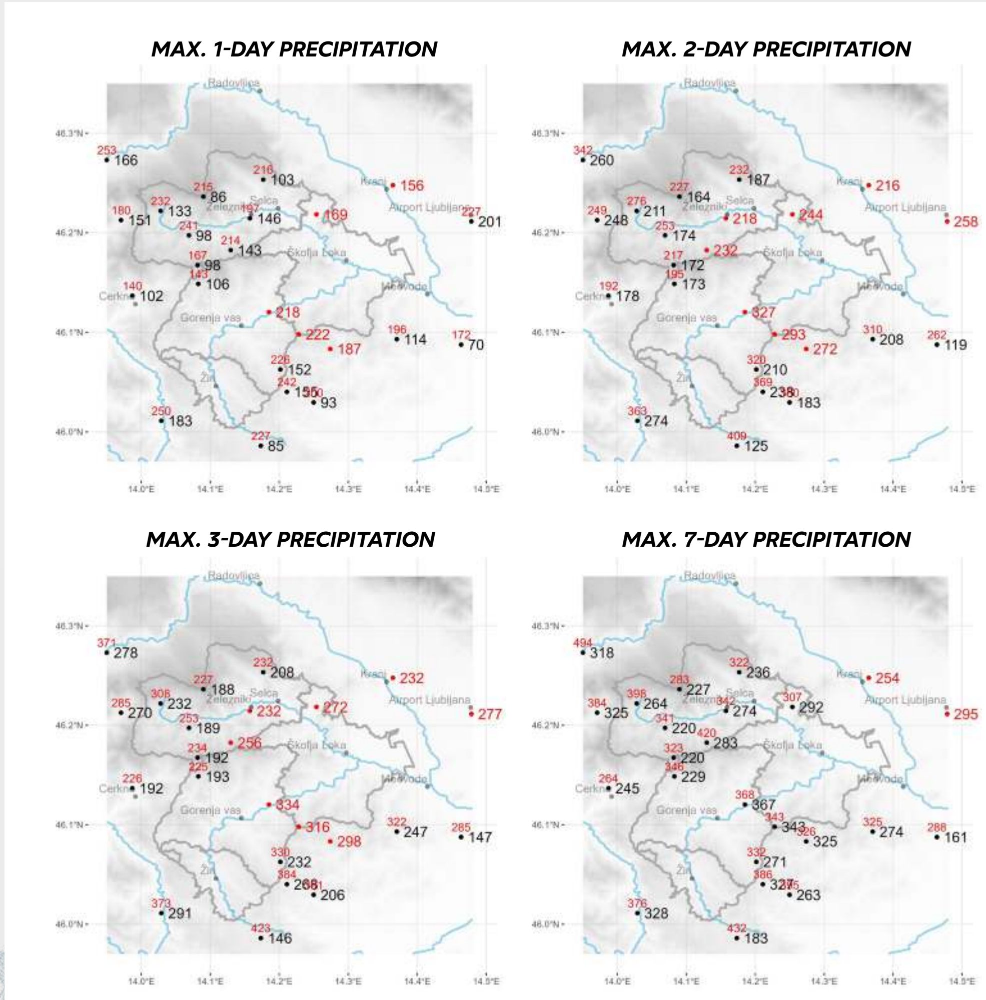


FIGURE 8: *Maximum 1-day (top left), 2-day (top right), 3-day (bottom left) and 7-day (bottom right) precipitation for the 2023 floods. Black denotes the measured value while red denotes the record value in the period 1950–August 2023. If measured value equals the record value, only one value in red is denoted.*

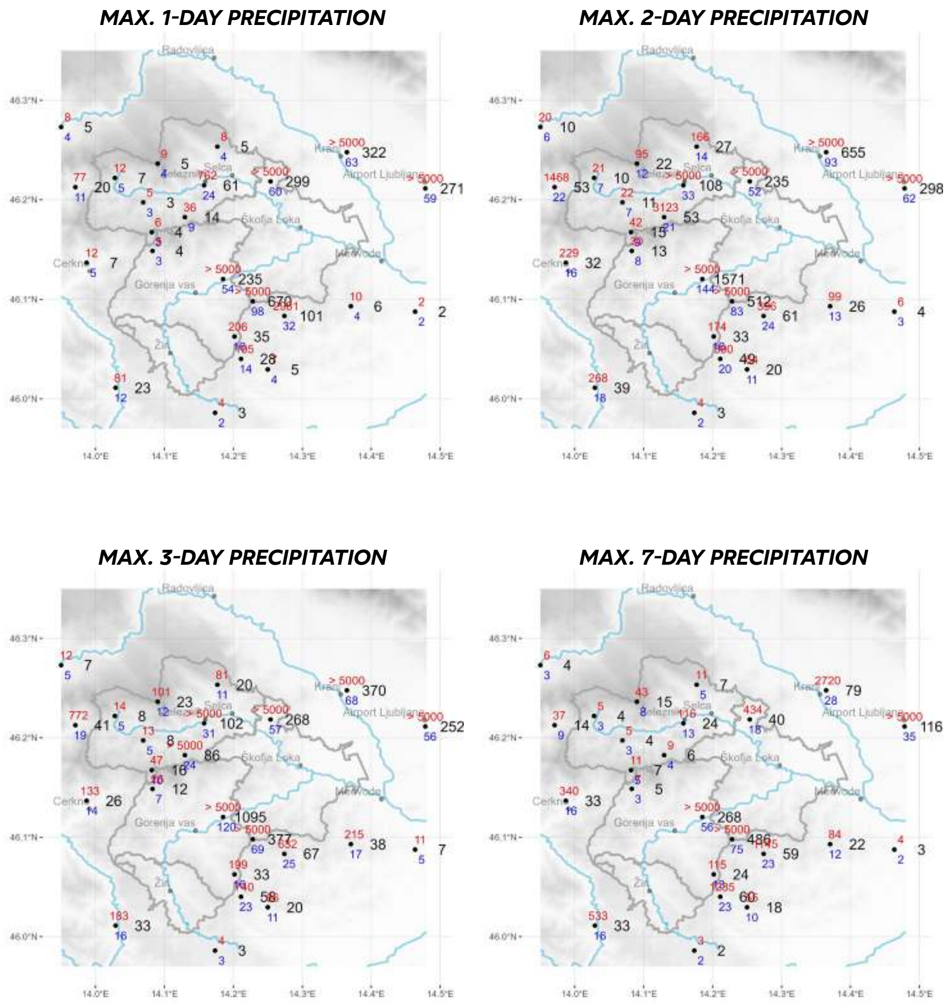


FIGURE 9: *Assessed return periods on an annual time scale for extreme 1-day (top left), 2-day (top right), 3-day (bottom left), 7-day (bottom right) precipitation for the 2023 flood event (in years). Black colour denotes the estimated value, while blue and red denote the lower and upper bound for 95 % confidence interval.*

The assessed **return periods** of recorded precipitation amounts have a very large uncertainty, exceeding the differences between the stations (***FIGURE 9***). For 1-day precipitation, the return periods were longest over the area of the Poljanska Sora catchment (from 100 for Črni vrh nad Polhovim Gradcem, to over 600 years for Pasja ravan) and east of the case study area (Kranj and Airport JP Ljubljana both over 250 years), while the return periods over the Selška Sora catchment (Železniki area) were shorter, with the only exception of Knape (approx. 300 years).

TABLE 3: *List of the highest 1- to 90-day precipitation in the case study area of the Sora catchment for the influential area of the Poljanska and Selška Sora rivers and their tributaries for the 2023 floods.*

Variable	**Station**	**Maximum event value** [mm]
1-day precipitation	Pasja ravan	222.1
2-day precipitation	Poljane nad Škofjo Loko	327.2
3-day precipitation	Poljane nad Škofjo Loko	334.1
7-day precipitation	Poljane nad Škofjo Loko	367.2
30-day precipitation	Martinj Vrh	587.5
60-day precipitation	Martinj Vrh	753.9
90-day precipitation	Martinj Vrh	1028.7

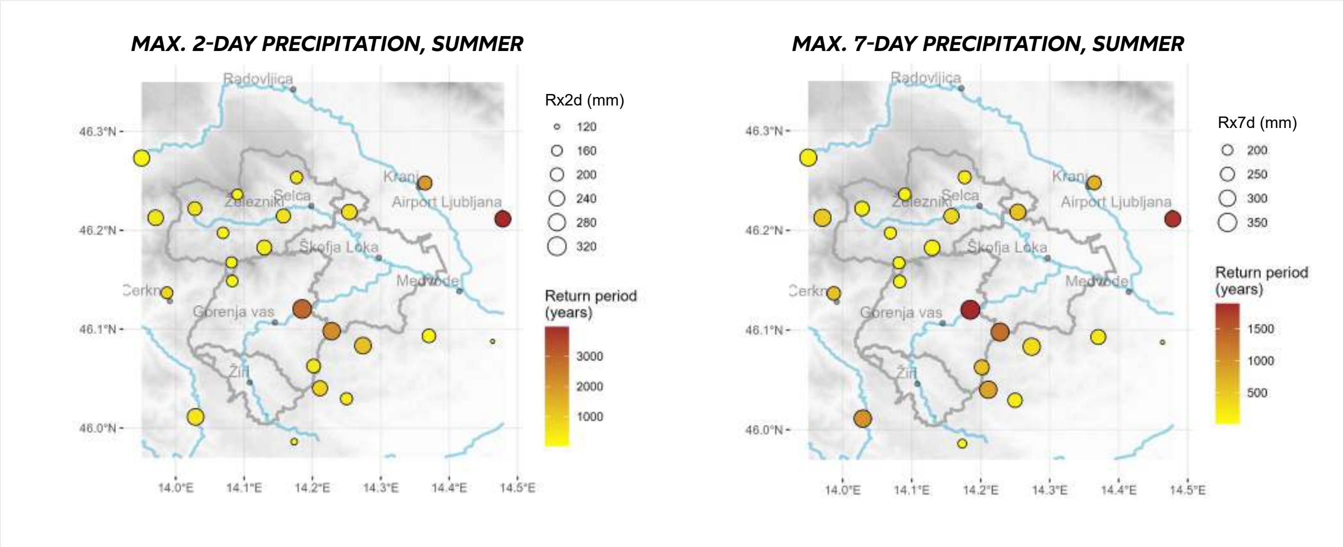


FIGURE 10: *Measured extreme values (circle size) and assessed return periods for summer (circle colour) for extreme 2-day (left) and 7-day (right) precipitation during the 2023 floods.*

For 2-day precipitation, the return periods were mostly even longer, the longest in Pasja ravan (over 1500 years). For 3-day precipitation, the return periods exceeded 100 years at four stations and for 7-day precipitation these were exceeded at two stations. These values are highly uncertain since the 95 % confidence intervals for assessed values are very large. Assessed return periods over the affected area are even longer on a seasonal level, indicating the rarity of such events in summer, particularly for accumulation periods of several days (***FIGURE 10***).

The flood event in 2023, caused by the extreme precipitation in August 2023, exceeded the major flood threshold on Poljanska Sora and Sora rivers. Record discharge values were recorded at the Žiri, Zminec and Suha gauging stations (***TABLE 4***). At the Medvode gauging station the major flood threshold was likely also exceeded with a record value, but the data for the peak discharge is missing due to gauging station malfunction. Record river discharges were reached at the Žiri, Zminec and Suha gauging stations on 4th August 2023. The return period at Zminec and Suha are estimated at more than 1000 years.

TABLE 4: *Highest discharge values measured at hydrological stations in the Sora catchment during the 2023 floods and mean August and yearly discharge in the reference period 1991–2020.*

Hydrological station	**Discharge** [m³/s]	**Mean August discharge** [m³/s]	**Mean yearly discharge** [m³/s]
Suha	797	8.04	18.6
Žiri	211	0.9	2.1
Zminec	516	4.4	10.5
Železniki	117	1.7	4.0
Vešter	277	2.6	7.2

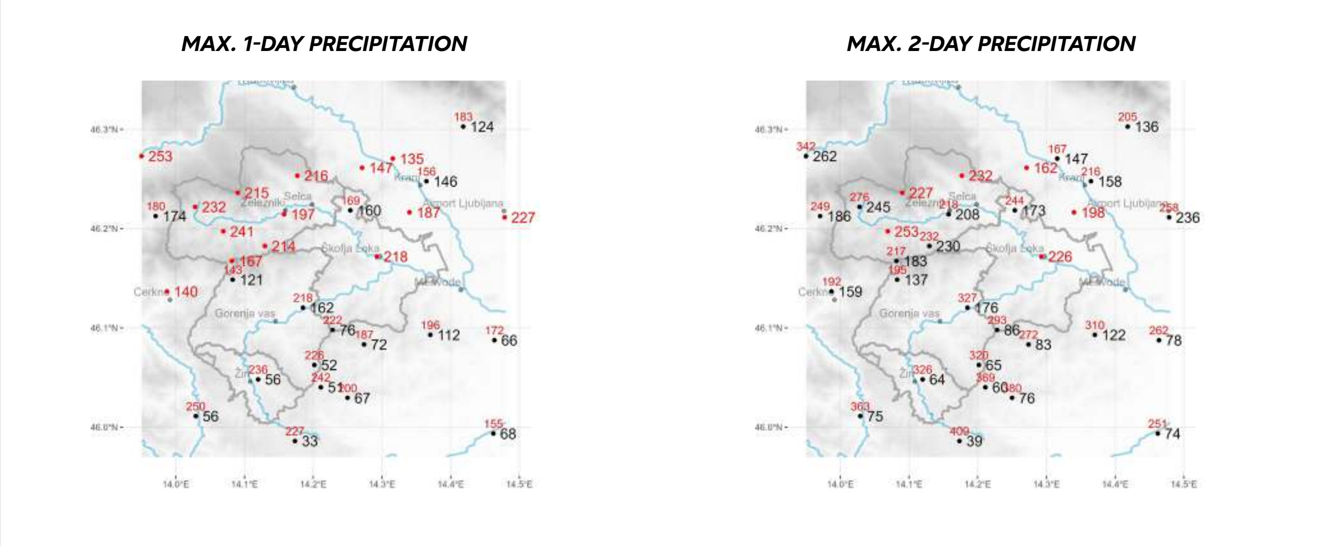


FIGURE 11: *Maximum 1-day (left) and 2-day (right) precipitation for the 2007 floods. Black denotes the measured value while red denotes the record value in the period 1950–August 2023. If measured value equals the record value, only one value in red is denoted.*

EXTREME PRECIPITATION AND DISCHARGE DURING THE FLOODS IN ŽELEZNIKI IN SEPTEMBER 2007 (AND COMPARISON WITH THE 2023 FLOODS)

The **maximum measured values** for 1- and 2-day precipitation during the event in 2007 are depicted in ***FIGURE 11***. The values denoted only in red at a specific location mean that the historical record value was measured during this event. 1-day record precipitation was measured in the north and north-west of the Sora catchment, around Železniki area over the Selška Sora river (northern Sora tributary) and in Škofja Loka, while no historical records were measured south of that area. The same holds for 2-day precipitation, which was only slightly higher than 1-day precipitation, since the majority of precipitation was recorded in the first day of the event. The record values for 2-day precipitation were recorded on a slightly smaller number of stations, while 3-day precipitation values were mostly the same as 2-day precipitation due to one-day event. The highest values for precipitation of different length are shown in ***TABLE 5***.

By comparing precipitation accumulations for the 2023 floods (***TABLE 3***) with the values for the 2007 floods (***TABLE 5***) it can be observed that 1-day maximum values over the area are slightly lower for the 2023 floods (for example Pasja ravan 222 mm vs. Davča 241 mm ~ 8 % difference), while the values for longer precipitation accumulations are much higher (30 % for 2-, 32 % for 3-, 45 % for 7-, 52 % for 30-, 53 % for 60- and 40 % for 90-day precipitation) than in 2007.

TABLE 5: *Highest 1- to 90-day precipitation in the case study area of the Sora catchment for the influential area of the Poljanska and Selška Sora rivers and their tributaries for the 2007 flood in Železniki.*

Variable	**Station**	**Maximum event value** [mm]
1-day precipitation	Davča	241.3
2-day precipitation	Davča	253.1
3-day precipitation	Davča	253.1
7-day precipitation	Davča	253.1
30-day precipitation	Davča	387.3
60-day precipitation	Martinj Vrh	492.1
90-day precipitation	Martinj Vrh	733.3

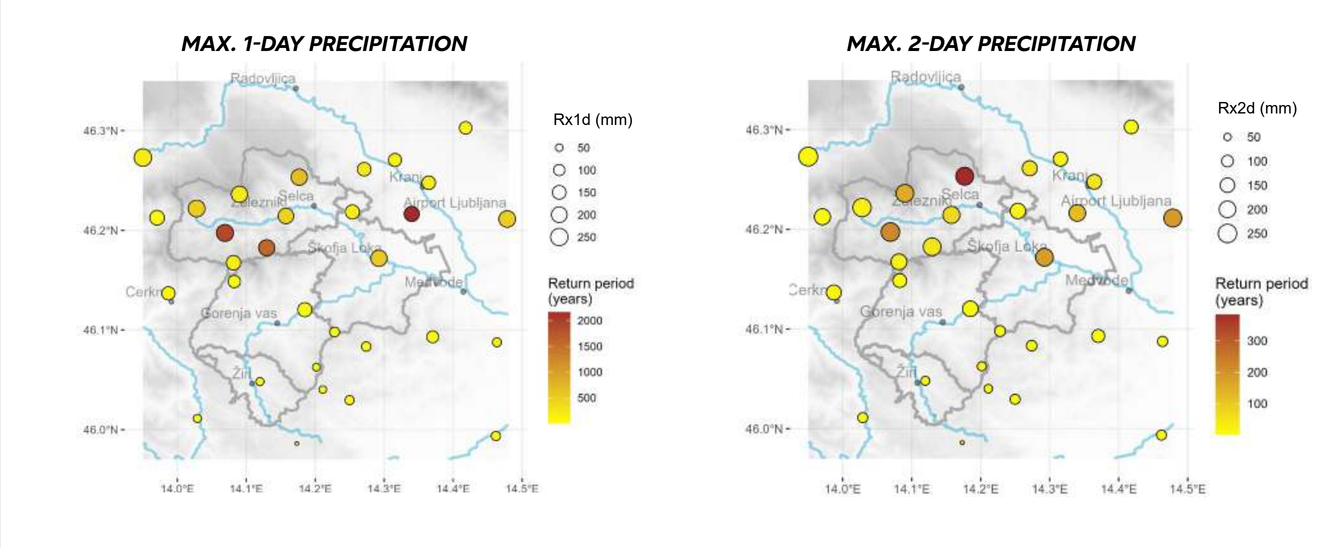


FIGURE 12: *Measured extreme values (circle size) and assessed return periods (circle colour) for extreme 1-day (left) and 2-day (right) precipitation during the 2007 floods.*

The assessed **return periods** for the precipitation amounts during the 2007 floods have a very large uncertainty, exceeding the differences between the stations. For 1-day precipitation, they were at least 200 years for the Železniki area and locally even exceeded 500 or 1500 years (***FIGURE 12***). The longest assessed return period was in Zgornje Bitnje (over 2000 years), while precipitation amount in Davča and Martinj Vrh also exceeded a return period of 1000 years. For 2-day precipitation, the return periods are shorter, with the longest one in Dražgoše (383 years). These values are highly uncertain since the 95 % confidence intervals for assessed values are very large as shown in ***FIGURE 13***.

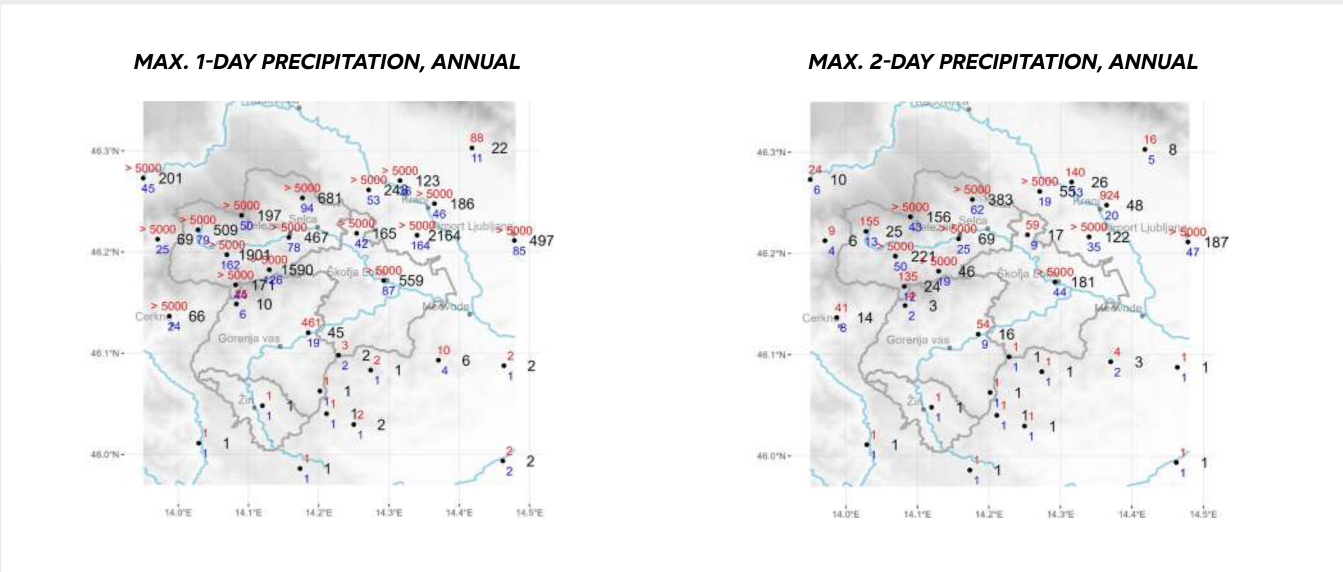


FIGURE 13: *Assessed return periods on an annual time scale for extreme 1-day (left) and 2-day (right) precipitation for the 2007 floods (in years). The estimated value of the return period is shown in black, while the lower and upper bound for 95 % confidence interval are shown in blue and red, respectively.*

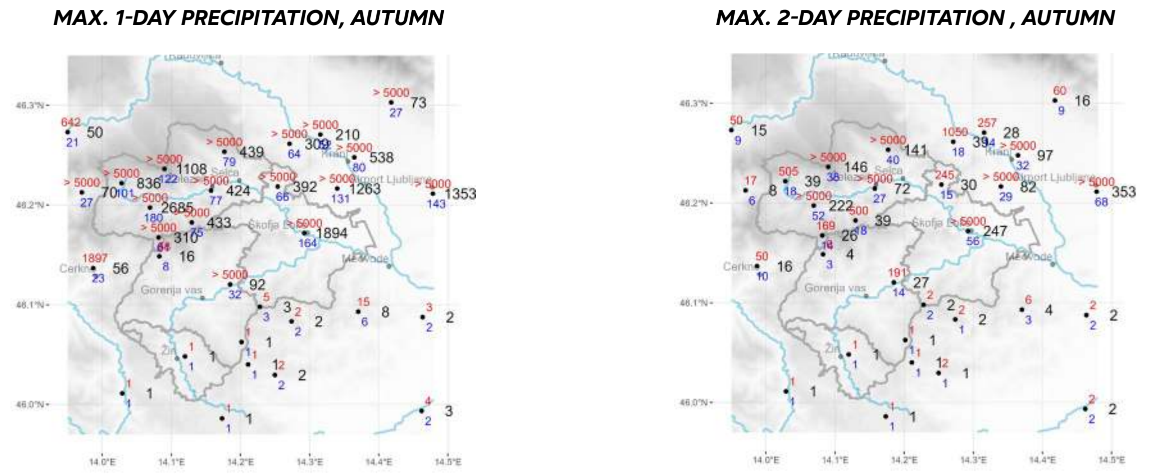


FIGURE 14: *Assessed return periods for autumn for extreme 1-day (left) and 2-day (right) precipitation for the 2007 floods event (in years). The estimated value of the return period is shown in black, while the lower and upper bound for 95 % confidence interval are shown in blue and red, respectively.*

The assessed return periods for 1-day extreme precipitation only for autumn are even higher, while they are lower than on an annual level for 2-day precipitation (***FIGURE 14***). 1-day extremes are less frequent in autumn than 2-day extremes, due to frontal as opposed to convective nature of precipitation in this season.

The extreme precipitation event in September 2007 caused the extreme flooding event that exceeded the major flood threshold on Selška Sora at Železniki and Vešter gauging stations (***TABLE 6***). The record river discharge was reached at Železniki gauging station on 18th September 2007 at 14.00, while no record peak discharges were observed at other stations. The assessed return period for the peak discharge at Železniki is between 100 and 300 years. At Žiri and Zminec gauging station, the river discharge did not exceed the flooding threshold.

The main difference between the 2007 floods in Železniki and the 2023 floods are:

1. **Time scale:** mostly extreme 1-day precipitation in 2007 in Železniki vs. stronger multi-day precipitation during the 2023 floods.
2. **Area affected:** the 2007 floods were mostly over the catchment area of the Selška Sora river (northern Sora tributary, Železniki area), while the 2023 floods were mostly over the catchment area of the Poljanska Sora river (southern Sora tributary).

TABLE 6: *Highest discharge values measured at hydrological stations in Sora catchment during floods 2007 and mean September and yearly discharge in the reference period 1991–2020.*

Hydrological station	**Discharge** [m³/s]	**Mean September discharge** [m³/s]	**Mean yearly discharge** [m³/s]
Suha	440	15.5	18.6
Zminec	122	8.7	10.5
Železniki	330	3.2	4.0
Vešter	352	5.4	7.2
Medvode	424	20.3	23.8

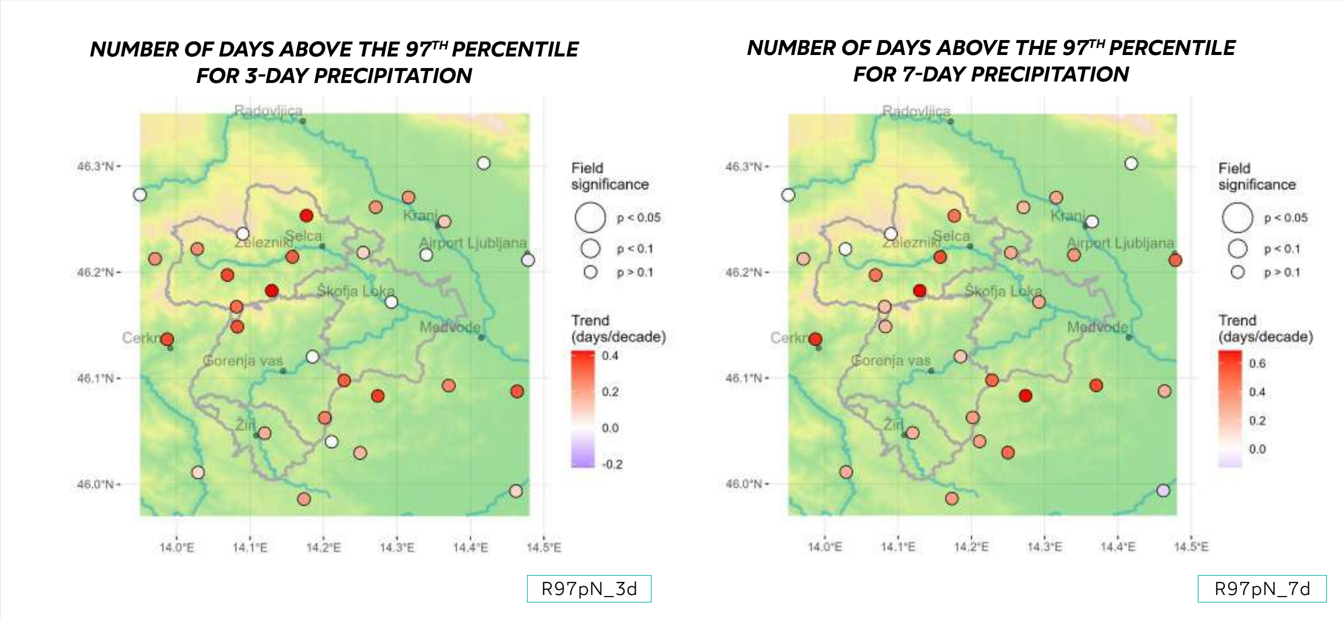


FIGURE 15: *Trend in the number of days above the 97th percentile of 3- (left) and 7-day (right) precipitation in the period 1950-August 2023, including field significance to account for spatial dependence between different stations in the case study area.*

TRENDS IN FREQUENCY AND INTENSITY OF EXTREME PRECIPITATION IN THE PERIOD 1950–2023

No linear trend in annual or seasonal number of 1- to 90-day precipitation exceeding the 97th percentile is statistically significant (at 5 % or 10 % level). The reason for this is a relatively high threshold; for most stations, over 30 % of years in the period 1950–2023 have no days exceeding the threshold. The thresholds (97th percentile of the reference period 1991–2020 wet days) range from 72 to 124 mm for 3-day precipitation and from 102 to 190 mm for 7-day precipitation. Despite this, 3- and 7-day precipitation show a positive signal (tendency) on an annual level for most stations in the pilot area, up to 0.4 days/decade for 3-day precipitation and up to 0.7 day/decade for 7-day precipitation (***TABLE 7*** and ***FIGURE 15***).

TABLE 7. *Number of weather stations with negative and positive signal (tendency) and the range of tendency for the extreme 3- and 7-day precipitation in the extended Sora catchment area. There are 31 weather stations analysed.*

Variable	**Positive**	**Negative**	**Range** [days/decade]
3-day precipitation	23	1	(−0.03, 0.43)
7-day precipitation	25	2	(−0.13, 0,69)

For the extreme (maximum) 1- to 90-day precipitation, the following statistically significant trends are observed (***TABLE 8***, ***FIGURES 16*** and ***17***):

- For **2-day extreme precipitation**, positive trends on an annual level for the north of the Sora catchment area (over the Selška Sora catchment, mean trend is 2.6 %/decade) and negative trends for summer mostly over the southern part of the Sora catchment (over the Poljanska Sora catchment, mean trend is −3.0 %/decade).
- For **3-day extreme precipitation**, positive trends on an annual level mostly for the north of the Sora catchment area (over the Selška Sora catchment, mean trend is 2.0 %/decade).
- For **30-day extreme precipitation**, negative trends for spring over both the Selška and Poljanska Sora catchments, with the mean trend over the area with significant trends −2.5 %/decade.
- For **60-day extreme precipitation**, positive trends on an annual level mostly over the Selška Sora catchment with the mean trend over the area with significant trends 2.2 %/decade.
- For **90-day extreme precipitation**, negative trends for spring for both the Selška and Poljanska Sora catchments (mean trend is −3.0 %/decade) and for summer for the Selška Sora catchment and some stations in the Poljanska Sora catchment (mean trend is −2.1 %/decade).

For other accumulation periods or seasons not listed in ***TABLE 8***, trends are not statistically significant.

TABLE 8: *Number of weather stations with significant trend, the direction of trend, mean trend (for significant trends at the 10 % level only), range of trend (for significant trends at the 10 % level only) and area with significant trend for seven selected combinations of precipitation sums and seasons with statistically significant trends. There are 31 weather stations analysed. Trends for other precipitation sums and seasons are mostly not statistically significant.*

Variable	**Season**	**Number of stations** [significance level in %]	**Direction**	**Mean trend** [%/decade]	**Range of trend** [%/decade]	**Area**
2-day precipitation	annual	8 (5 %) 13 (10 %)	positive	2.6	(1.5, 3.7)	Selška Sora catchment
2-day precipitation	summer	0 (5 %) 14 (10 %)	negative	−3.0	(−4.0, −2.1)	mostly Poljanska Sora catchment
3-day precipitation	annual	4 (5 %) 15 (10 %)	positive	2.0	(1.3, 2.9)	mostly Selška Sora catchment
30-day precipitation	spring	0 (5 %) 23 (10 %)	negative	−2.5	(−3.2, −1.8)	Selška and Poljanska Sora catchment
60-day precipitation	annual	1 (5 %) 9 (10 %)	positive	2.2	(1.7, 3.2)	mostly Selška Sora catchment
90-day precipitation	spring	16 (5 %) 29 (10 %)	negative	−3.0	(−3.9, −1.7)	Selška and Poljanska Sora catchment
90-day precipitation	summer	0 (5 %) 18 (10 %)	negative	−2.1	(−2.9, −1.6)	Selška Sora catchment, some stations in Poljanska Sora catchment

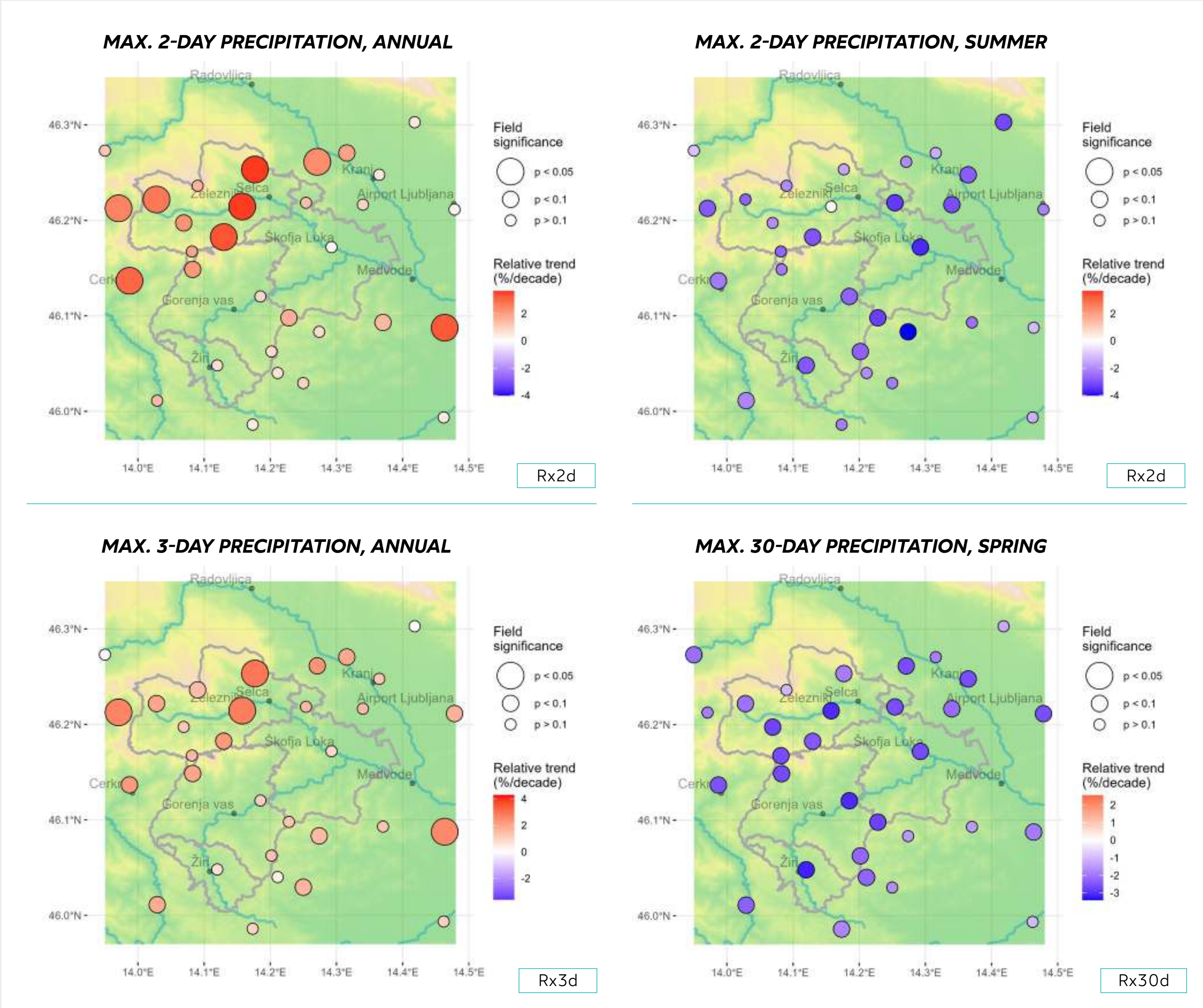


FIGURE 16: *Relative trend in maximum 2-day precipitation on an annual level (top left) and for summer (top right), in maximum 3-day precipitation on annual level (bottom left) and in maximum 30-day precipitation for spring (bottom right) in the period 1950-August 2023, including field significance to account for spatial dependence between different stations in the case study area.*

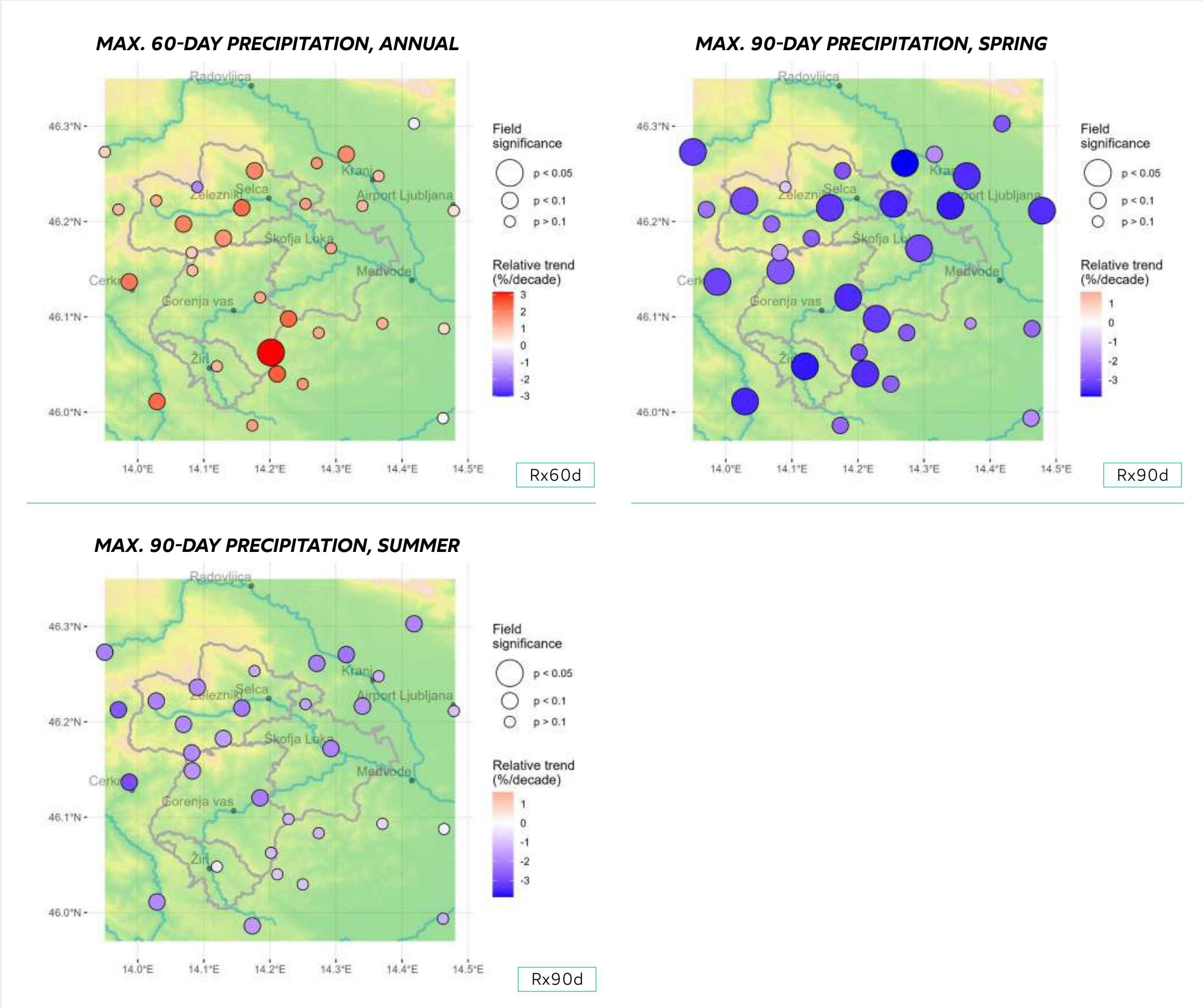


FIGURE 17: *Relative trend in maximum 60-day precipitation on an annual level (top left) and in maximum 90-day precipitation for spring (top right) and summer (bottom left) in the period 1950-August 2023, including field significance to account for spatial dependence between different stations in the case study area.*

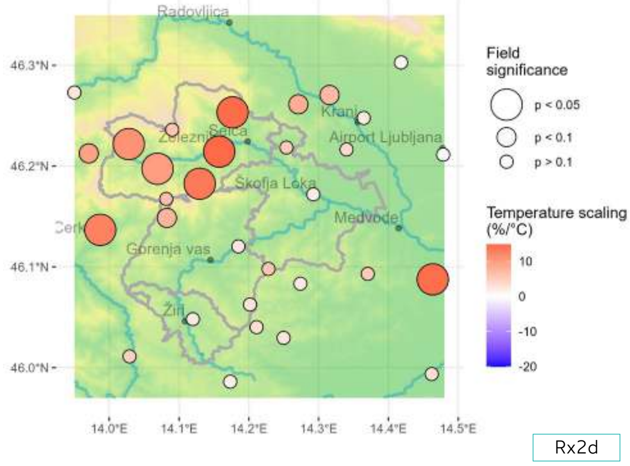
In addition to the temporal trends, the trends in precipitation extremes of different lengths were also analysed depending on the temperature over a larger area, from which weather changes come over the Sora catchment. The following statistically significant trends for temperature scaling are observed (***TABLE 9***, ***FIGURE 18***):

- For **2-day extreme precipitation**, positive trends on an annual level for the Selška Sora catchment and negative trends for summer mostly for the Poljanska Sora catchment. Mean temperature scaling on an annual level is 11.3 %/°C and thus higher than the Clausius-Clapeyron scaling (CC-scaling is approx. 7 %/°C).
- For **3-day extreme precipitation**, negative trends for summer mostly for the Poljanska Sora catchment with a mean scaling value −15.5 %/°C.
- For **60-day extreme precipitation**, positive trends on an annual level for the Selška Sora catchment and some stations in the Poljanska Sora catchment with a mean scaling value 8.8 %/°C.
- For **90-day extreme precipitation**, positive trends for summer for the Selška Sora catchment and some stations in the Poljanska Sora catchment with a mean scaling value −9.7 %/°C.

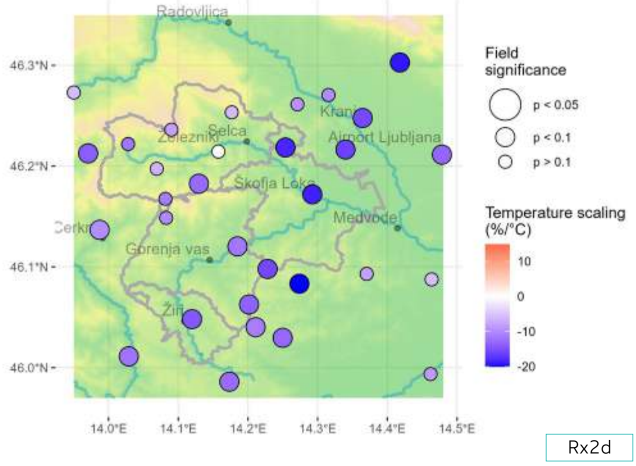
TABLE 9: *Temperature scaling: number of weather stations with significant scaling, the direction of scaling, mean scaling (for significant scaling at the 10 % level only), range of scaling (for significant scaling at the 10 % level only) and area with significant trend for five selected combinations of precipitation sums and seasons with statistically significant trends. There are 31 weather stations analysed. Trends for other precipitation sums and seasons are mostly not statistically significant.*

Variable	**Season**	**Number of stations** [significance level in %]	**Direction**	**Mean trend** [%/°C]	**Range of trend** [%/°C]	**Area**
2-day precipitation	annual	7 (5 %) 11 (10 %)	positive	11.3	(7.2, 14.9)	Selška Sora catchment
2-day precipitation	summer	0 (5 %) 18 (10 %)	negative	−14.6	(−20.0, −9.8)	mostly Poljanska Sora catchment
3-day precipitation	summer	0 (5 %) 13 (10 %)	negative	−15.5	(−19.5, −12.0)	mostly Poljanska Sora catchment
60-day precipitation	annual	1 (5 %) 13 (10 %)	positive	8.8	(7.1, 11.8)	Selška Sora catchment, some stations in Poljanska Sora catchment
90-day precipitation	summer	14 (5 %) 21 (10 %)	negative	−9.7	(−13.9, −7.0)	Selška Sora catchment, some stations in Poljanska Sora catchment

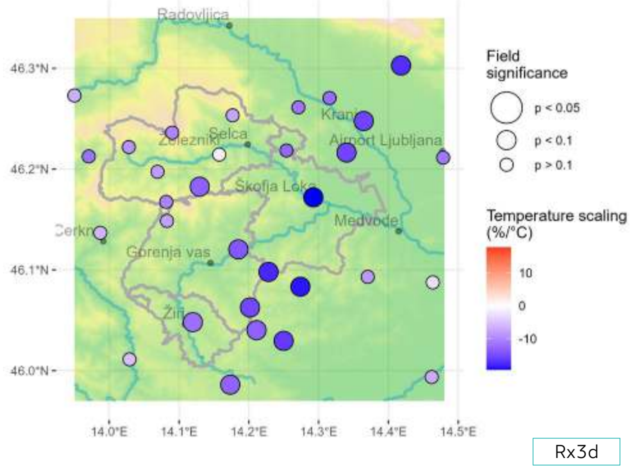
MAX. 2-DAY PRECIPITATION, ANNUAL



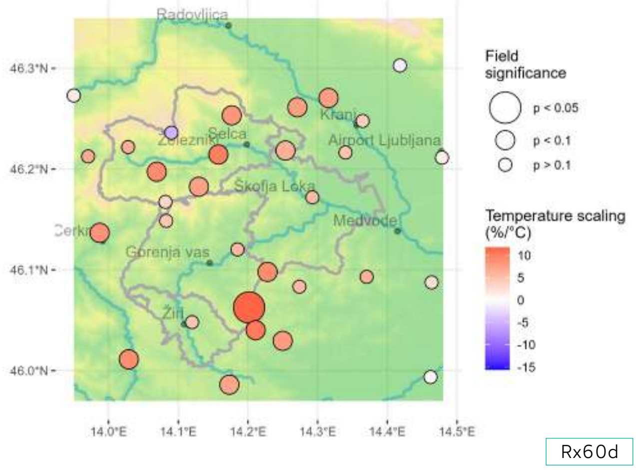
MAX. 2-DAY PRECIPITATION, SUMMER



MAX. 3-DAY PRECIPITATION, SUMMER



MAX. 60-DAY PRECIPITATION, ANNUAL



MAX. 90-DAY PRECIPITATION, SUMMER

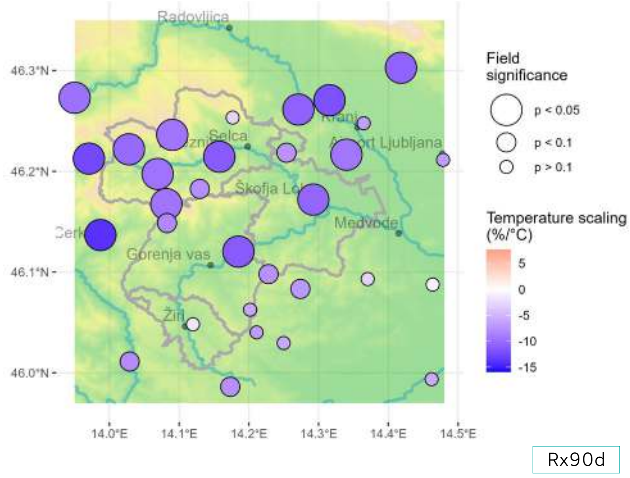


FIGURE 18: *Temperature scaling in maximum 2-day precipitation on an annual level (top left) and for summer (top right), in maximum 3-day precipitation for summer (middle left), in maximum 60-day precipitation on an annual level (middle right) and in maximum 90-day precipitation for summer (bottom left) in the period 1950-August 2023, including field significance to account for spatial dependence between different stations in the case study area.*

PRECIPITATION THRESHOLDS FOR FLOODS IN SORA RIVER CATCHMENT IN THE PERIOD 1961–2023

The measured peak discharges of overflowing and flooding events were related to the measured daily precipitation in the Sora catchment from October 1961–August 2023. 93 overflowing and flooding events were considered with discharge exceeding 1st flood warning level, and 33 flooding events with discharge exceeding 2nd flood warning level (of which 8 were considered 3rd warning level flood). The 2nd and 3rd warning level floods were analyzed jointly as these events are both considered extreme and the decision whether to issue a 2nd or 3rd level warning follows a predetermined protocol in hydrological service of Slovenian Environment Agency (ARSO). The river discharge data from three hydrological gauging stations with long continuous records were analysed: Vešter on Selška Sora, Zminec on Poljanska Sora and Suha on Sora, as well as daily precipitation data from 19 meteorological stations.

While precipitation is the most important meteorological driver for flooding events, the occurrence of overflowing or flooding depends also on other factors, such as the maximum precipitation intensity, the actual soil moisture (represented by the 14-day precipitation), season, soil infiltration capacity, and the topography. In particular, the maximum precipitation intensity is extremely important for flash floods, because the occurrence of a flash flood mainly depends on a high intensity precipitation in a short time (in hours). Thus, the precipitation thresholds in the Sora river catchment provided with this analysis are rough estimates. Furthermore, the conditions on the Selška Sora have changed significantly since 2022, due to the river management and flood protection infrastructure, so the precipitation thresholds have probably changed considerably.

The determined precipitation threshold values represent the peak total precipitation amounts measured at any meteorological station in the catchment. The distribution of peak 2-day and 14-day precipitations for all overflowing or flooding events is shown in ***FIGURE 19***. The results show that 2-day precipitation, preceding the overflowing on Selška Sora and Sora, is higher than the precipitation in the Poljanska Sora catchment. The 2-day precipitation thresholds for overflowing and flooding events were 80 mm for all events on Selška Sora, 90 mm on Sora, and 60 mm for 99 % of events (of 77) on Poljanska Sora (***TABLE 10***).

The 2-day precipitation threshold for the flood events (2nd and 3rd warning level) was 80 mm, when considering the entire catchment area, while for the sub-catchments the 2-day precipitation thresholds were: 110 mm on Selška Sora, 80 mm on Poljanska Sora and 170 mm on Sora (where 4 of the 5 flooding events exceeded 3rd flood warning level). In addition, the total 14-day precipitation in flooding events was at least 110 mm in Poljanska Sora catchment, 200 mm in Selška Sora catchment and 210 mm in Sora (at Suha gauging station) catchment area.

TABLE 10: *2- and 14-day precipitation thresholds based on the minimum total precipitation at which the overflowing and flood events were recorded in the period 1961–2023. Overflowing and flooding events are all events that exceeded the 1st warning level, and flooding events all events that exceeded the 2nd warning level.*

	Overflowing and flooding events		**Flooding events**	
	2-day precipitation threshold [mm]	**14-day precipitation threshold** [mm]	**2-day precipitation threshold** [mm]	**14-day precipitation threshold** [mm]
Selška Sora	80	150	110	200
Poljanska Sora	60	110	80	110
Sora	90	120	170	210

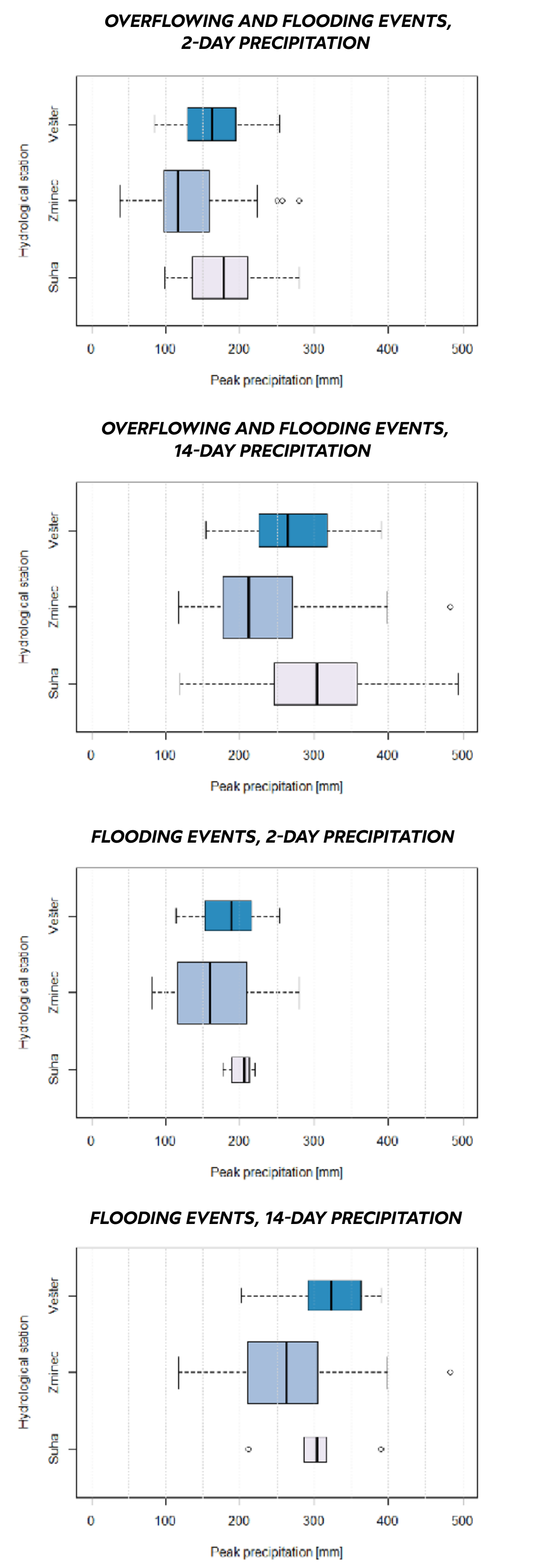


FIGURE 19: *The total 2- and 14-day precipitation [mm] for overflowing and flooding events at the hydrological stations Suha, Zminec and Vešter. The width of the boxes is proportional to the square-roots of the number of observations in the groups.*

PRECIPITATION THRESHOLDS FOR LANDSLIDES

In the study by Jemec Auflič et al. (2016), the maximum 24-hour precipitation threshold, above which a landslide always occurs, was determined at 70–300 mm for the Sora catchment, based on the frequency of landslide occurrence per spatial unit correlated with a lithological unit of Slovenia and 24-hour maximum rainfall data, within the system for landslide prediction in time (Masprem). In this report, daily precipitation was related with the landslides data available in the Sora catchment, but due to limited and discontinuous records, the results for the precipitation threshold were inconclusive.

WHAT TO EXPECT IN THE FUTURE?

Projections show the greatest increase in annual precipitation in the case of GWL 3 °C. In this case, the agreement of the models is the highest and the model ensemble median indicates more than 5 % increase in annual precipitation. Precipitation increases in winter (up to 20 %) and spring (up to 10 %) contribute the most to the annual increase, while in summer, the model ensemble median is always very close to the mean precipitation amount in the reference period (model spread is also the largest in summer).

In case of extreme 1- to 3-day precipitation, averaged over the case study area, the greatest changes (more than 20 %) in extremes are expected in spring, while changes up to 15 % are expected in other seasons. Changes in maximum 1-day precipitation amount are most unreliable in summer, while for the other seasons an increase under GWL 3 °C and 4 °C can be observed, from 5 to 20 %, or even more for spring in some areas (***FIGURE 20***). The frequency of 1-day extreme precipitation (days above the 97th percentile) will increase in all seasons, the most in spring and winter and the least in summer.

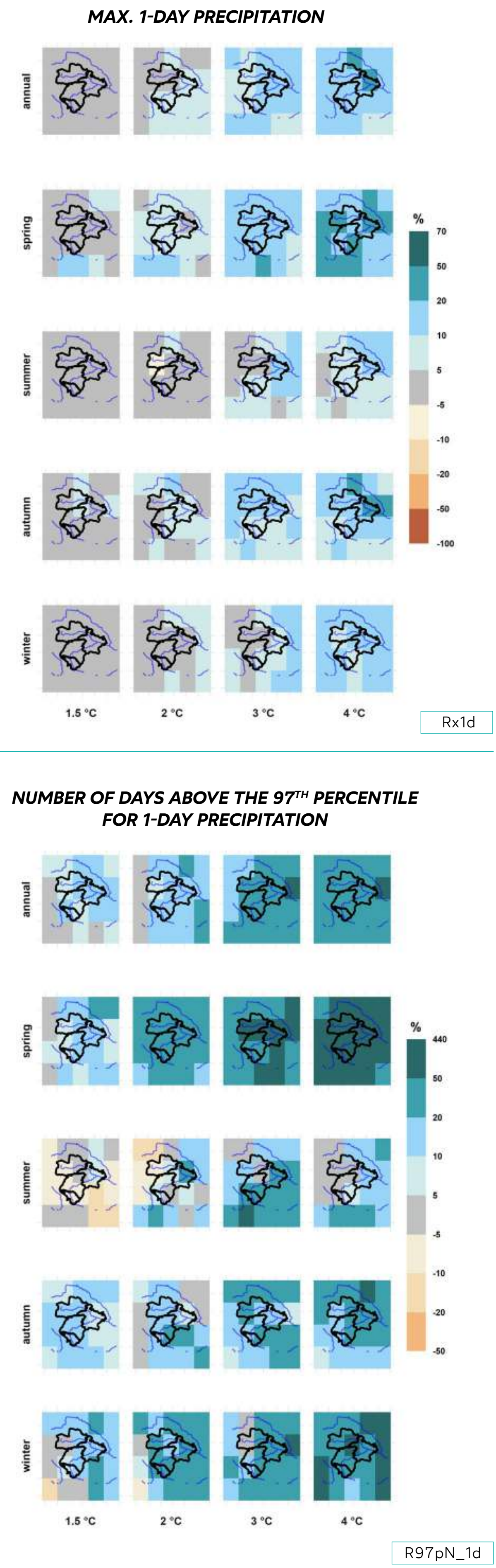


FIGURE 20: *Relative change in the intensity (top) and frequency (bottom) of 1-day extreme precipitation events for four global warming levels relative to 1991–2020, represented by the median of the model simulation ensemble.*

The maximum 3-day precipitation is also expected to increase the most in spring under GWL 3 °C and 4 °C. In the other seasons, the increase is mostly limited to 15 %. The frequency of 3-day extreme precipitation will generally increase by more than 20 % (even more than 50 % in spring and winter for GWL 3 °C and 4 °C) but the increase shows spatial variation between seasons (***FIGURE 21***).

Similar findings apply to the change in 7- to 90-day precipitation maxima. Spring and winter show the greatest increase, while in other seasons the changes mostly remain below 10 % (for GWL 3 °C and GWL 4 °C). The same applies to the frequency of extreme events as the greatest positive changes are expected in spring and winter and generally increase with increasing accumulation period.

The probability of the occurrence of extreme 1-day precipitation is expected to increase slightly in the future. Maximum 1-day precipitation in autumn that is as extreme as the 1-in-50-year event in 1991–2020 is projected to become up to 2.4 times as likely under GWL 3 and 4 °C. In other words, a 50-year event in the reference period might become a 21-year event in a 3 °C to 4 °C warmer climate. The likelihood of a maximum 3-day summer precipitation as extreme as the 1-in-50-year event in 1991–2020 will stay the same in the future.

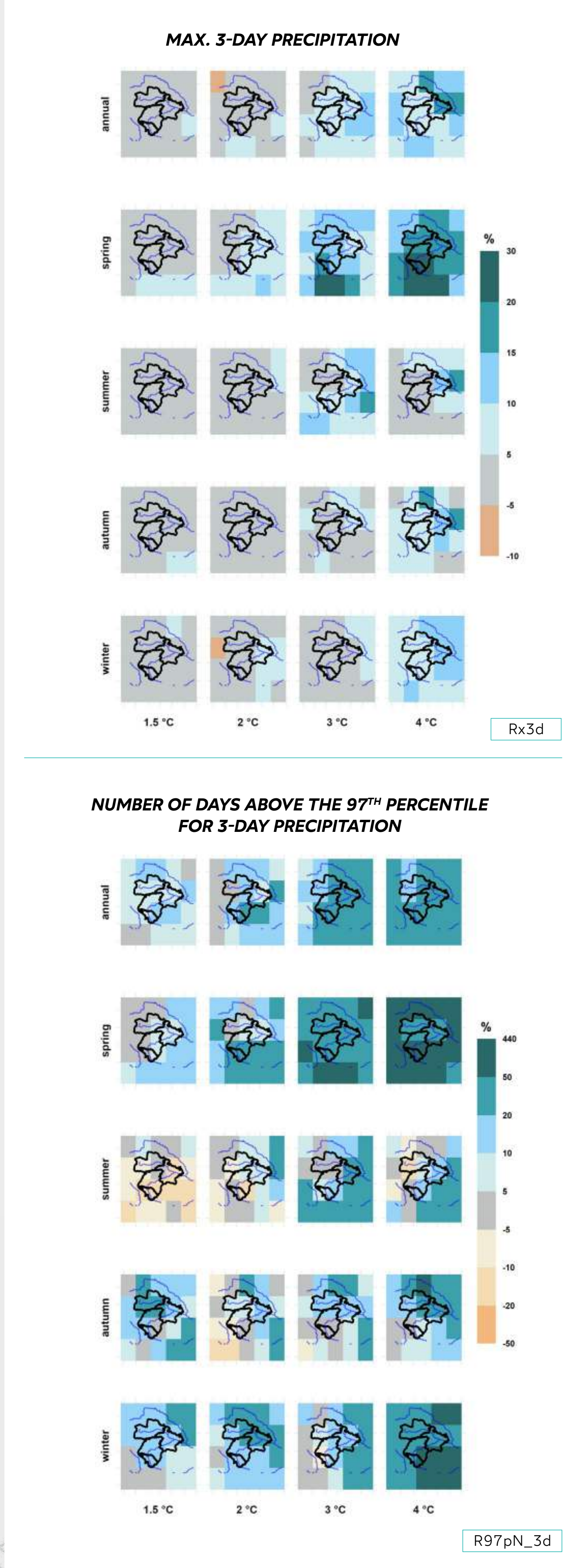


FIGURE 21. *Relative change in intensity (top) and frequency (bottom) of 3-day extreme precipitation events for four global warming levels relative to 1991–2020, shown by the median of the model simulation ensemble.*

METHODOLOGY

ASSESSMENT OF TRENDS AND PROBABILITY OF OCCURRENCE

Trends, except trends in extreme values, were assessed with Theil-Sen estimator. The frequency of extreme values was estimated with classical extreme value theory (fitting corresponding data to the generalised extreme value distribution), and trends in extreme values with non-stationary extreme value theory. The collective significance of the trends on a given pilot area (field significance) was evaluated from individual significance tests, controlling the false discovery rate. The methodology of each method is briefly described below.

Trend assessment with Theil-Sen estimator

Trends for values not connected to extreme values were estimated with Theil-Sen estimator or Sen's slope estimator. This is a robust method of linear regression that is not influenced by outliers. It is nonparametric method and does not assume any specific distribution for the data. On the other hand, it is hardly less reliable in the cases where all conditions for the least square method are met. Calculation of trends is quite simple: it is the median of all possible slopes formed by pairs of points for a given collection of data points. Each pair contributes to the slope calculation, regardless of whether the points lie on a straight line or not. At the same time an accurate confidence interval for the trend can be estimated even when there are nonnormality and heteroscedasticity (Wilcks, 2016).

Statistical significance of the time series was assessed with Mann-Kendall trend test. It is a nonparametric test, without assuming normality, but the data should have no serial correlation. The null hypothesis was rejected when the p-value associated with Mann-Kendall statistics was lower than 0.05 or 0.10 respectively. Non-serial correlation, if existed, was achieved by Zhang's method of pre-whitening (Wang and Swail, 2001).

Generalized extreme value distribution (GEV) and estimation of return periods of extreme events

The probability of extreme events was calculated with classical extreme value theory. The classical extreme value theory focuses on the statistical behaviour of extreme values of block maxima, usually corresponding to the annual or seasonal maxima. If the process is stationary, then under quite common conditions, for some large value of blocks (which in our case corresponds to the number of years) block maxima have a limiting distribution, called *generalised extreme value distribution* (GEV distribution) (Coles, 2001). The GEV distribution is a family of continuous probability distributions with three parameters: location (μ), scale (σ) and shape parameter (ξ).

Block maxima are fit to GEV distribution with maximum likelihood estimation, which also makes possible the estimation of confidence intervals for parameters and return levels.

Estimates of extreme quantiles of the annual maximum distribution were obtained from the GEV distribution and expressed in the form of return levels z_p. The return level z_p is associated with the return period $1/p$, where p is the probability of occurrence for the value z_p or more. More precisely, z_p is exceeded by the annual maximum in any particular year with probability p (Coles, 2001).

If a large number of years considered had study quantity equal to zero, the probability for the selected event was adjusted. This adjustment was made by dividing the probability by the ratio of years with non-zero data and total number of years for which data were available.

Trend assessment for extreme values

The GEV distribution is valid for block extremes for stationary sequence. It can be generalised to non-stationary processes, e.g. for those with trends, possibly due to long-term climate changes. This can be achieved with GEV distribution with time dependent parameters; in our case appropriate model was linear in location parameter only:

$$\mu(t) = \mu_0 + \mu_1 t$$

The parameter μ_1 corresponds to the annual rate of change in annual maximum value of the variable it concerns. For linear model that means that the levels with all return periods change for the same amount in time. More complex models were also examined but they were mostly statistically insignificant. Statistical significance of the models is checked with the *likelihood ratio test* (Coles, 2001).

Temperature scaling

In addition to using time as covariate in trend assessment of extreme values, smoothed temperature anomaly for Europe relative to the period 1991–2020 (temperature climate signal) was used as covariate for trend assessment of extremes. Trend was calculated with nonstationary GEV distribution with location parameter linear in temperature anomaly:

$$\hat{\mu} = \hat{\mu}_1 \Delta T + \hat{\mu}_0$$

where ΔT is the temperature anomaly. Temperature scaling (%/°C) was calculated as ratio μ_1/μ_0 (Zeder & Fischer, 2020).

Field significance

The collective significance of the trends (field significance) was evaluated from individual significance tests. The straightforward approach, *controlling the false discovery rate* (FDR), was chosen to protect against overstatement or overinterpretation of multiple-testing results (Wilks, 2016). The idea of the method is to construct the meta-test which uses the results of many individual tests to address the global null hypothesis that all individual local (i.e., in grid points or in measurement points) null hypothesis are true. If the global null hypothesis cannot be rejected, it cannot be concluded with confidence that any of the individual local tests show meaningful violation of their respective null hypotheses. The failure to achieve field significance protects us to a degree from being misled into believing results from many erroneous rejections of true local null hypothesis that will invariably occur. We have chosen $\alpha_{FDR} = 2\alpha_{global}$ which produces approximately correct global test levels for data grids exhibiting moderate to strong spatial correlations (Wilks, 2016).

ANALYSIS OF PROJECTED CHANGES UNDER DIFFERENT GLOBAL WARMING LEVELS

The projected changes in the pilot area were assessed for different levels of global warming by considering the available EURO-CORDEX projections listed under Data. The global warming levels (GWLs) considered were + 1.5, + 2, + 3 and + 4 °C with respect to the pre-industrial baseline period 1850-1900, following the approach included in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021). For each GWL, the corresponding 20-year period when global mean temperature reaches that level of increase with respect to the baseline period was identified for each model and RCP (Representative Concentration Pathway) simulation (https://github.com/mathause/cmip_warming_levels). Since some models and RCP scenarios do not include all GWLs, only simulations covering all considered GWLs were considered, namely RCP 8.5 simulations.

It is important to note, that GWLs cannot be translated into a specific temporal interval since it varies among the models. However, for assigning a temporal horizon to projected results, the highest GWL 3 °C and GWL 4 °C are reached by models in the second half of the 21st century under high emission scenarios.

For the assessment of future changes and return periods, the 20-year interval associated with each GWL was considered and extended over a 30-year period by adding 5 years before and after the GWL interval. Projected changes were evaluated for selected model simulations relative to the 1991–2020 baseline and reported as model ensemble median and range.

ANALYSIS OF SYNOPTIC CONDITIONS FOR PILOT EVENTS

Mean sea level pressure (MSLP) data from -80° West to 40° East and 30° to 70° North for the last 70 years from the ERA5 reanalysis was used to calculate 'Gross-Wetter-Typen' (GWT), which is a circulation type classification and is based on correlations between mean sea level pressure fields that are grouped into 18 clusters. The COST733 (Philip et al., 2014) software was used for that. Specific pilot events were then characterised by the mean GWT pattern derived over 7 decades of ERA5 data and by analysing the specific daily MSLP pattern at event occurrence. Furthermore, for the specific season when the event has happened, trends in GWT occurrences over the 70-year period were evaluated with a 99 % confidence interval.

REFERENCES

Bertalanič et al., 2018. Ocena podnebnih sprememb v Sloveniji do konca 21. stoletja: sintezno poročilo. Ministrstvo za okolje in prostor, Agencija Republike Slovenije za okolje, Ljubljana.

Coles, S., 2001. An Introduction to Statistical Modeling of Extreme Values. Springer, London, 209 pp.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi: 10.1017/9781009157896

Jemec Auflič, M., Šinigoj, J., Krivic, M., Podboj, M., Peternel, T. and Komac, M., 2016. Landslide prediction system for rainfall induced landslides in Slovenia (Masprem). *Geologija*, 59(2), 259-271.

Philipp, A., Beck, C., Esteban, P., Kreienkamp, F., Krennert, T., Lykoudis, S.P., Pianko-Kluczynska, K., Post, P., Rasilla-Alvarez, D., Spekat, A., Streicher, F., 2014. *COST733CLASS v1.2 User guide.*

Rusjan, S., Kobold, M., and Mikoš, M., 2009. Characteristics of the extreme rainfall event and consequent flash floods in W Slovenia in September 2007. *Nat. Hazards Earth Syst. Sci.*, 9, 947–956, doi: 10.5194/nhess-9-947-2009

Scherrer, S. C., Fischer, E. M., Posselt, R., Liniger, M. A., Croci-Maspoli, M., Knutti, R., 2016. Emerging trends in heavy precipitation and hot temperature extremes in Switzerland. *J. Geophys. Res. Atmos.*, 121, 2626-2637, doi: 10.1002/2015JD024634

Slovenian Environment Agency, 2010. The 2007 Hydrological Yearbook of Slovenia. Ministry of the Environment and Spatial Planning, Slovenian Environment Agency, Ljubljana.

Wang, X. L., and Swail, V. R., 2001. Changes of Extreme Wave Heights in Northern Hemisphere Oceans and Related Atmospheric Circulation Regimes. *J. Climate,* 14, 2204-2221, doi: 10.1175/1520-0442(2001)014<2204:COEWHI>2.0.CO;2

Wilcox, R. R., 2001. Fundamentals of Modern Statistical Methods. Springer, New York, 258 pp.

Wilks, D. S., 2016. The Stippling Shows Statistically Significant Grid Points: How Research Results are Routinely Overstated and Overinterpreted, and What to Do about It. *Bull. Amer. Meteor. Soc.*, 97, 2263–2273, doi: 10.1175/BAMS-D-15-00267.1