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Changes in annual maximum discharge occurrence in Slovenia during the period 1961–2023

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Abstract: The study compares changes in annual maximum (AM) discharge occurrence at 33 gauging stations in Slovenia for the period 1961-2023. The entire period was divided into two sub-periods, namely the period 1961-1990 and the period 1991-2023. The frequency of AM occurrence per day of the year was calculated for all stations under consideration, and the kernel density estimate was calculated for the two periods. The findings reveal that, except for one gauging station, the AM discharge has occurred later during the recent three decades (1991-2023) than during the first 30-year period (1961-1990). The shift ranged from one to 35 days. This shift could be mainly attributed to higher air temperatures in the spring and summer months, which intensify precipitation events. At four stations, the day of maximum density shifted from spring to autumn and, at one station, from autumn to spring. All of these stations are located in the eastern part of the country. In contrast, gauging stations in Alpine regions of the western part of the country show smaller shifts, attributed to reduced snow accumulation and earlier snowmelt.

Keywords: Timing of annual maximum (AM) discharge; Seasonality; Seasonal change; Slovenia.

1 INTRODUCTION

It is anticipated that a warming climate will exert an influence on the magnitude and timing of river floods (Mitková et al., 2024; Scussolini et al., 2024; Zhanibek et al., 2025). Blöschl et al. (2019, 2017) have already shown this for Europe. They used a pan-European database from more than 4,200 gauging stations for the period 1960-2010. Their findings reveal the presence of a clear climate signal in flood observations in Europe. They identified different regional patterns of both increasing and decreasing trends in flood discharges in Europe (Blöschl et al., 2019) and also different regional patterns related to the changes in timing of European floods (Blöschl et al., 2017).

Slovenia's geographical location gives the country a diverse climate that includes temperate continental, Mediterranean, and alpine climates (Dolšak et al., 2016; Ogrin et al., 2023). The sub-Mediterranean climate is present in the coastal southwestern part of the country, but its influence extends inland. The temperate continental climate dominates the north-eastern and eastern regions. Mountain climate is particularly pronounced in the Alps and the Karawanks mountains, and its effect is also felt in the High Dinaric plateaus (Ogrin et al., 2023). Annual precipitation varies significantly across the country, ranging from less than 900 mm in the east to over 3,000 mm in the west. Also, the rainfall erosivity follows this pattern and some of the highest European values can be found in Slovenia reaching up to 10,000 MJ*mm*ha^{-1}*h^{-1}*year^{-1} (Panagos et al., 2023). The areas with a sub-Mediterranean climate receive the most precipitation in autumn, while the areas with a temperate continental climate receive the most precipitation in the summer months (Dolšak et al., 2016).

Climate is the most important factor in defining discharge regimes in Slovenia, as they depend primarily on the annual distribution of precipitation and temperature as well as the duration and extent of snow cover (Frantar et al., 2008; Frantar and Hrvatin, 2008; Hrvatin and Zorn, 2022). Five different discharge regimes were identified in Slovenia, namely Alpine nival-pluvial, Alpine pluvial-nival, Dinaric pluvial-nival, Pannonian pluvial-nival and Mediterranean pluvial regime (Frantar and Hrvatin, 2008). A comparison of the discharge regimes in the period 1971-2000 with the regimes in the period 1961-1990 revealed significant differences (Frantar and Hrvatin, 2008). Because of decreased effect of snow melting and increased effect of summer evaporation, the differences in discharge regimes are gradually diminishing (Frantar and Hrvatin, 2008).

A combination of precipitation distribution, which varies both geographically and temporally (Rajah et al., 2014), and more intense precipitation, has led to an escalation in the frequency of extreme flood events in Slovenia (Bezak et al., 2023; Oblak et al., 2021; Šraj and Bezak, 2025, 2020). Analyses show that extreme flood events have occurred more frequently since 1990 than before (Kobold et al., 2012). Concurrently, there has been an observed increase in the severity of drought conditions in Slovenia (Cunja et al., 2019; Domadenik et al., 2023; Petan and Koprivšek, 2024; Zalokar et al., 2021). Likewise, the findings of Petan and Koprivšek (2024), who analysed river flows in Slovenia, indicate clear changes in the inter-annual distribution of river flows and an increase in unusual river flow conditions, especially drought conditions. Paleo hydrological evaluation of the Sava River catchment in Slovenia also revealed temporal changes in occurrence of droughts both based on precipitation and discharge data, which indicates a general positive trend in drought frequency in the last decades (Ramírez Molina et al., 2023; Tootle et al., 2023). In general, however, past analyses have shown a decrease in discharges during the spring and summer months and an increase during the autumn months (Oblak et al., 2021). Additionally, no clear geographical pattern has been identified, and the trends do not appear to be significantly influenced by the geographical characteristics of the gauging stations (Oblak et al., 2021; Šraj et al., 2016; Šraj and Bezak, 2020). These findings align with broader European research, which similarly indicates an absence of a uniform pattern in the increase or decrease of flood discharge series (Blöschl et al., 2019; Mudelsee et al., 2003). As the climate changes, so does the timing of floods, as shown for Europe by Blöschl et al. (2017). Also, this change has no uniform pattern as high waters occur earlier at some gauging stations and later at the others (Blöschl et al., 2017; Mediero et al., 2015).

Given that no detailed analysis of the occurrence of annual maximum (AM) in Slovenia has been conducted in recent decade the need for a detailed analysis has arisen, especially after an extreme flood event in August 2023 (Bezak et al., 2023; Šraj and Bezak, 2025). Therefore, the main aim of the study was to investigate the changes in the timing of AM occurrence in Slovenia during the period 1961-2023.

2 DATA AND METHODS

In order to investigate the main objective of the present study more than 30 discharge gauging stations in Slovenia were selected for which information on the annual maximum (AM) discharge and corresponding time of occurrence were available for the period 1961–2023 (ARSO, 2025). A total of 33 gauging stations met the selection criteria (Fig. 1). Table 1 provides an overview of the main characteristics of the selected gauging stations (see Attachment). The AM events were defined as the maximum discharge values in a given calendar year. Discharge is calculated based on continuous water level measurements and the rating curve application to convert water level into discharge. It should be noted that the type of water level measurement has changed in recent decades. Since 2010, high-frequency (1–5 minutes) radar or pressure probe measurements have been used, whereas limnigraph measurements were mostly used from roughly 1960 (1950–1970) to 2010 (2000). Before 1960, daily observations were mostly used; however, this data is not included in the study. An example of AM data for one of the stations is shown in Fig. 2.

In order to investigate the changes in the timing of AM discharges, the entire period of available data was divided into two periods, namely the older period from 1961–1990 and the more recent period from 1991–2023. This division was motivated by the findings of previous studies, which has already demonstrated changes in the frequency of floods after 1990 in Slovenia (Kobold et al., 2012). Furthermore, the total number of drought seasons in Slovenia has more than doubled since 1992, as has their duration (Petan and Koprivšek, 2024). The World Meteorological Organization (WMO) also recommends using the period from 1961 to 1990 to understand the impact of climate change (WMO, 2021) and other potential natural and anthropogenic drivers. For all these reasons, we selected 1961 as the starting year for our study and 1990 as the limit (i.e., turning point) between the two periods to investigate changes in the timing of the AM events in Slovenia. All the analyses were performed using “ggplot2” (Wickham, 2016) and “dplyr” (Wickham et al., 2023) packages in R software tool (R Core Team., 2021).

First, the frequency of AM occurrence per day of the year was calculated for all stations under consideration. Additionally, the kernel density estimate (Sheather and Jones, 1991), which is a smoothed version of the histogram, was calculated for the two periods (1961–1990 and 1991–2023). Moreover, the maximum values identified using the kernel density estimate were verified by separating the data into 10–days periods and checking, in which period the maximum number of AM occurred.

In order to investigate possible drivers of changes, the dependence between AM changes and station characteristics (i.e., location, catchment size, elevation) was investigated. These analyses were also conducted separately for the spring and autumn AM. In addition, a comparison was made with Copernicus essential climate variables (i.e., surface air temperature, surface relative humidity, topsoil volumetric soil moisture and precipitation) (Hersbach et al., 2018). The global anomaly in these four variables was investigated, with the reference period set to 1981–2010. Hence, monthly values were extracted for the period 2011–2023 for 33 Slovenian catchments. For the selected period, the trend (slope) in these variables was compared with the identified changes in the occurrence of AM discharge in Slovenia.

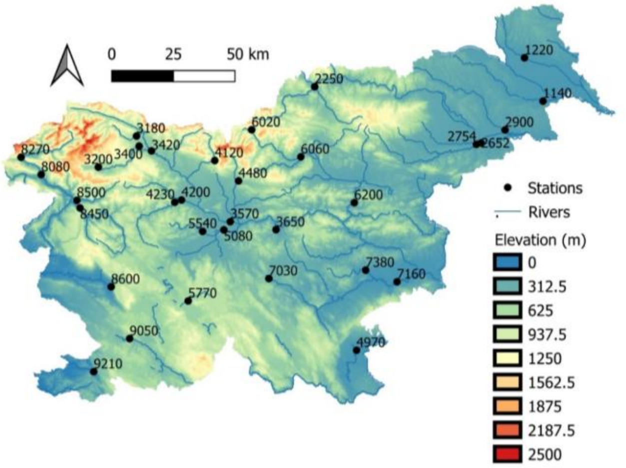

Fig. 1. Location of the considered gauging stations on the map of Slovenia. Station IDs are shown in Table 1.

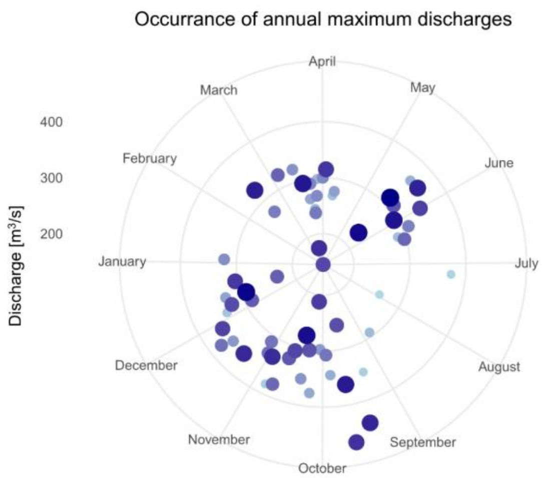

Fig. 2. An example of a graphical representation of AM discharges for the gauging station Podbočje on Krka River (ID 7160) for the period 1961–2023. The blue circles represent the annual maximum (AM) discharges [m^3/s] positioned at the time of the year when they occurred. The darker colour and larger size denote a later year of the AM occurrence.

3 RESULTS AND DISCUSSION

An analysis was performed for 33 gauging stations (Table 1) for the two periods: 1961–1990, and 1991–2023. The results of the analysis are presented in Table 2 and graphically in Figs. 3 and 4. The AM peaks were identified based on the maximum of the kernel density function and verified by distributing the data into 10–days intervals and checking the maximum event values in these intervals. A comparison of the results of both types of analysis demonstrated that the data does not allow for the precise determination of the day of AM occurrence as the 10–day intervals with the highest frequency in some cases occurred several times containing two to seven out of 30 or 33 cases (Table 2). However, combining both methods yielded comparable results and also enabled an assessment of their reliability.

Table 1. Basic characteristics of the considered discharge gauging stations and corresponding catchments in Slovenia (ARSO, 2025)

	ID	River	Gauging station	Catchment area [km^2]	Longitude	Latitude	Station elevation [m.a.s.l.]
1	1140	Ščavnica	Pristava I	272.5	16.2367	46.5189	169.77
2	1220	Ledava	Polana	208.2	16.1420	46.6783	191.40
3	2250	Meža	Otiški Vrh I	550.89	15.0308	46.5781	333.97
4	2652	Dravinja	Videm	767.34	15.9068	46.3669	209.21
5	2754	Polskava	Tržec	189.16	15.8717	46.3624	214.07
6	2900	Pesnica	Zamušani	477.8	16.0389	46.4144	201.86
7	3180	Radovna	Podhom	166.8	14.0904	46.3938	566.07
8	3200	Sava Bohinjka	Sveti Janez	94	13.8913	46.2786	524.95
9	3400	Jezernica	Mlino	8.57	14.1047	46.3575	467.52
10	3420	Sava	Radovljica	907.9	14.1701	46.3404	408.09
11	3570	Sava	Šentjakob	2285	14.5872	46.0843	268.19
12	3660	Sava	Litija	4821.4	14.8277	46.0559	230.44
13	4120	Kokra	Kokra	112.2	14.5036	46.3062	522.85
14	4200	Sora	Suha	566	14.3307	46.1624	329.47
15	4230	Poljanska Sora	Zminec	305.5	14.2954	46.1538	343.31
16	4480	Nevljica	Nevlje	82.21	14.6296	46.2332	379.94
17	4969	Lahinja	Gradac	221.3	15.2500	45.6137	129.00
18	5078	Ljubljanica	Moste	1762.5	14.5492	46.0557	280.80
19	5540	Šujica	Razori	46.95	14.4425	46.0484	298.37
20	5770	Cerkniščica	Cerknica	47.3	14.3694	45.7942	559.58
21	6020	Savinja	Solčava	63.7	14.6979	46.4200	636.01
22	6060	Savinja	Nazarje	457.3	14.9573	46.3216	336.97
23	6200	Savinja	Laško	1668.16	15.2384	46.1543	215.03
24	7029	Krka	Podbukovje	321.44	14.7897	45.8770	259.22
25	7160	Krka	Podbočje	2238.1	15.4602	45.8651	146.32
26	7380	Radulja	Škocjan	108.14	15.2967	45.9078	159.71
27	8080	Soča	Kobarid	437	13.5910	46.2477	195.86
28	8270	Učja	Žaga	50.2	13.4824	46.3101	342.50
29	8450	Idrijca	Hotešk	442.83	13.7984	46.1287	160.81
30	8500	Bača	Bača pri Modreju	142.31	13.7802	46.1559	164.43
31	8601	Vipava	Miren	589.9	13.6126	45.8944	96.38
32	9050	Reka	Cerkvenikov mlin	377.9	14.0655	45.6552	341.72
33	9210	Rižana	Kubed	204.5	13.8808	45.5329	57.68

Table 2. The Julian days with the highest probability of occurrence of AM discharges according to the kernel density estimation and the differences between the two periods (1991–2023 and 1961–1990). A negative sign indicates an earlier occurrence, while a positive sign indicates a later occurrence in the last decades (i.e., 1991–2023 compared to 1961–1990). The number of days with AM occurrence within 10-day intervals corresponding to the maximum density is given in brackets next to the Julian day.

	ID	Julian day of max density 1961–1990 (Number of days in 10–day intervals)	Julian day of max density 1991–2023 (Number of days in 10–day intervals)	Difference between the periods [days]
1	1140	86 (3)	322 (2)	+236
2	1220	271 (2)	128 (5)	–143
3	2250	295 (3)	299 (4)	+4
4	2652	298 (3)	300 (3)	+2
5	2754	310 (3)	323 (3)	+13
6	2900	93 (4)	326 (4)	+233
7	3180	299 (3)	308 (6)	+9
8	3200	299 (4)	306 (7)	+7
9	3400	293 (4)	318 (4)	+25
10	3420	305 (3)	306 (6)	+1
11	3570	295 (4)	320 (4)	+25
12	3660	295 (5)	314 (5)	+19
13	4120	302 (3)	319 (5)	+17
14	4200	298 (4)	319 (5)	+21
15	4230	285 (3)	312 (5)	+27
16	4480	293 (4)	304 (3)	+11
17	4969	309 (4)	320 (5)	+11
18	5078	305 (3)	308 (3)	+3
19	5540	280 (3)	307 (3)	+27
20	5770	267 (3)	302 (3)	+35
21	6020	282 (3)	310 (6)	+28
22	6060	291 (3)	314 (5)	+23
23	6200	297 (4)	302 (3)	+5
24	7029	289 (2)	311 (3)	+22
25	7160	92 (5)	306 (3)	+214
26	7380	110 (4)	298 (3)	+188
27	8080	286 (4)	303 (6)	+17
28	8270	288 (4)	300 (7)	+12
29	8450	303 (4)	310 (5)	+7
30	8500	300 (3)	307 (6)	+7
31	8601	312 (3)	320 (6)	+8
32	9050	314 (5)	325 (4)	+11
33	9210	320 (3)	321 (4)	+1

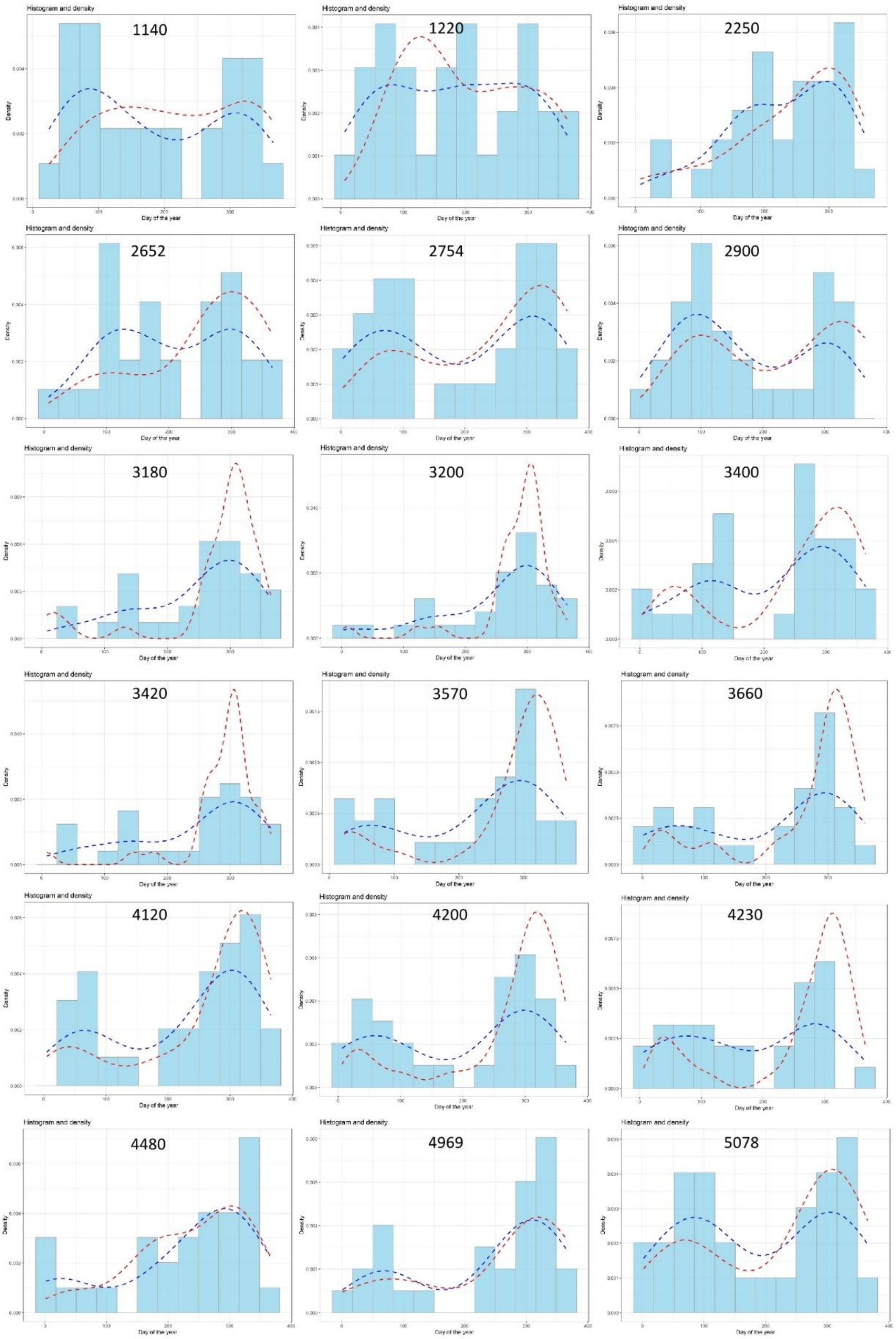

Fig. 3. The histograms and kernel density functions for the first 18 of the 33 gauging stations. The histograms are presented in light blue for the first period (1961–1990) with the corresponding density shown in a blue dashed line. The density for the second period (1991–2023) is shown in a red dashed line. The x-axis of each graph shows the day of the year, and the y-axis shows the density. Station IDs are shown in Table 1.

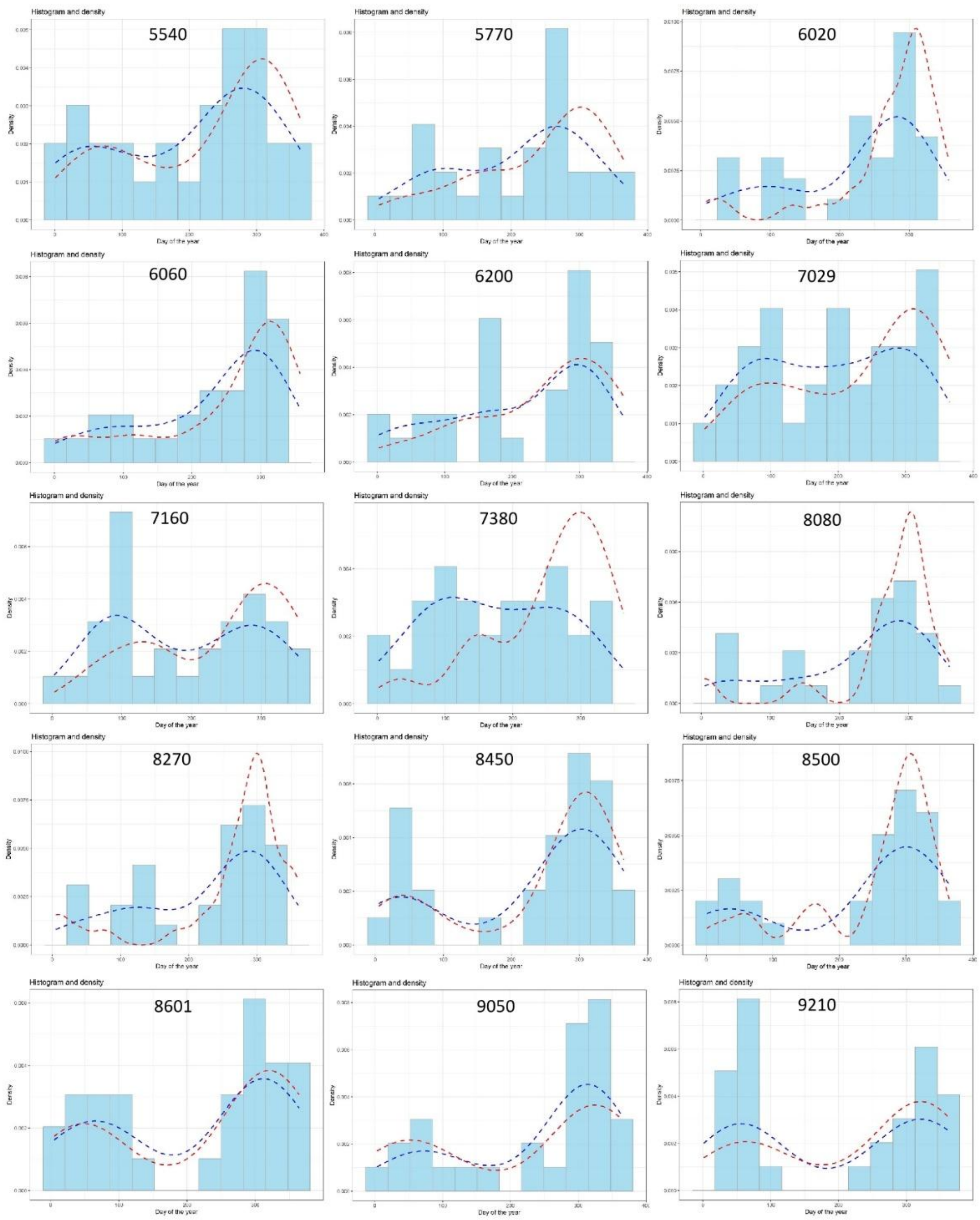

Fig. 4. The histograms and kernel density functions for the other 15 of the 33 gauging stations. The histograms are presented in light blue for the first period (1961–1990) with the corresponding density shown in a blue dashed line. The density for the second period (1991–2023) is shown in a red dashed line. The x-axis of each graph shows the day of the year and the y-axis shows the density. Station IDs are shown in Table 1

The findings indicate that, except for one gauging station (1220), the AM discharge has occurred later during the recent three decades (1991–2023) than during the initial 30-year period (1961–1990) (Table 2 and Fig. 5). The results show that, at four stations (1140, 2900, 7160, 7380), the day of maximum density shifted from spring to autumn and, at one station (1220), from autumn to spring. At these stations, the shift was more than 140 days (Table 2). It should be noted that at the gauging stations mentioned, there were two fairly equivalent maxima in the first 30-year period (1961–1990), i.e., the second maximum density was very close to the first indicating similar frequency of AM events in spring and autumn. This is the reason for the large shift. All of the stations mentioned are located in the eastern part of the country (Fig. 5). At all other stations (28 out of 33) the shift ranged from one to 35 days (Table 2). This shift could be mainly linked to higher air temperatures in the spring and summer months of a temperate continental climate, which can lead to more extreme precipitation events during the April-June period (de Luis et al., 2014), due to the enhanced water-holding capacity of a warmer atmosphere (Blöschl et al., 2019). Although it is difficult to attribute the time shift to the location of the gauging station, it is noteworthy that smaller shifts predominantly occur within the western half of Slovenia and mostly at gauging stations with headwaters in the Alpine part of the country, characterized by the Alpine nival-pluvial regime. This phenomenon can be attributed to decreased winter snow depth and extent, which has been a consistent trend in Slovenia in recent years due to higher air temperatures (ARSO, 2021). Therefore, winter precipitation is more likely to results in direct runoff and precipitation is not accumulated within the catchment as snow. Hence, less runoff events are attributed to the snowmelt, especially in catchments at moderate altitudes, since the decrease in the number of days with snow cover is more pronounced at lower elevations (Mikoš et al., 2022; Parajka et al., 2019).

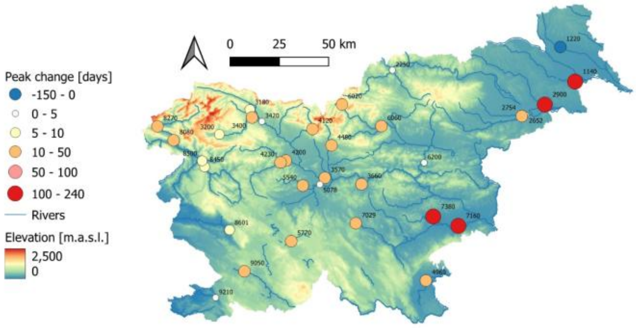

Fig. 5. The differences (in days) in the timing of AM discharge occurrence between the two periods (1991–2023 and 1961–1990). Blue colour indicates an earlier and red colour a later occurrence of the AM. Station IDs are shown in Table 1.

It has also been observed that the majority of gauging stations have not demonstrated a clear spring peak, or that the spring peak is much smaller compared to the autumn peak (Figs. 3 and 4). Hence, these gauging stations are characterized by a dominant pluvial water regime without significant impact of snowmelt or the impact of snowmelt is less significant in comparison to that of the autumn precipitation. Furthermore, the spring peak disappeared at five gauging stations (2652, 4480, 5770, 6020, 7380) and appeared at one station (1220) in the second period, indicating a shift in the occurrence of the AM events. The same finding was reported by Zhanibek et al. (2025), who analysed changes in river flow in the Zhaiyk–Caspian water basin in Kazakhstan. These findings are consistent with the results of Oblak et al. (2021), who reported a decrease in discharges during the spring and summer months and an increase during the autumn months in Slovenia. Additional analyses of the relationship between shifts in the occurrence of spring AM in Slovenia and possible influential variables are presented in Fig. 6. The results show that gauging stations located in the eastern part of the country are generally associated with positive changes in spring AM, while those in the western part are associated with negative changes. Furthermore, gauging stations at higher elevations show a negative change in spring AM discharge occurrence, linked to changes related to snow cover characteristics (Mikoš et al., 2022) (Fig. 6). Additionally, it can also be seen that the detected change may be related to the anomalies in surface air temperature (e.g., Copernicus, 2025) (Fig. 6).

Furthermore, the results show that autumn AM discharge occur later over the last three decades (1991–2023) compared to the first 30-year period (1961–1990) at all considered gauging stations except at the station 1220 (Table 2). The aforementioned assertion is also supported by the results in Figs. 3 and 4. Practically all stations, with the exception of the stations 1220 and 9050, show an increase in the probability of the occurrence of AM during the autumn period of the last 33 years compared to the initial 30 years. Furthermore, at certain gauging stations, the probability of an autumn AM has increased significantly when comparing the two analysed periods (Figs. 3 and 4). Consequently, it is not unexpected to observe that at some of these gauging stations, the spring peak is not that clear anymore and has been superseded by the autumn peak. In general, no geographical dependence of the results of changes in the occurrence of the autumn AM was observed. Kostevc et al. (2022), who analysed specific discharges in Slovenia for the period 1960–2018, also determined that high waters are predominantly absent in Slovenia during the first half of the year. They also argued that the highest values of specific discharges of high discharges are extensively recorded throughout Slovenia during the second half of the year, particularly in the months of September, October, and November. Overall, we can conclude that the autumn AM have shifted later in the year at all of the considered gauging stations except one (1220), for which the autumn peak is unclear (Fig. 3).

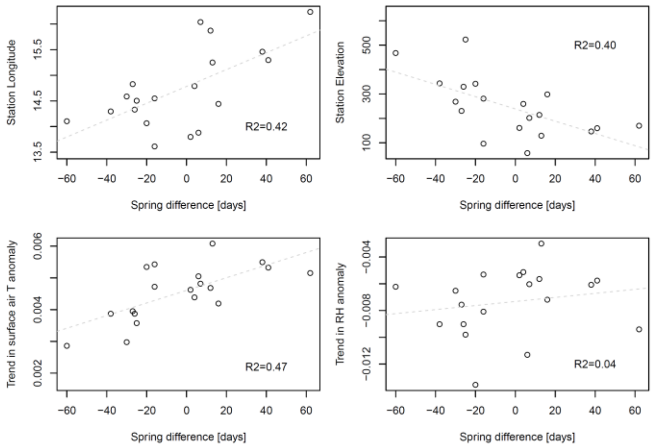

Fig. 6. The dependence between the shift in the occurrence of spring AM and various variables, including station longitude, station elevation and trends in surface air temperature (T) and relative humidity (RH) anomalies. The best fitted trend line is shown with a dotted grey line, along with the corresponding R^2 values. Most of the listed R^2 values are statistically significant at the 0.05 significance level according to the test for association between paired samples.

This shift is significant, meaning that the autumn AM occurred on average 15 days later in the period 1991–2023 than in the period 1961–1990. The reason may be attributed to higher air and sea temperatures at the end of the summer period in this part of Europe, which can generate extreme storm events and decreased snow precipitation at the end of autumn and beginning of winter. Further analysis indicates that the autumn changes are primarily driven by altered precipitation patterns throughout the year. Hence, Table 3 shows the basic descriptive statistics of monthly precipitation for the second half of the year at the 33 discharge gauging stations considered. As can be seen, the monthly precipitation sum decreases in July and August - despite the August 2023 flood (Bezak et al., 2023; Šraj and Bezak, 2025) - and increases in September, October, and December. November is the exception, with generally decreasing precipitation. The increase in monthly precipitation totals in December is evident (Table 3), and in combination with higher air temperatures, most of precipitation in December falls as rain rather than snow. Therefore, more AM events were recorded in December in the period 1991–2023 than in the period 1961–1990. More specifically, an average of 2.7 AM events were recorded in December for 33 considered gauging stations for the period 1961-1990. For the period 1991–2023, this number increased to an average of 5.6 AM events (Table 4). This increase was also detected in September, October, and November (Table 4), despite the mostly decreasing trends in November precipitation. Moreover, the number of AM events decreased in July and August in the period 1991-2023 period compared to the 1961–1990 period (Table 4).

Table 3. Basic statistics of monthly precipitation trends (mm/10 years) for 33 gauging stations.

Month	Average [mm/10 years]	Minimum [mm/10 years]	Maximum [mm/10 years]
July	–4.2	–8.7	–1.3
August	–2.4	–12.7	1.8
September	5.5	–4.5	10.1
October	2.1	–1.8	11.2
November	–4.2	–12.9	–1.6
December	6.7	–0.3	16.1

Table 4. Mean number (based on 33 gauging stations) of AM events in different months for 1961–1990 and 1991–2023 periods. Please note that number of years in the second period (i.e., 1991–2023) is larger for 3 years.

Month	Mean number of AM events in 1961–1990	Mean number of AM events in 1991–2023
July	1.1	0.7
August	1.7	1.1
September	2.9	3.8
October	4.3	5.6
November	5.4	7.4
December	2.7	5.6

4 CONCLUSION

In order to investigate the changes in the timing of annual maximum (AM) discharges in Slovenia, an analysis of AM data from 33 gauging stations for the period 1961–2023 was conducted. The period of available data was divided into two periods, namely the first period from 1961–1990 and the more recent period from 1991–2023. Based on the results presented the following conclusions can be made:

- The timing of AM discharge has shifted later in the year at all analysed gauging stations, except for one, over the recent three decades. This shift ranged from one to 35 days, excluding stations where the day of maximum density shifted from spring to autumn or vice versa. These shifts are likely driven by rising spring and summer temperatures, leading to more intense precipitation events. Smaller shifts predominantly occur within the western half of the country at gauging stations with headwaters in the Alpine catchments. These shifts are attributed to reduced snow accumulation and earlier snowmelt.
- The observed reduction or disappearance of spring AM at several gauging stations indicates a shift toward a dominant pluvial regime, with diminished influence from snowmelt.
- The shift of autumn AM, averaging 15 days, is accompanied by an increased probability of AM occurrences in autumn at most stations. This shift can be attributed to higher air and sea temperatures in this part of Europe, which can generate extreme storm events and decreased snow precipitation at the end of autumn and beginning of winter. More specifically, the number of AM events has increased in December, November, and October as a result of these changes.

It can be concluded that a considerable shift occurred in the seasonal pattern of AM between the two analysed time periods. These changes have many potential implications for water resources management and the implementation of flood protection measures.

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