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DISCHARGE REGIMES OF SLOVENIAN RIVERS: 1991–2020

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The Rinka Waterfall as a spring of the Savinja River is a natural monument of national importance.

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ABSTRACT: Various researchers have examined discharge regimes of rivers in Slovenia in the past 75 years: four major studies made by Ilešič, Kolbezen, Hrvatin, and lastly Hrvatin and Frantar have analysed and classified the regimes, and clustered them into regime types. They have varied due to changes in discharge characteristics, mainly as a consequence of climate change. In the present paper, we used average monthly discharges between 1991–2020 to calculate the discharge coefficients and determine the modern typology of the regime types on 36 streams at 45 gauging stations. The final result was five types of contemporary discharge regimes which are a consequence of the landscapes' heterogenous climate- and geodiversity characteristics as well as human interventions.

KEYWORDS: discharge regime, typology, hydrograph, hydrogeography, cluster analysis, climate changes, Slovenia

Pretočni režimi slovenskih rek: 1991–2020

IZVLEČEK: Pretočne režime slovenskih rek so v zadnjih 75 letih preučevali različni avtorji: štiri ključne študije Ilešiča, Kolbezna, Hrvatina ter nazadnje Hrvatina in Frantarja so predstavile analizo in klasifikacijo režimov v različnih kategorijah. Slednje so se medsebojno razlikovale zaradi odtočnih sprememb, večinoma posledice podnebnih sprememb. V tem članku smo uporabili povprečne mesečne pretoke 36 vodotokov na 45 vodomernih postajah med letoma 1991 in 2020, da smo izračunali pretočne količnike in določili tipologijo pretočnih režimov tega obdobja. Končni rezultat je pet tipov današnjih pretočnih režimov, ki so posledica heterogenih značilnosti podnebja in geodiverzitete pokrajin ter človekovega delovanja.

KLJUČNE BESEDE: pretočni režim, tipologija, hidrogram, hidrogeografija, razvrščanje v skupine, podnebne spremembe, Slovenija

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1 Introduction

Studying discharge regimes has been a traditional topic of hydrogeographic and hydrologic research for nearly a century since it reflects the climatic characteristics and other factors in a drainage basin. Monthly discharge coefficient (fr. *coefficient mensuel de débit*, si. *mesečni pretočni količnik*), defined by Pardé (1933) as the ratio between the average monthly and average yearly discharge, shows us the dynamics of water runoff throughout the year while making it possible to link average monthly discharges with the distribution and type of precipitation, as well as the temperatures, and consequently the evaporation that decreases the runoff in an area. Hydro-meteorological trends and anthropogenic functions affect river discharges, which can lead to evapotranspiration rate changes (Krebs et al. 2021), as well as changes in river biodiversity and ecosystem functions (Palmer and Ruhi 2019).

The importance of discharges, which are the flown-away surplus precipitation not being used for transpiration nor being evaporated, is that they provide elementary data for the majority of further hydrological analyses (Bat et al. 2008). When they are measured at a certain gauging station, they reflect the characteristics of their catchment areas and significantly contribute to the water cycle (World Meteorological Organisation 2020). They are a water balance parameter and, for example, a basis for determining discharge regimens, which show rivers' average fluctuation across the year, discharge trends, which can show temporal variability, specific runoffs, which is a value of runoff water quantity per time interval per area, runoff coefficients, which shows the percentage of precipitation that ran off, etc. (Bat et al. 2008). In this article, we focus on discharge regimes, which are in Slovenia influenced primarily by climate (including precipitation and temperature both temporal and regional distributions as well as the rate of snowmelt), secondly by geodiversity and vegetation, and thirdly, but increasingly by human activities (Hrvatin 1998; Frantar and Hrvatin 2008).

Studying discharge regimes is not only of scientific and regional planning importance; it has a vital educational role as well. It is essential to keep regime-type analyses (scientifically and commercially-editorially) up to date since learning about them is prescribed in national secondary education curriculums for geography (Polšak et al. 2008) and hence also integrated into textbooks (e.g. Ogrin et al. 2022; Senegačnik 2022) and tested at national geography matricular examinations (Gaál et al. 2019). When studying geography, this content is one of the introductory topics in hydrogeography courses at all three Slovenian universities (Stojilković 2023).

The aims of this paper are: (i) to overview the existing literature on discharge analyses and their clustering for Slovenian rivers, (ii) to analyse the mean discharge data for them and to determine present-day clusters, and (iii) to describe them and briefly address the changes that they have faced since last national-level analyses.

1.1 From discharge variability in centennial perspective to current state

Temporal variability of river discharges shows various trends that correspond or relate to other events or changes in purely natural conditions of the catchment area (primarily climate change, but also changes after floods and earthquakes…) or anthropogenic changes triggered by human activity (land use changes, urbanization, etc.). In Slovenian rivers' case, most stations have been running for 50–70 years. However, there are certain that collect data from the beginning of the 20th century. On a global scale, Slovenian rivers belong to the temperate hydroclimate type, characterised by relatively low seasonal precipitation variability, but they are more prone to hazardous events since individual storms have a great impact on their hydrology (Hansford et al. 2020). Even if the Slovenian territory is characterized as low in its variability on a global scale, a more detailed overview points to substantial differences in mean monthly and mean annual discharges. The latter are predominantly decreasing, while maximum and extreme discharges are increasing (Frantar et al. 2008; Oblak et al. 2021).

The gauging stations that have one of the longest records in Slovenia are Litija and Laško. Centennial illustration (Figures 1 and 2) of discharge changes per 30-year spans was done for the rivers Sava (stations Litija & Litija I) and Savinja (stations Laško & Laško I) since they have obtained data recordings for their stations from the very beginning of the 20th century, which is the period we wanted to illustrate with the two examples, or even from earlier years. As seen from Figures 1 and 2, monthly variations among the periods are visible in each month, the most drastic being in April and November.

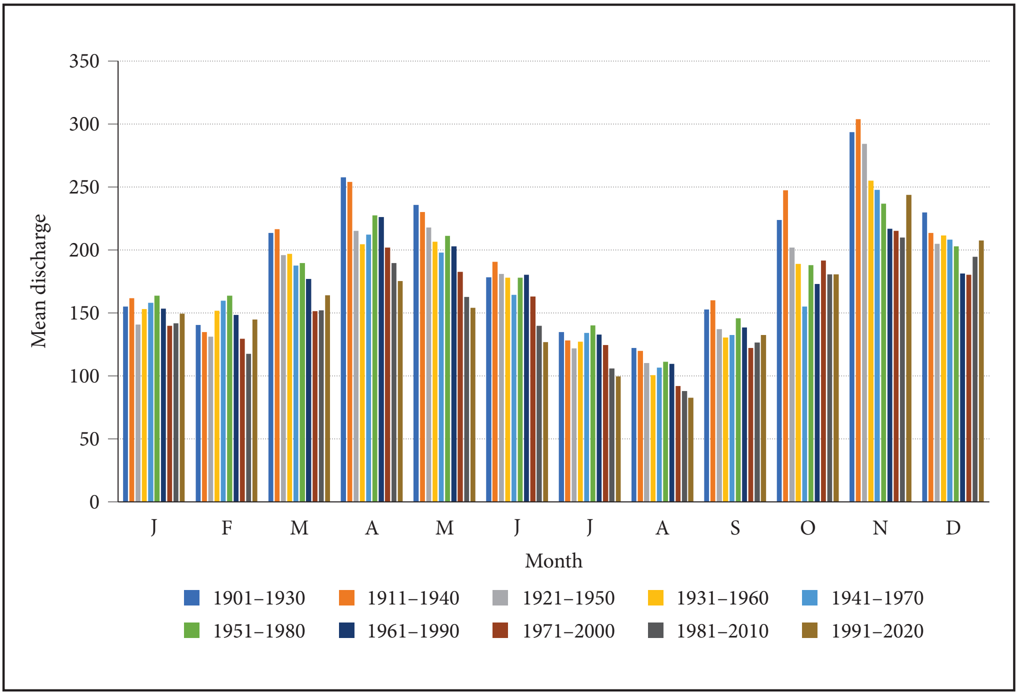


Figure 1: Mean monthly discharges for the Sava River in Litija in different periods.

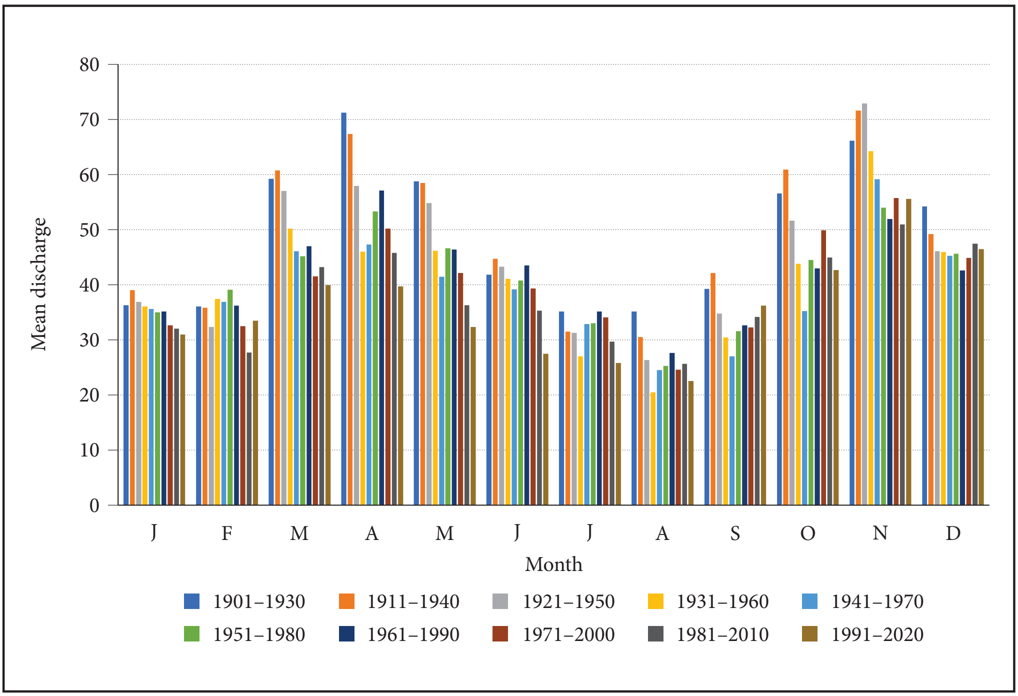


Figure 2: Mean monthly discharges for the Savinja River in Laško in different periods.

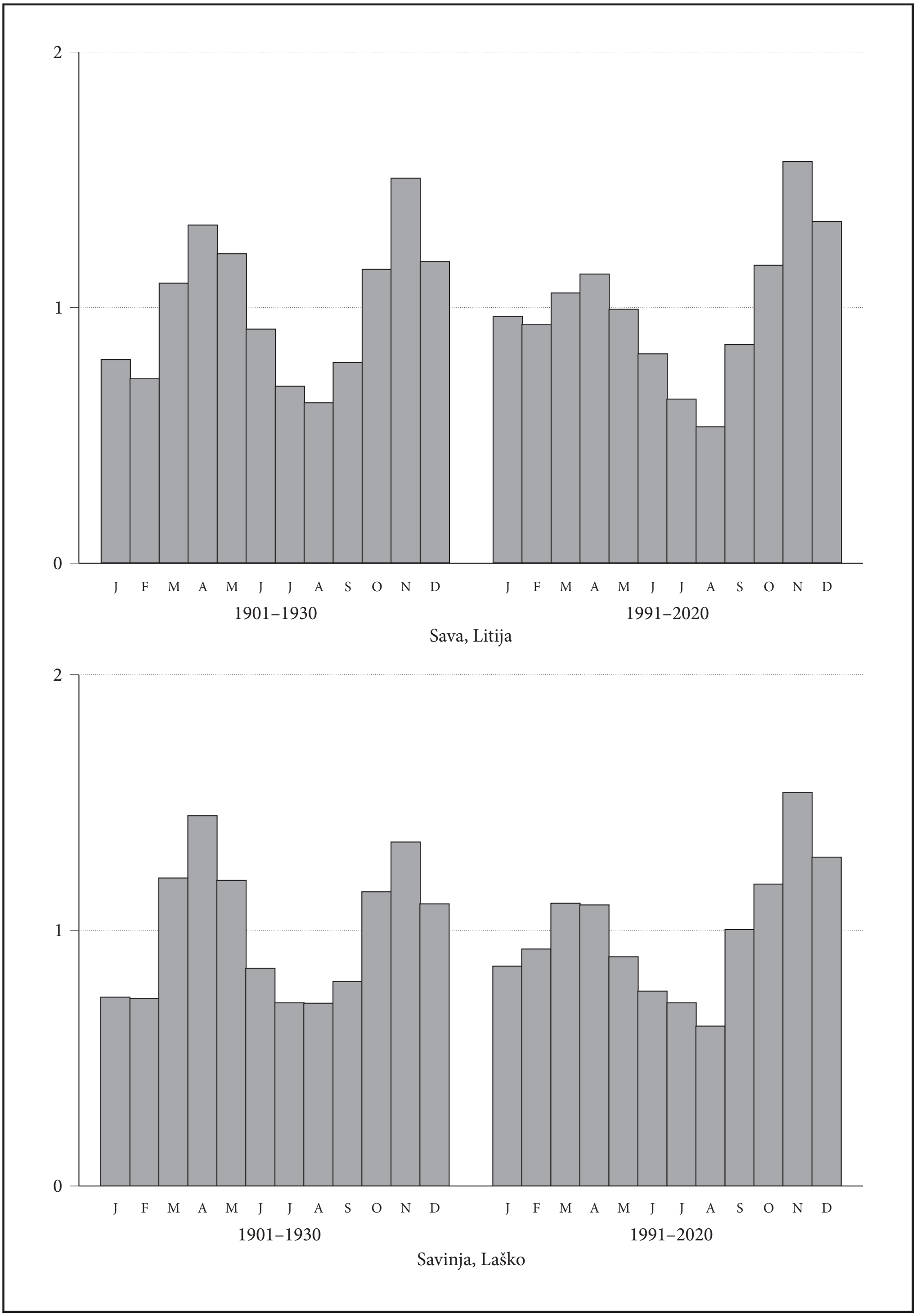


Figure 3: Comparison of discharge coefficients for the Sava (in Litija, above) and the Savinja (in Laško, bellow) Rivers between 1901–1930 and 1991–2020.

Looking at discharge coefficients, as calculated in the next chapter, for both rivers for the periods 1901–1930 and 1991–2020 (Figure 3), monthly coefficients have changed for both of them. In the case of the Sava River (Figure 3, above), the main discharge peak is the autumn one in both cases, with the values decreasing the most in spring, and being the highest and intensifying in November. The primary low in August has even decreased, whereas even more importantly, the winter one increased significantly. Both of them can be classified as pluvial-nival regimes. However, the regime changed for the Savinja River over time (Figure 3, below): in the 1901–1930 period it had its main peak in spring due to snow-melt in the river basin, whereas both lows were characterised by the same value; hence the regime being nival-pluvial. In the second period, the winter low considerably rose, and the spring values lowered, which is a consequence of the rising temperatures, less snow precipitation and snow retinence. Notably higher is the month discharge in November and December. The second hydrograph reflects the characteristics of the pluvial-nival one.

1.2 Previous research

There have been discharge regime scientific classifications published in the last 75 years in Slovenia (Table 1), beginning with Ilešič's (1947) discharge regimes in former Yugoslavia, which puts the rivers of present Slovenia

Table 1: Discharge regime types in Slovenia according to different authors.

Period	Regime types (and river examples)	Source
1898–1913 (littoral) & 1923–1938 (inland)	• Pure nival (Drava) • Transitional nival (Mura, upper Soča) • Alpine nival-pluvial (upper Sava, Savinja) • Moderate Mediterranean nival-pluvial (Tržiška Bistrica, Kamniška Bistrica) • Central-European pluvial-nival (Sotla) • Moderate Mediteranean pluvial-nival (Sora, Ljubljanica) • Mediterranean pluvial-nival (Vipava, Idrijca)	Ilešič 1947
Not specified	• Pure nival (Drava) • Transitional nival (Mura) • Mediterranean transitional nival (upstream Soča, Sava Dolinka) • Nival-pluvial (Sava Bohinjka, Kamniška Bistrica) • Moderate Mediterranean pluvial-nival (Savinja, lower Sava) • Moderate Mediteranean karst pluvial-nival (Krka, Kolpa) • Moderate continental pluvial nival (Sotla, Ledava) • Mediterranean pluvial (Rižana)	Stele 1987
1961–1990	• Nival (Mura, Drava) • Nival-pluvial (upstream Soča, upstream Savinja, upstream Sava, Meža, Mislinja) • Pluvial-nival (downstream Savinja, Dravinja, downstream Sava, Krka) • Continental pluvial-nival (Pesnica, Sotla, Mirna) • Mediterranean pluvial-nival (Vipava, Bača, Ljubljanica, Kolpa, Idrijca, central Soča) • Pluvial (Reka, Rižana, Pivka)	Kolbezen 1998
1961–1990	• Alpine nival (Drava, Mura) • Alpine high mountain nival-pluvial (upstream Savinja, Kamniška Bistrica, upstream Soča, Sava Dolinka and Bohinjka) • Alpine medium mountain nival-pluvial (Tržiška Bistrica, Kokra, central stream Savinja and Sava) • Alpine pluvial-nival (downstream Sava, Dreta) • Dinaric-Alpine pluvial-nival (Ljubljanica, Krka, Voglajna) • Dinaric pluvial-nival (Idrijca, Vipava, Sora, Unica, Kolpa) • Pannonian pluvial-nival (Ledava, Ščavnica, Pesnica, Sotla) • Mediterranean pluvial (Pivka, Reka, Rižana)	Hrvatin 1998
1971–2000	• Alpine nival-pluvial (Sava Dolinka and Bohinjka, Savinja at Solčava, upstream Soča, Kamniška Bistrica, Mura, Drava) • Alpine pluvial-nival (Soča at Solkan, Sava, Savinja from Nazarje onward, Meža, Paka) • Dinaric pluvial-nival (Idrijca, Sora, Unica, Vipava, Ljubljanica, Krka, Kolpa) • Pannonian pluvial-nival (Temenica, Mirna, Sotla, Voglajna, Dravinja, Pesnica, Ščavnica, Ledava) • Mediterranean pluvial (Pivka, Reka, Rižana)	Frantar and Hrvatin (2005; 2008)

in greater perspective. 40 years later Stele (1987) mapped the regimes, re-grouped the rivers, and pointed out the continental or Mediterranean emphasis on the regimes when naming them. For 1961–1990, there are two classifications: by Kolbezen (1998) and by Hrvatin (1998), which mainly differ in fragmentation of certain subtypes. The latest comprehensive analysis was done by Frantar and Hrvatin (2005; 2008) for the period 1971–2000, who reduced the number of (sub)types and reclassified certain elements.

Besides national discharge analyses, there have also been meso-regional analyses across the country in recent years for example in Slovene Alps (Hrvatin and Zorn 2017a), White Carniola (Plut et al. 2013), Carinthia (Kovačič and Brečko Grubar 2021), Slovene Istria (Trobec 2012; Kovačič 2016; Kovačič and Brečko Grubar 2019; Brečko Grubar and Kovačič 2021) and the Soča (Comici and Bussani 2007), Sava (Frantar 2003) and Vipava (Jelovčan and Šraj 2022) catchment areas, and local-level analyses for example in the Idrija Hills (Hrvatin and Zorn 2017b), the Kamniška Bistrica Valley (Trobec 2017), and the Jezersko (Trobec 2019) and Loški potok (Trobec 2022) municipalities.

2 Materials and methods

To preserve comparability with previous research regarding the Slovenian discharge regimes topic (Hrvatin 1998; Frantar and Hrvatin 2005) we performed a cluster analysis and carried it out in the SPSS environment. The same methodology was also applied to discharge regimes clustering in Croatia (Čanjevac 2013; Čanjevac and Orešić 2018). Five steps included in the cluster analysis (Ferligoj 1989) point out both materials and methods: analysis items selection, variables set determination, items' similarities calculation, classification method usage, and, lastly, results evaluation.

The criteria for selecting the 45 gauging stations on 36 streams (Table 2) were (i) distribution throughout the country and (ii) complete data on mean monthly discharges from 1991 to 2020 if existing, with a maximum tolerance of 24 missing months. The data was obtained from the webpage of the Slovenian Environmental Agency (2023). Twenty-five data sets for the selected stations are complete, whereas 20 are partially incomplete in minor scope. Some of the gauging stations were moved in the studied period and because of that Table 2 provides data on all of them, whereas further calculations are made for joint data.

Table 2: Gauging stations and their basic geographic parameters (Slovenian Environmental Agency 2023).

Station number	Station name	Unified station name used in this article	Stream name	Catchment area [km^2]	Mileage [km]	Monitoring start [year]	Complete or missing data [months (year)]
1060	Gornja Radgona I	Gornja Radgona	Mura	10197.20	106.64	1946	Complete
1140	Pristava I	Pristava	Ščavnica	272.77	5.78	1975	Complete
1220	Polana I	Polana	Ledava	209.37	44.33	1962	Complete
2010	HE Dravograd	HE Dravograd	Drava	12071.70	133.86	1965	Complete
2250	Otiški vrh I	Otiški vrh	Meža	552.60	1.35	1953	Complete
2390	Otiški vrh I	Otiški vrh	Mislinja	231.56	1.68	1973	3 (2015)
2650 & 2652	Videm I & Videm	Videm	Dravinja	767.08 & 767.34	4.38 & 4.16	1946	4 (2014)
2900	Zamušani I	Zamušani	Pesnica	479.76	9.86	1961	Complete
3080	Blejski most	Blejski most	Sava Dolinka	508.79	906.23	1963	12 (2007)
3200	Sveti Janez	Sveti Janez	Sava Bohinjka	94.35	32.80	1951	Complete
3420	Radovljica I	Radovljica	Sava	907.96	900.95	1953	Complete
3650 & 3660	Litija I & Litija	Litija	Sava	4849.33 & 4849.67	818.65 & 818.15	1895	Complete
3850	Čatež I	Čatež	Sava	10232.42	736.69	1976	Complete
4120	Kokra I	Kokra	Kokra	113.10	18.01	1957	3 (2015), 4 (2016)
4200	Suha I	Suha	Sora	568.86	7.98	1953	12 (1991)
4430	Vir	Vir	Kamniška Bistrica	208.58	9.58	1978	1 (1991), 5 (2014)

Station number	Station name	Unified station name used in this article	Stream name	Catchment area [km^2]	Mileage [km]	Monitoring start [year]	Complete or missing data [months (year)]
4740 & 4750	Rakovec I & Rakovec	Rakovec	Sotla	560.06 & 561.30	8.07 & 8.00	1926	Complete
4860	Metlika	Metlika	Kolpa	1966.27	181.50	1926	Complete
4969 & 4970	Gradac I & Gradac	Gradac	Lahinja	218.89 & 219.12	7.75 & 7.32	1952	Complete
5030	Vrhnika	Vrhnika	Ljubljanica	1135.12	38.73	1926	3 (2014)
5078 & 5080	Moste I & Moste	Moste	Ljubljanica	1777.96 & 1778.16	11.83 & 11.39	1924	Complete
5770	Cerknica I	Cerknica	Cerkniščica	49.50	4.60	1961	12 (1996), 4 (2015)
5880	Hasberg	Hasberg	Unica	Karst (catchment area cannot be assessed)	16.37	1926	Complete
6020	Solčava I	Solčava	Savinja	63.41	89.45	1959	4 (2015), 8 (2016), 12 (2018)
6060	Nazarje	Nazarje	Savinja	457.11	56.64	1926	Complete
6200	Laško I	Laško	Savinja	1668.16	14.34	1953	Complete
6240	Kraše	Kraše	Dreta	100.82	7.66	1959	2 (2015), 5 (2016)
6300	Šoštanj	Šoštanj	Paka	131.64	12.45	1920	8 (1991)
6720	Celje II	Celje	Voglajna	202.89	2.18	1967	4 (2015)
7029 & 7030	Podbukovje I & Podbukovje	Podbukovje	Krka	346.92 & 348.06	91.34 & 91.27	1959	7 (2015)
7160	Podbočje	Podbočje	Krka	2252.98	16.05	1926	Complete
7308 & 7310	Rožni Vrh I & Rožni Vrh	Rožni Vrh	Temenica	80.51 & 81.05	20.56 & 20.06	1956	12 (2002)
7340	Prečna	Prečna	Prečna	295.19	4.92	1953	Complete
7380	Škocjan	Škocjan	Radulja	108.14	7.03	1961	3 (2014), 3 (2015)
7440 & 7441	Sodražica & Sodražica I	Sodražica	Bistrica	28.19 & 30.13	12.84 & 12.44	1963	Complete
8030 & 8031	Kršovec & Kršovec I	Kršovec	Soča	157.90 & 158.07	118.50 & 118.41	1945	Complete
8080	Kobarid I	Kobarid	Soča	437.06	94.41	1941	Complete
8180	Solkan I	Solkan	Soča	1580.35	44.23	1980	12 (2004)
8350	Podroteja I	Podroteja	Idrijca	111.25	42.73	1977	4 (2015)
8500	Bača pri Modreju	Bača pri Modreju	Bača	143.06	1.54	1940	Complete
8560 & 8561	Vipava I & Vipava II	Vipava	Vipava	131.90 & 131.92	43.55 & 43.47	1960	Complete
8600 & 8601	Miren & Miren I	Miren	Vipava	589.96 & 588.29	2.47 & 2.42	1950	9 (2015)
9050	Cerkvenikov mlin	Cerkvenikov mlin	Reka	332.12	7.95	1952	Complete
9210	Kubed II	Kubed	Rižana	204.66	13.25	1965	3 (2015)
9300	Podkaštel I	Podkaštel	Dragonja	93.16	6.46	1955	12 (1997), 4 (2014)

The variables set, which were all of the same type, included mean monthly discharge coefficients, which were calculated according to the following equation:

$$C_m = \frac{Qs_m}{Qs_y}$$

where: is monthly discharge coefficient, is average period monthly discharge, is average period annual discharge, is the studied month and is the studied year. The monthly discharge coefficient explains the ratio between mean monthly and mean annual discharge for a selected period.

The similarity was calculated using squared Euclidian distance, which is similar to the Manhattan distance used by Hrvatin (1998) and Frantar and Hrvatin (2005) and the cluster analysis was performed using Ward's method.

The merging of the items into clusters was presented with a dendrogram, which is suitable for presenting gradual merging (Ferligoj 1989).

The results were evaluated by performing non-hierarchic *k*-means method analysis, where the number of the desired clusters was set in advance. When the number of clusters (*k)* was selected, the clusters were formed in a way that the variety among the clusters was the greatest whereas it was the smallest within them (Čanjevac 2013).

Subsequently, the clusters were named following the so far Slovene hydrogeographical terminology (Hrvatin 1998; Frantar and Hrvatin 2005) and described. The naming of the regimes is formed including macro- or mesoregional name followed by discharge regime type. The hydrographs in Figures 5 to 10 present the discharge coefficients per month. All of the gauging stations in the continuation of the text are named according to their initial names having their subsequent numbers omitted (e.g. the stations Vipava I and Vipava II are referred to as Vipava).

3 Results

After performing hierarchical statistical analyses on monthly discharge coefficients of the selected rivers, the coefficients were grouped into six groups at 1.5 levels of joining distance (Figure 4). If the distance is 2, there are four groups, at 4 three groups, and 5 two. The results were confirmed by the non-hierarchical k-means method. The clusters are presented as discharge regime groups in the continuation and with their corresponding symbols in Figure 11, where a specific colour is attributed to each regime type that we propose. To keep the established naming of the groups, we maintained the one proposed by Frantar and Hrvatin (2005; 2008) to the greatest extent (as specified in Table 1), updating it as per the now-established regionalisation of Slovenia (Žiberna et al. 2004).

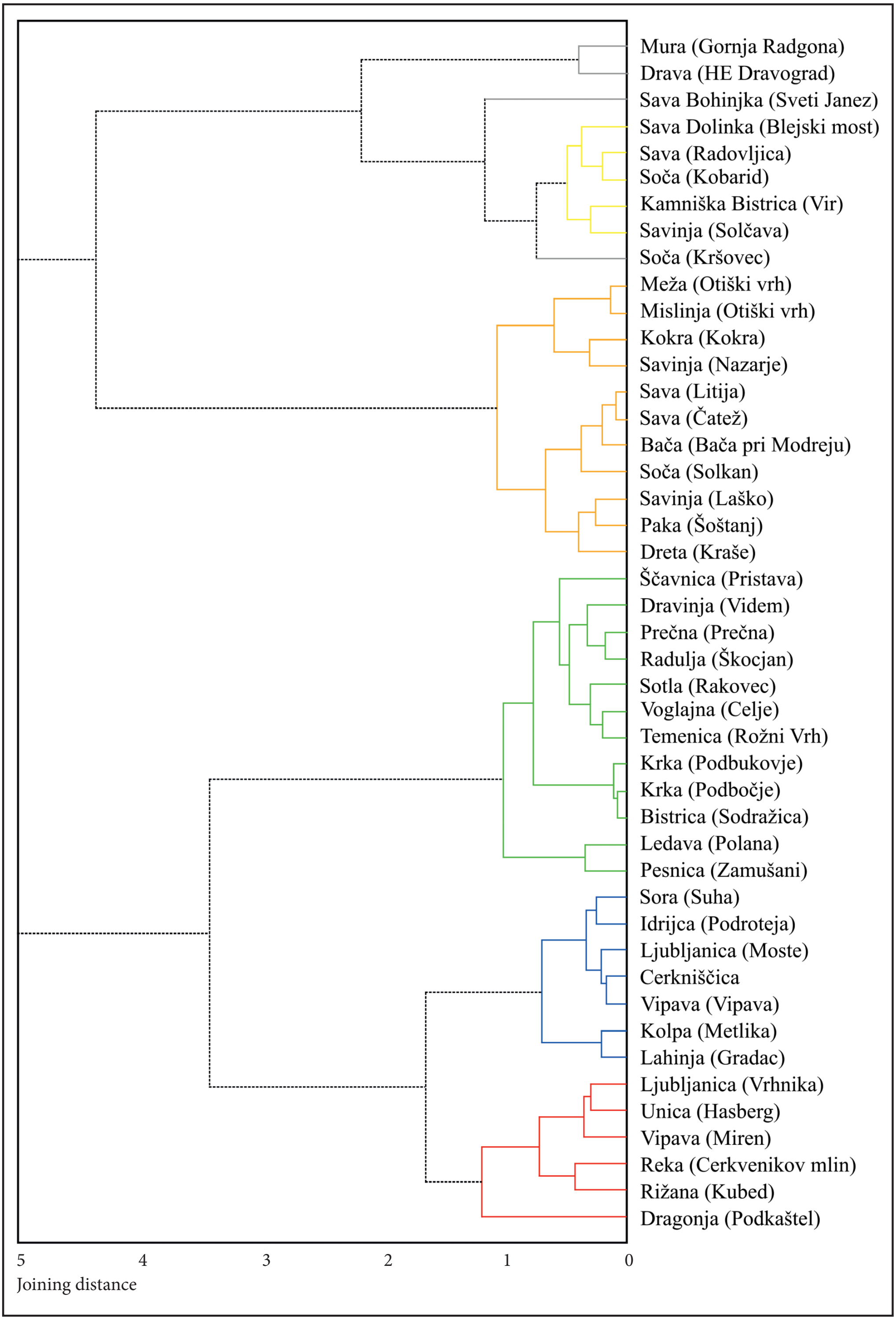
3.1 Alpine rivers

Slovenian rivers having the upper part of their catchment in the high mountains and gauging stations close to the spring or in the upper stream for the period 1991–2020 show more characteristics of the influence of the snow factor, but their flow regime could hardly be generally defined as the nival-pluvial regime.

Only the Mura hydrograph shows the characteristics of the snow regime, with a pronounced peak in May and June and a low from December to March. The Drava already shows a more pronounced above-average discharge in October and November, which is likely to be a secondary peak in the future, similar to the Sava Bohinjka and the Soča. The Soča in Kršovec has very even discharge peaks (discharge coefficient in May 1.55, in November 1.58), while the Sava Bohinjka has a more pronounced peak in spring (discharge coefficient in May 1.83, in November 1.62). The lows are more pronounced in both rivers in winter (flow coefficients in February 0.30 and 0.48) than in summer (flow coefficients 0.60 and 0.61). The hydrographs of the Drava (HE Dravograd), the Mura (Gornja Radgona), the Sava Bohinjka (Sveti Janez) and the Soča (Kršovec) were classified as the ones of the nival-pluvial discharge regime (Figure 5).

The Sava Dolinka (Blejski most), Sava (Radovljica), Soča (Kobarid), Savinja (Solčava) and Kamniška Bistrica (Vir) have lower spring peaks (May flow coefficients ranging from 1.36 to 1.17) than autumn peaks (November from 1.59 to 1.86), which is due to the lower contribution of snow to the discharge (Figure 6). Winter lows are also not pronounced or, except for the Mura, the Drava, the Sava Bohinjka and the Soča at the Kršovec gauging station, are very equal to or even higher than the summer lows. In the typification of the discharge regimes for the period 1971–2000, the rivers listed were classified in the Alpine nival-pluvial discharge regime, including the Mura and the Drava (Frantar and Hrvatin 2005; Frantar and Hrvatin 2008), which as a subcluster differed slightly from other streams in the aforementioned studies (ibid.) as well as this one. Their discharges differ from the others in the group because of the different catchments' locations in the Alpine areas and their sizes.

Figure 4: The dendrogram of the discharge clusters at 5 joining distance. ➤ p. 16


Mura (Gornja Radgona)
Drava (HE Dravograd)
Sava Bohinjka (Sveti Janez)
Sava Dolinka (Blejski most)
Sava (Radovljica)
Soča (Kobarid)
Kamniška Bistrica (Vir)
Savinja (Solčava)
Soča (Kršovec)
Meža (Otiški vrh)
Mislinja (Otiški vrh)
Kokra (Kokra)
Savinja (Nazarje)
Sava (Litija)
Sava (Čatež)
Bača (Bača pri Modreju)
Soča (Solkan)
Savinja (Laško)
Paka (Šoštanj)
Dreta (Kraše)
Ščavnica (Pristava)
Dravinja (Videm)
Prečna (Prečna)
Radulja (Škocjan)
Sotla (Rakovec)
Voglajna (Celje)
Temenica (Rožni Vrh)
Krka (Podbukovje)
Krka (Podbočje)
Bistrica (Sodražica)
Ledava (Polana)
Pesnica (Zamušani)
Sora (Suha)
Idrijca (Podroteja)
Ljubljanica (Moste)
Cerkniščica
Vipava (Vipava)
Kolpa (Metlika)
Lahinja (Gradac)
Ljubljanica (Vrhnika)
Unica (Hasberg)
Vipava (Miren)
Reka (Cerkvenikov mlin)
Rižana (Kubed)
Dragonja (Podkaštel)
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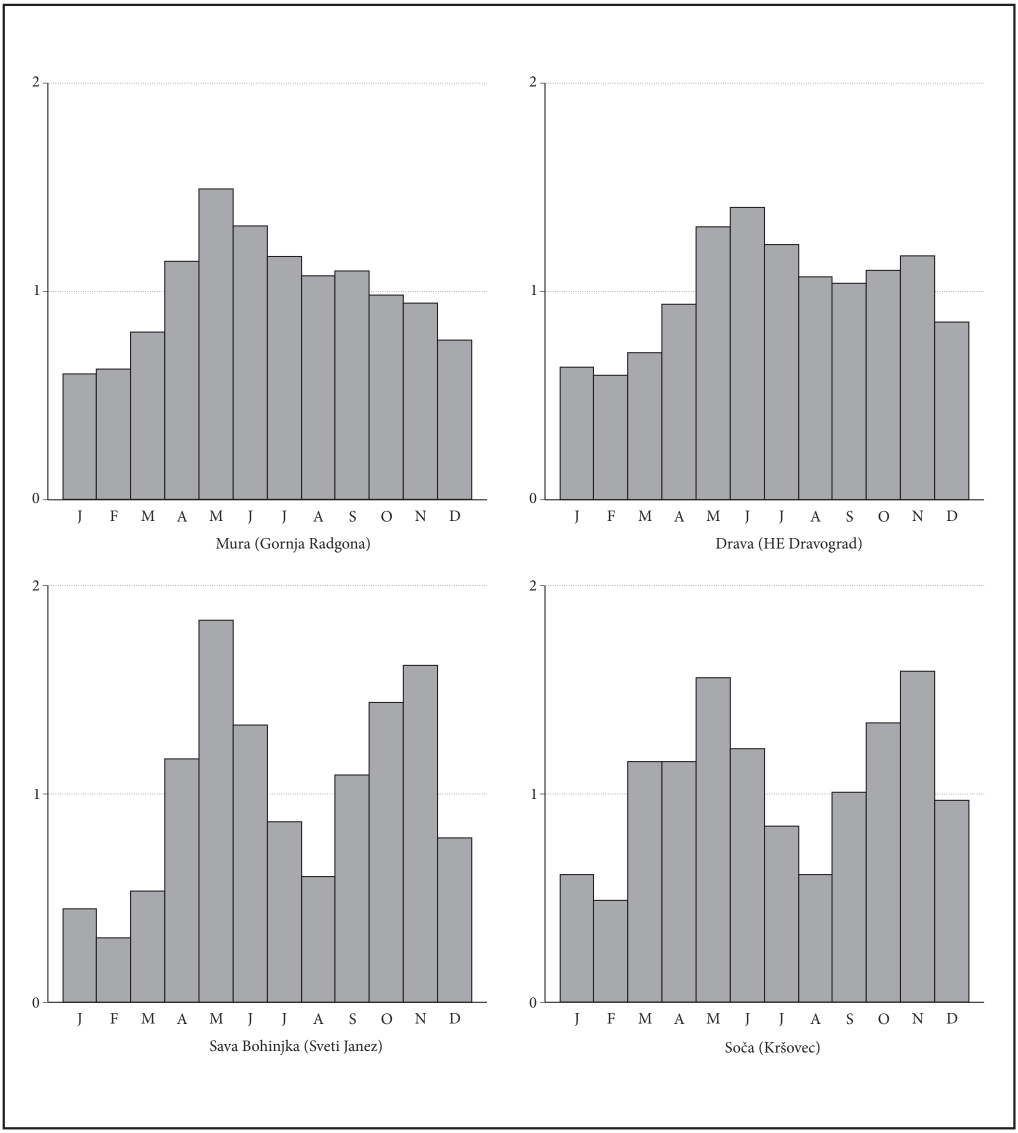
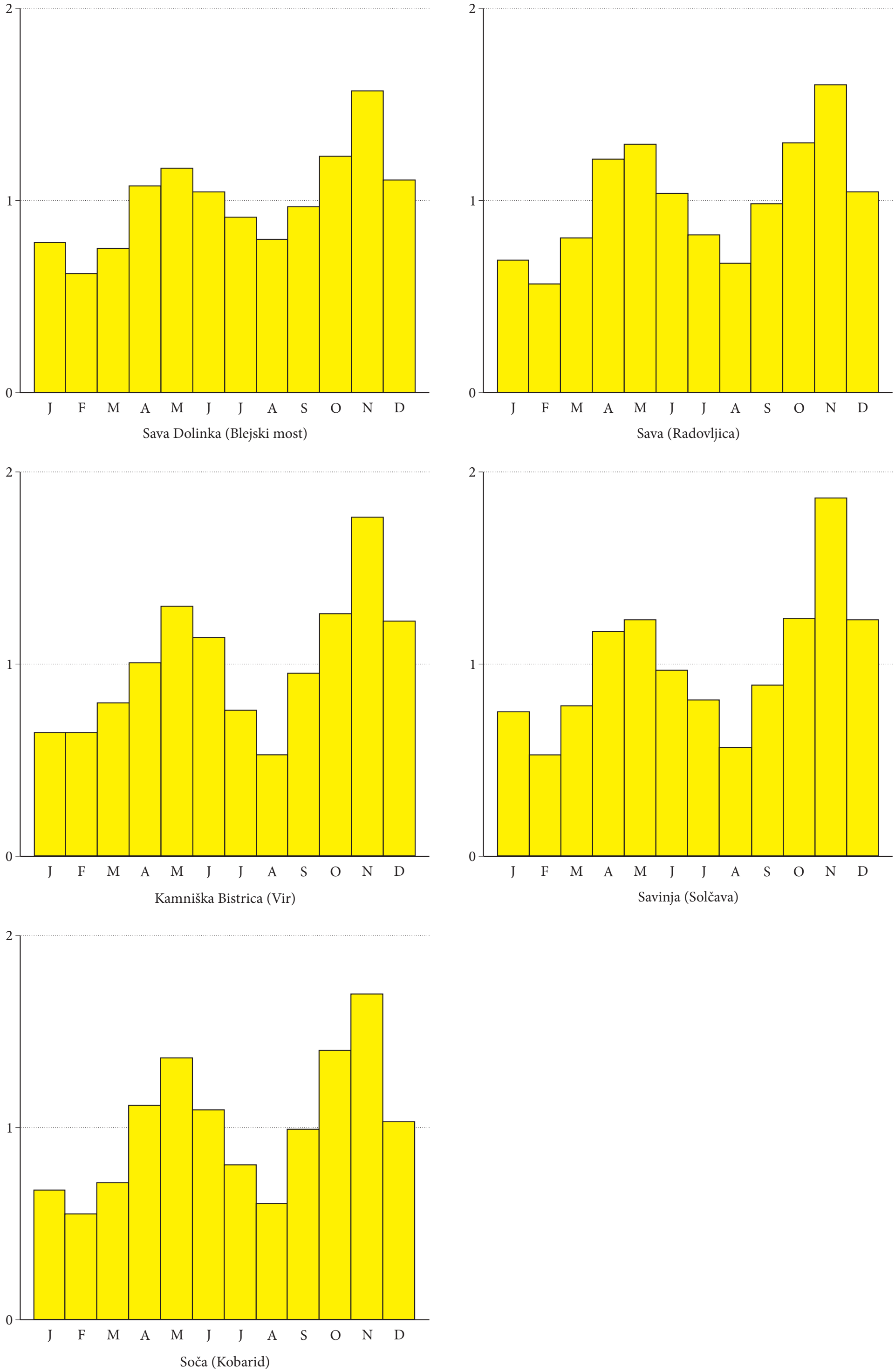


Figure 5: Hydrographs of the Alpine rivers with major nival influence.

Figure 6: Hydrographs of the Alpine rivers with minor nival influence. ➤ p. 18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Sava Dolinka (Blejski most)
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Sava (Radovljica)
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1
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J F M A M J J A S O N D
Kamniška Bistrica (Vir)
2
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0
J F M A M J J A S O N D
Savinja (Solčava)
2
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J F M A M J J A S O N D
Soča (Kobarid)

3.2 Pre-Alpine rivers of northern and western Slovenia

The hydrographs of selected gauging stations on rivers in the northern and north-western part of Slovenia exhibit the characteristics of a pluvial-nival discharge regime with a pronounced autumn peak. The Soča (Solkan), Bača (Bača pri Modreju), Kokra (Kokra), Sava (Litija and Čatež), Meža (Otiški vrh), Mislinja (Otiški vrh), Paka (Šoštanj), Dreta (Kraše), Savinja (Nazarje and Laško) were classified in this group (Figure 7). In November, discharge coefficients ranged from 1.41 (Meža) to 1.74 (Soča Solkan), the spring peak in April was around the mean annual value for all rivers, and in May discharge coefficients were already below 1 in eight cases and higher in three. The winter low is also less prominent, with all 11 gauging stations having a lower discharge coefficient in August than in February. In February they ranged between 0.69 (Kokra) and 0.98 (Sava Čatež), while in August they ranged between 0.77 (Meža) and 0.48 (Bača and Soča at Solkan). In the typification of discharge regimes for the period 1971–2000, the rivers mentioned above were classified as belonging to the Alpine pluvial-nival discharge regime (Frantar and Hrvatin 2005; Frantar and Hrvatin 2008).

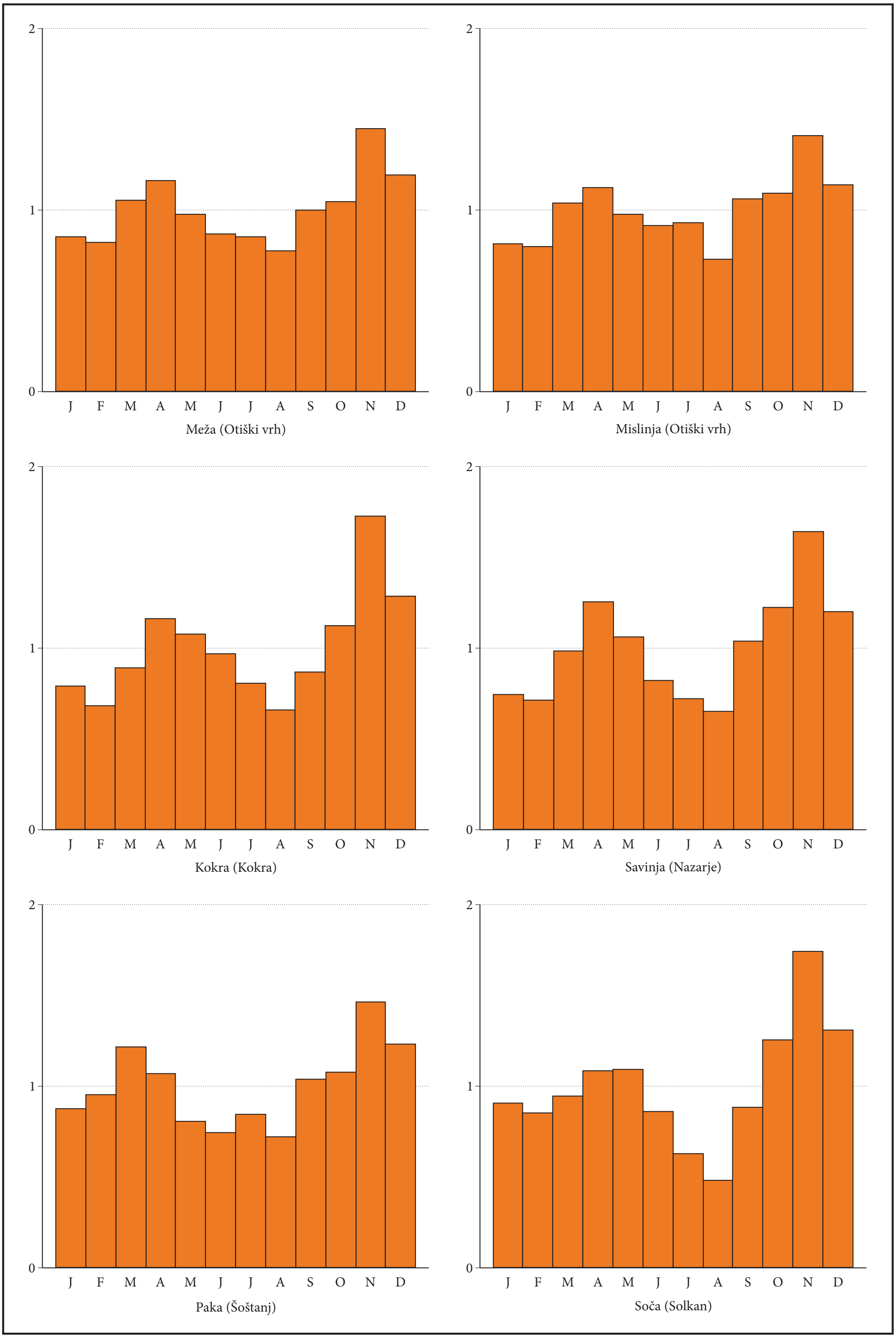
3.3 Sub-Pannonian rivers of north-eastern and south-eastern Slovenia

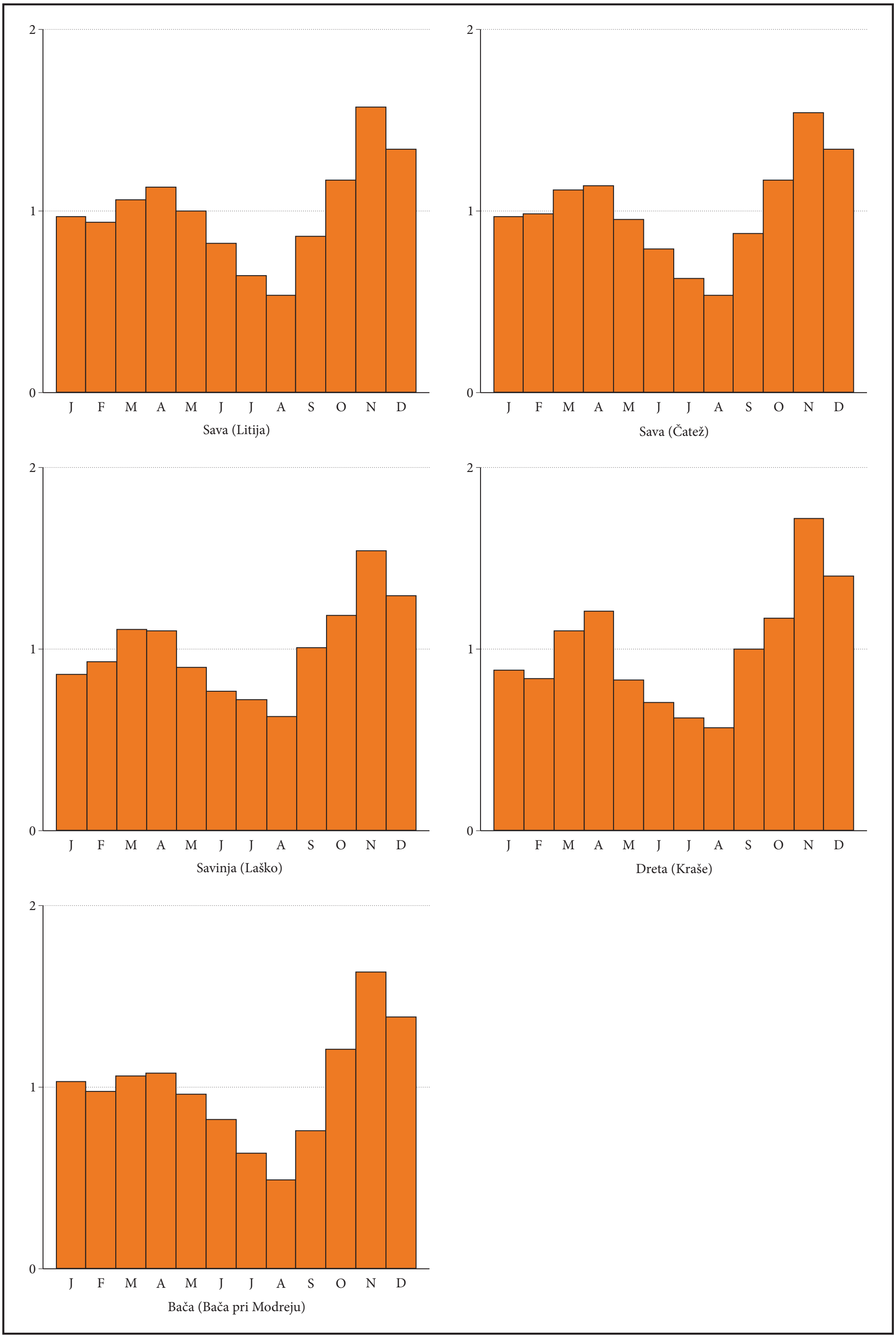
The hydrographs (Figure 8) for gauging stations on mostly smaller rivers in eastern and south-eastern Slovenia reflect the characteristics of a pluvial-nival discharge regime with a weak influence of the snow factor. The Ledava (Polana), the Ščavnica (Pristava), the Pesnica (Zamušani), the Dravinja (Videm), the Voglajna (Celje), the Sotla (Rakovec), the Prečna (Prečna), the Temenica (Rožni Vrh), the Radulja (Škocjan), the Krka (Podbukovje and Podbočje), and the Bistrica (Sodražica) fall into this group. The hydrographs show a pronounced summer low and an insignificant winter low, and a slightly higher autumn peak than the spring peak. The values of the discharge coefficients in August range from 0.38 (Sotla) to 0.72 for Ledava, where the influence of the reservoir is evident. The river with the second highest discharge coefficient in August is the Dravinja with 0.58. The summer below-average conditions for four rivers (Ledava, Ščavnica, Pesnica and Voglajna) last from April to September, and for the others from May to August. The autumn peak in November and December is more pronounced than the spring peak, despite the values of the flow coefficients being very similar. In March they ranged from 1.22 (Prečna) to 1.47 (Ledava), in November from 1.19 (Ledava) to 1.46 (Ščavnica) and in December from 1.34 (Dravinja) to 1.52 (Sotla). Of the 12 rivers, 7 have a flow coefficient higher in December than in November, 3 the same and only two (Krka at Podbukovje and Bistrica) slightly lower. All rivers also have above-average discharges in February and March; four have above-average and eight below-average discharges in January, with discharge coefficients close to the mean annual average. The winter low is thus almost non-existent. In the typification of flow regimes for the period 1971–2000, the Ledava, Ščavnica, Pesnica, Dravinja Voglajna, Sotla and Temenica rivers were classified as belonging to the Pannonian pluvial-nival discharge regime, and the Krka river to the Dinaric pluvial-nival discharge regime (Frantar and Hrvatin 2005; 2008).

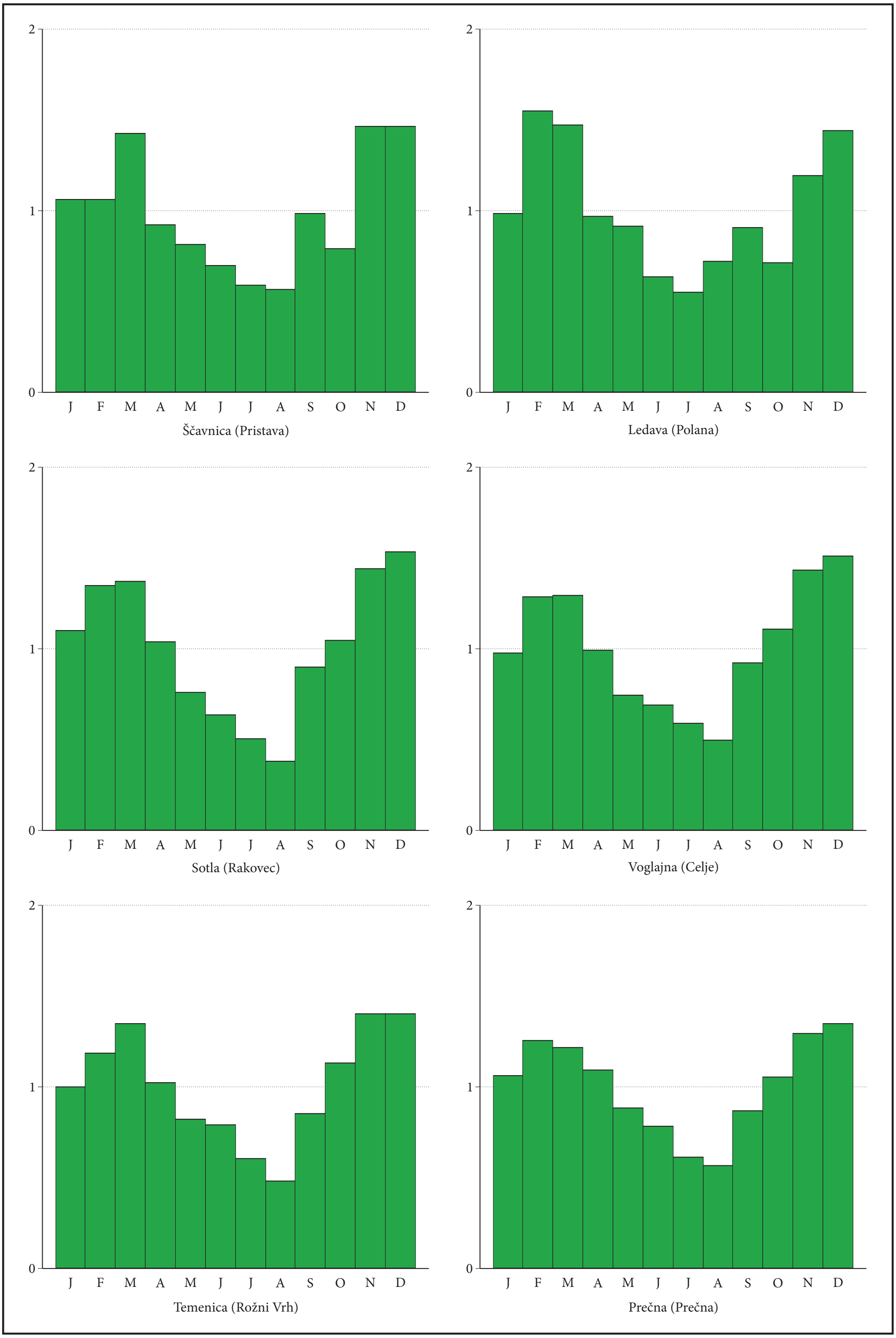
3.4 Dinaric rivers of central and southern Slovenia

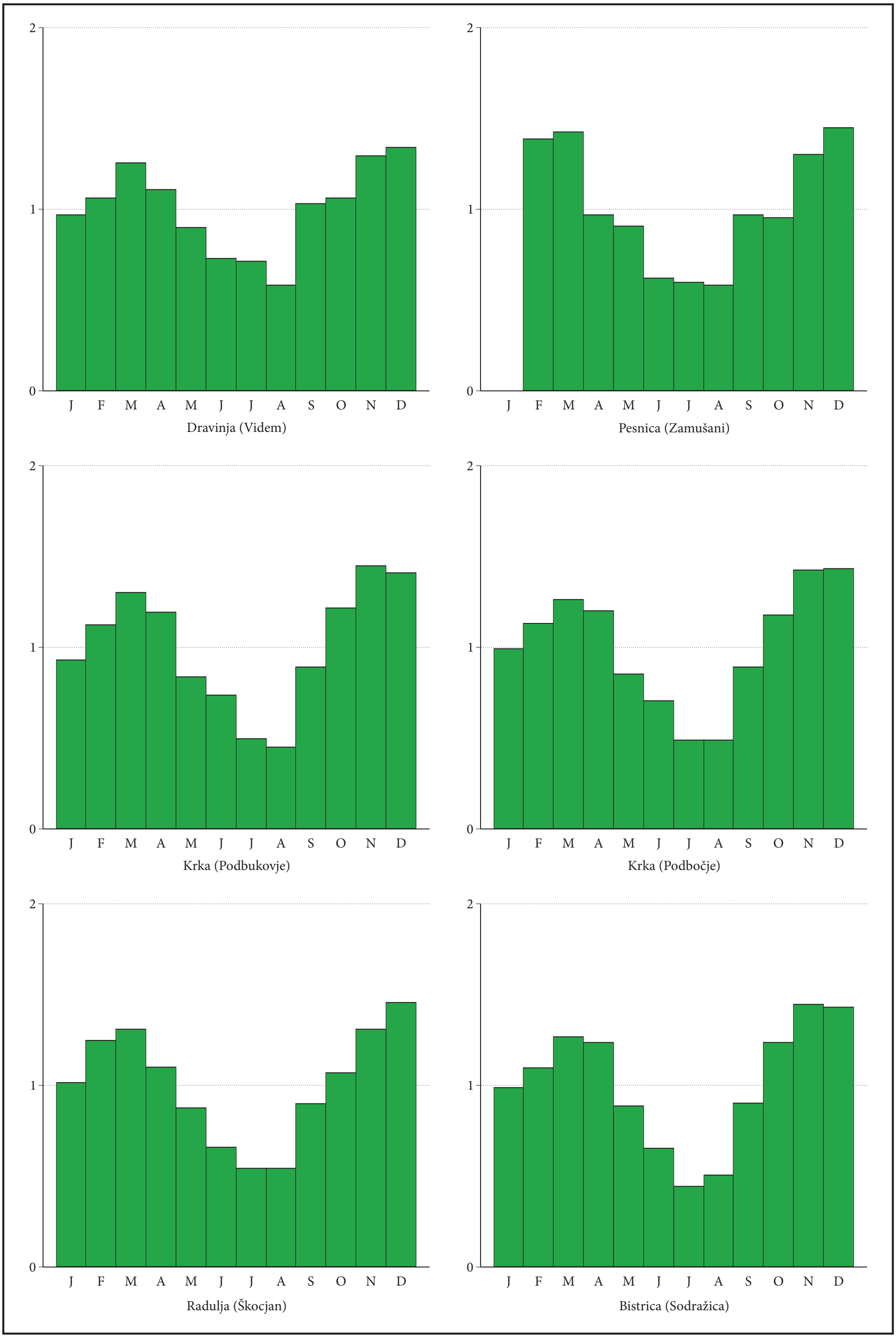
The gauging stations on rivers in central and southern Slovenia have very similar hydrographs. The Sora (Suha I), Ljubljanica (Moste), Idrijca (Podroteja), Vipava (Vipava), Cerkniščica (Cerknica), Kolpa (Metlika) and Lahinja (Gradac) are included in this group (Figure 9). In the typification of discharge regimes for the period 1971–2000, all of the rivers listed were classified as belonging to the Dinaric pluvial-nival discharge regime (Frantar and Hrvatin 2005; Frantar and Hrvatin 2008). The hydrographs for the period 1991–2020 show a completely undistinguished influence of the snow factor. Six of them have above-average mean monthly discharges from October to April, and only one (the Sora) is slightly below the average in January. The discharge coefficients in January are between 0.97 (Sora) and 1.16 (Ljubljanica), and in February between 1.04 (Sora) and 1.35 (Lahinja). In contrast to the previous group, the discharge coefficients are higher in

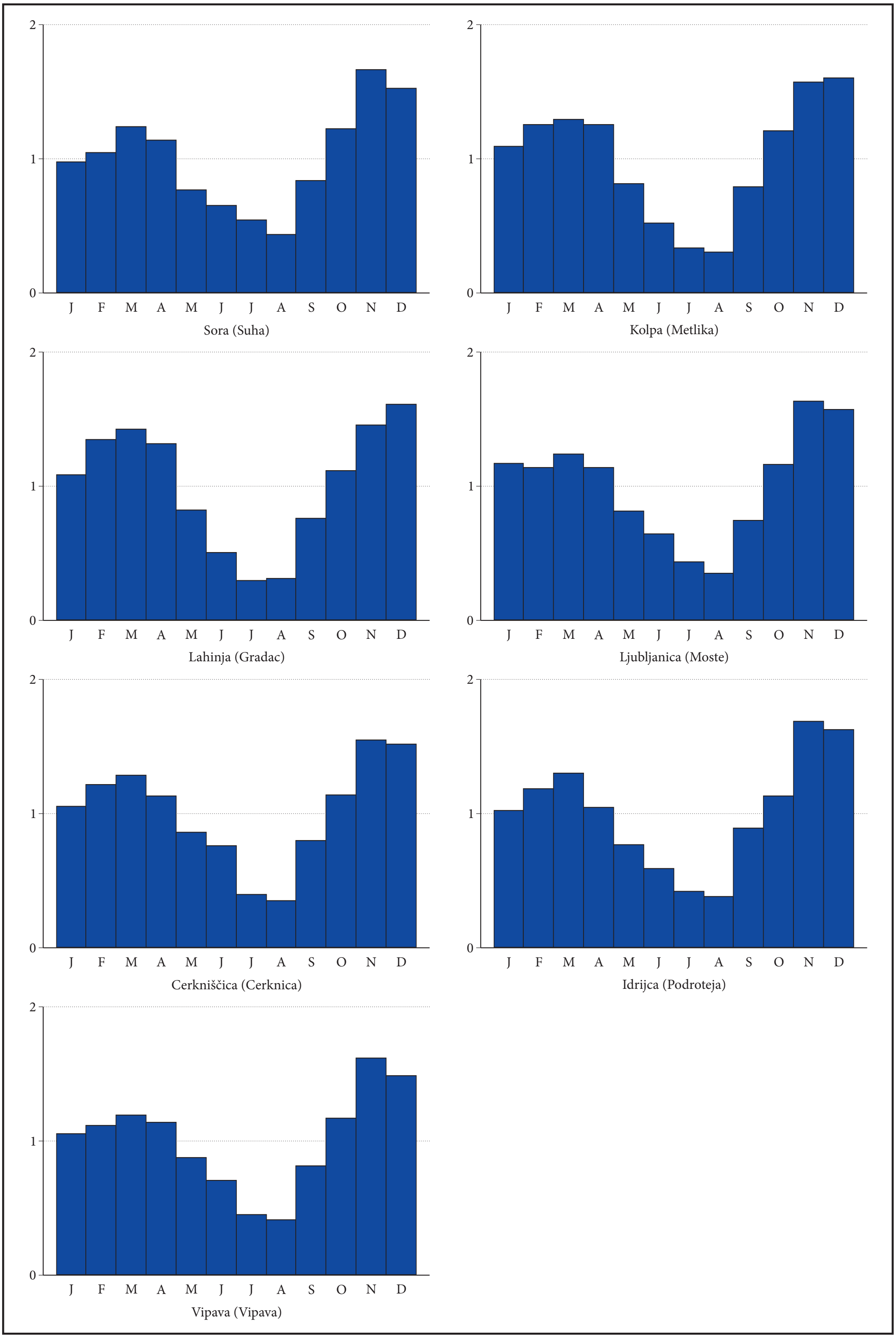
Figure 7: Hydrographs of the pre-Alpine rivers of northern and western Slovenia. ➤ p. 20–21
Figure 8: Hydrographs of the sub-Pannonian rivers of north-eastern and south-eastern Slovenia. ➤ p. 22–23
Figure 9: Hydrographs of the Dinaric rivers of central and southern Slovenia. ➤ p. 24


2
1
0
J F M A M J J A S O N D
Meža (Otiški vrh)
Mislinja (Otiški vrh)
Kokra (Kokra)
Savinja (Nazarje)
Paka (Šoštanj)
Soča (Solkan)


2
1
0
J F M A M J J A S O N D
Sava (Litija)
2
1
0
J F M A M J J A S O N D
Sava (Čatež)
2
1
0
J F M A M J J A S O N D
Savinja (Laško)
2
1
0
J F M A M J J A S O N D
Dreta (Kraše)
2
1
0
J F M A M J J A S O N D
Bača (Bača pri Modreju)


2
1
0
J F M A M J J A S O N D
Ščavnica (Pristava)
2
1
0
J F M A M J J A S O N D
Ledava (Polana)
2
1
0
J F M A M J J A S O N D
Sotla (Rakovec)
2
1
0
J F M A M J J A S O N D
Voglajna (Celje)
2
1
0
J F M A M J J A S O N D
Temenica (Rožni Vrh)
2
1
0
J F M A M J J A S O N D
Prečna (Prečna)


2
1
0
J F M A M J J A S O N D
Dravinja (Videm)
Pesnica (Zamušani)
Krka (Podbukovje)
Krka (Podbočje)
Radulja (Škocjan)
Bistrica (Sodražica)


2
1
0
J F M A M J J A S O N D
Sora (Suha)
Kolpa (Metlika)
Lahinja (Gradac)
Ljubljanica (Moste)
Cerkniščica (Cerknica)
Idrijca (Podroteja)
Vipava (Vipava)

November than in December, and the difference between the autumn and spring peaks is more pronounced. The discharge coefficients in November range from 1.45 (Lahinja) to 1.68 (Idrijca), and in March from 1.19 (Vipava) to 1.42 (Lahinja). The discharge coefficients in April are similar to those in February. The distinct summer low is similar to that of rivers in north-eastern and south-eastern Slovenia, with discharge coefficients of between 0.29 (Lahinja) and 0.54 (Sora) in July, and between 0.30 (Kolpa) and 0.43 (Sora) in August.

3.5 Rivers of south-western Slovenia

The last group consists of the rivers of south-western Slovenia, namely the Rižana (Kubed), the Dragonja (Podkaštel), the Reka (Cerkvenikov mlin), the Vipava (Miren), the Ljubljanica (Vrhnika) and the Unica (Hasberg) (Figure 10). In the typification of the discharge regimes for the period 1971–2000, except the last two, they were all classified as belonging to the Mediterranean pluvial discharge regime (Frantar and Hrvatin 2005; 2008). The hydrographs are characterised by an autumn peak with discharge coefficients in November between 1.49 (Dragonja) and 2.01 (Reka), and in December between 1.69 (Ljubljanica) and 1.96 (Dragonja). In the hydrographs of the Unica, the Rižana and the Dragonja, the discharge coefficients in December are higher than those in November. January values are lower than those for December for all rivers, including February for the Ljubljanica and the Unica. In January, the discharge coefficients range from 1.12 (Vipava) to 1.35 (Unica), and in February from 1.09 (Ljubljanica) to 1.77 (Dragonja). From March onwards, the discharge coefficients decrease, except for the Ljubljanica and the Unica, where this only occurs in April, and the group differs from the previous groups in this respect. All rivers have below-average discharges from May to September, and only the Rižana and the Dragonja in October. Summer flow coefficients range from 0.19 (Dragonja) to 0.35 (Vipava) in July, and from 0.09 (Dragonja) to 0.23 (Reka) in August. Of the other rivers with a slightly different hydrograph, the Dragonja stands out as the only one with a complete basin in Slovenian Istria. It has a high discharge coefficient in February (1.77) and an extremely low one in August (0.09).

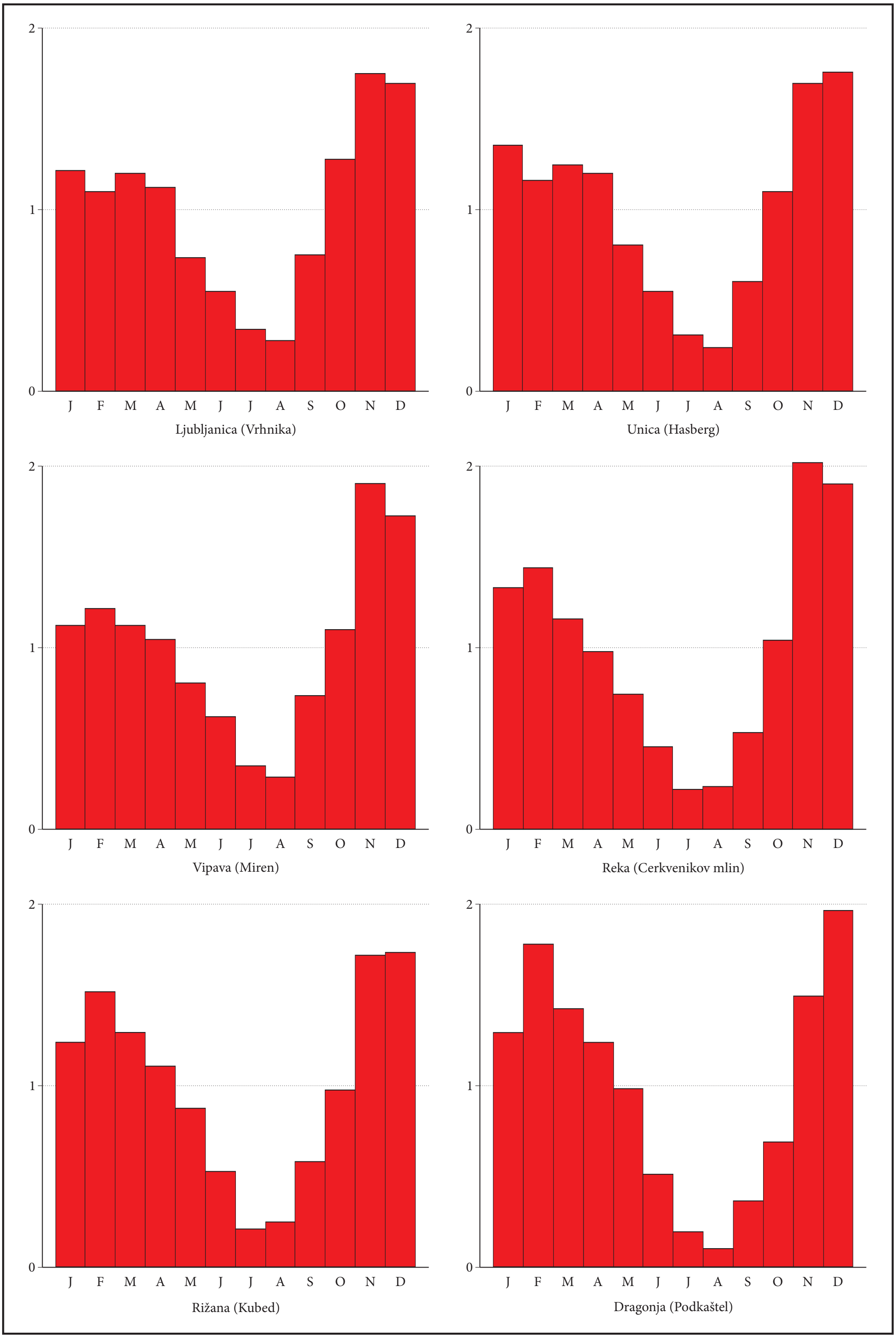
4 Discussion

As shown in the Results section, the discharge capacities of several streams changed, redistributing the coefficient values throughout the year. Secondly, the discharge characteristics changed in certain cases in such a drastic way, that the streams clustered differently as in the previous observation periods, as well as changed their discharge type changed. Hence, it is imperative to further elaborate on the changes, as well as to present an up-to-date classification of the streams according to their discharge regime characteristics.

4.1 Similarities and differences between the 1991–2020 period and previous periods

Comparing the hydrographs for the reference period 1991–2020 with those for 1960–1990 (Hrvatin 1998) and 1971–2000 (Frantar and Hrvatin 2008) – as can also be seen in Figures 1 and 2 – we observed that the influence of the snow factor has decreased at most gauging stations on Slovenian rivers. The exceptions are the rivers with a catchment and part of the catchment hinterland in the high mountains. In the last two periods, the February discharges have risen the most (Kobold 2022). Related to that, above-average discharges, where the influence of snowmelt was noticeable, have mostly decreased and become insignificant. Yet until 2010, the spring and autumn peaks had become similar (Hrvatin and Zorn 2017a), whereas since then – as shown in this study – the trend has continued. Conversely, autumn peaks, with a peak in November and/or December, have strengthened. Less pronounced are the winter lows, when, except for the rivers of the first group (Figure 5), the values of the flow coefficients are mostly above or slightly below the mean annual value. To take the example of the Otiški vrh gauging station on the Meža River, which has been similarly discussed by Kovačič and Brečko Grubar (2021): the flow coefficient decreased from 1.52 to 1.16 in April, from 1.20 to 0.97 in May, whereas increased from 1.17 to 1.44 in November

Figure 10: Hydrographs of the rivers of south-western Slovenia. ➤ p. 26


2
1
0
J F M A M J J A S O N D
Ljubljanica (Vrhnika)
2
1
0
J F M A M J J A S O N D
Unica (Hasberg)
2
1
0
J F M A M J J A S O N D
Vipava (Miren)
2
1
0
J F M A M J J A S O N D
Reka (Cerkvenikov mlin)
2
1
0
J F M A M J J A S O N D
Rižana (Kubed)
2
1
0
J F M A M J J A S O N D
Dragonja (Podkaštel)

and from 0.86 to 1.19 in December. Similar changes are shown by the data for the Solkan I gauging station (Figure 7) on the Soča River, where the flow coefficient decreased from 1.29 to 1.08 in April, from 1.32 to 1.09 in May, from 1.16 to 0.86 in June, with noticeably lower coefficients in the summer months, while on the contrary, it increased from 1.36 to 1.74 in November, from 0.97 to 1.30 in December (Kolbezen 1998; Bat et al. 2008), which points at the intensification of the rain regime that has a crucial effect on the discharge of the major part of this river (Comici and Bussani 2007; Siché and Arnaud-Fassetta 2014), which is also under great influence of anthropogenic activities (e.g. channelisation and dams) (Siché and Arnaud-Fassetta 2014).

Authors have pointed at regime change downstream for several major Slovenian rivers, and at gaining effect of the pluvial factor through time, such as the Sava River (Frantar 2003). For the last monitoring period, many of the hydrographs of the catchment hinterland of gauging stations in north-eastern, south-eastern, central and south-western Slovenia, with hilly, moderately rugged or lowland terrain, increasingly show the characteristics of a rainfall flow regime. Differences between the characteristics of the autumn and spring above-average flow coefficients and the differences in the summer below-average flow coefficients have become apparent, which has not only been observed in this study but also by several other authors (e.g. Kovačič and Brečko Grubar 2019) who dealt with specific streams or regional/local analyses. The flows of the above-mentioned areas (i.e. north-eastern, south-eastern, central and south-western Slovenia) also form one of two major clusters – that is the cluster solely affected by rain, which is a major difference from the penultimate (Frantar and Hrvatin 2005; Frantar and Hrvatin 2008) and ante-penultimate (Hrvatin 1998) national analyses.

A comparison of the period 1991–2020 with the periods 1961–1990 and 1971–2000 shows that flow coefficients are noticeably lower in March and April and noticeably higher in November and December. Similar trends had already been established for earlier periods (Plut et al. 2013) and are pointed out by detailed contemporary studies comparing the same periods (Kobold 2022). To illustrate: at the Pristava gauging station on the Ščavnica River, the flow coefficient decreased from 1.51 to 1.06 in February, from 1.73 to 1.42 in March and from 1.30 to 0.92 in April, increased from 1.24 to 1.46 in November and from 1.16 to 1.46 in December. Another example is the Krka River in Podbočje, where the flow coefficient decreased from 1.48 to 1.19 in April and from 0.95 to 0.85 in May, while in November it increased from 0.97 to 1.17 and in December it increased from 1.18 to 1.43. Similar changes can be observed on other rivers of groups 3, 4 and 5 (Figures 8–10). On the Reka (Cerkvenikov mlin) (Figure 10), the discharge coefficient increased from 1.65 to 2.10 in November, and from 1.45 to 1.89 in December (Kolbezen 1998; Bat et al. 2008).

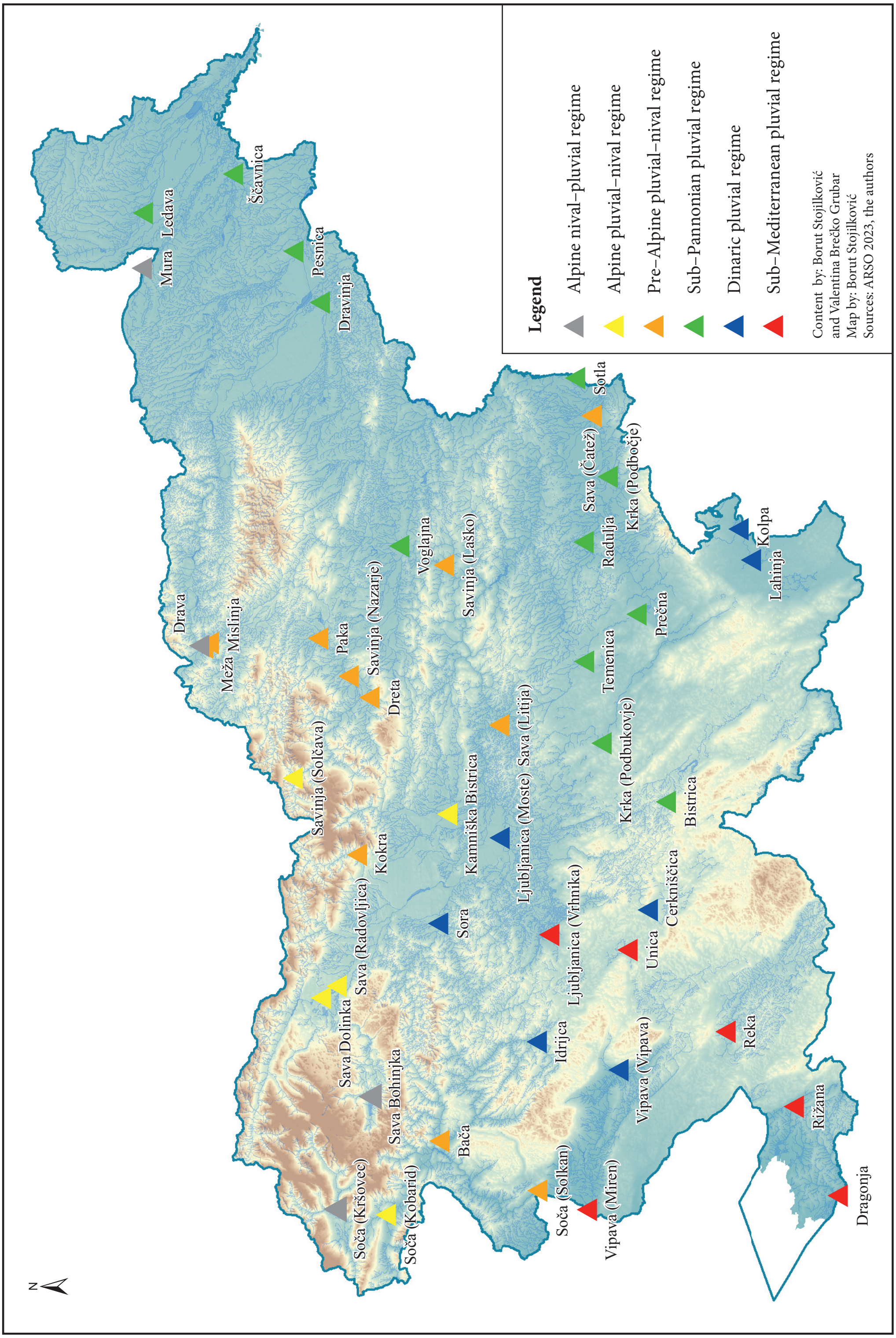
For most rivers, we also observed a variation between periods, with the 1971–2000 period showing lower or higher discharge coefficients than in the first and last periods. The reason for this is lower snow precipitation and snow residence (Hrvatin et al. 2020), as well as the rising share of forested land in Slovenia (Hrvatin and Zorn 2017a). Land use in particular is another factor that affects water discharge (Hrvatin and Zorn 2017a; Palmer and Ruhi 2019). From circa 1850 onwards, land use has changed greatly in Slovenia mainly due to political-economic evolution (Gabrovec and Kumer 2019). Still, more specifically, in the last two decades, land use has changed in many Slovenian regions following certain trends (Žiberna and Konečnik Kotnik 2020): arable land is getting smaller (from 13.2% to 11.6% in the period 2000–2020); in the vicinity of the cities it becomes built-up area due to suburbanisation, whereas in marginal areas firstly transform into pastures and then into forests. Unsustainable land use in areas of great flood hazard intensifies drastic responses in water resources (including runoff coefficient) in various areas in Slovenia (Žiberna 2014), which needs further empirical analysis, but exceeds the scope of this study.

4.2 Classification of discharge types in the period from 1991 to 2020

Based on the results, their analysis and the so-far literature (Hrvatin 1998; Frantar and Hrvatin 2005; Frantar and Hrvatin 2008), it is reasonable to divide the rivers and name the groups as suggested below and illustrated in Figure 11.

The first group (i.e. the Alpine rivers) should be split into two subgroups because the influence of the snow factor is more pronounced in the Mura, the Drava, the Sava Bohinjka and the Soča (Kršovec) than

Figure 11: Types of discharge regimes of Slovenian rivers (1991–2020). ➤ p. 28


Legend
Alpine nival–pluvial regime
Alpine pluvial–nival regime
Pre–Alpine pluvial–nival regime
Sub–Pannonian pluvial regime
Dinaric pluvial regime
Sub–Mediterranean pluvial regime
Content by: Borut Stojilković and Valentina Brečko Grubar
Map by: Borut Stojilković
Sources: ARSO 2023, the authors
N
Ledava
Ščavnica
Mura
Pesnica
Dravinja
Drava
Mislinja
Meža
Paka
Savinja (Nazarje)
Dreta
Voglajna
Savinja (Laško)
Sotla
Sava (Čatež)
Krka (Podbočje)
Radulja
Kolpa
Lahinja
Temenica
Prečna
Savinja (Solčava)
Sava (Litija)
Krka (Podbukovje)
Kamniška Bistrica
Ljubljanica (Moste)
Bistrica
Kokra
Sora
Ljubljanica (Vrhnika)
Cerkniščica
Unica
Sava (Radovljica)
Sava Dolinka
Sava Bohinjka
Idrijca
Vipava (Vipava)
Reka
Bača
Soča (Kršovec)
Soča (Kobarid)
Soča (Solkan)
Vipava (Miren)
Rižana
Dragonja

in the other rivers. The discharge regime of this group should be called **Alpine nival-pluvial regime** (si. *alpski snežno-dežni režim*), as in the classification of the discharge regimes for the period 1971–2000 (Frantar and Hrvatin 2005; Frantar and Hrvatin 2008).

For the other Alpine rivers, the influence of the rain factor is stronger or the snow factor is weaker and the label **Alpine pluvial-nival regime** (si. *alpski dežno-snežni režim*) would be more appropriate for their discharge regimes. This could lead to confusion when comparing the proposed classification with the previous classification, i.e. of Frantar and Hrvatin (2005; 2008), where rivers with an alpine pluvial-nival discharge regime are identified as rivers of our second group (i.e. pre-Alpine rivers of northern and western Slovenia).

For the next group, the influence of the snow factor is still evident and we suggest retaining the definition of the predominant pluvial-nival regime as in the previous classification (Frantar and Hrvatin 2005; Frantar and Hrvatin 2008) but referring to it by a different name. Given that the catchment hinterland is morphology-wise largely comprised of the hills or lower mountains and intermediate basins, we suggest its name to be **pre-Alpine pluvial-nival regime** (si. *predalpski dežno-snežni režim*).

The rivers of the third group (i.e. sub-Pannonian rivers of north-eastern and south-eastern Slovenia) have almost no winter low and could be classified as a rain-fed discharge regime. Given the established naming of the macro-regions of Slovenia (Žiberna et al. 2004), the name **sub-Pannonian pluvial regime** (si. *obpanonski dežni režim)* is appropriate.

Similar changes were also identified for the rivers of the fourth group (of the Dinaric rivers of central and southern Slovenia), which can be classified as having a pluvial regime, hence the **Dinaric pluvial regime** (si. *dinarski dežni režim)*.

Lastly, we confirm the fifth group to keep its category of a pluvial regime, but – given the widely accepted current regionalisation of Slovenia as well as accordance with regime classifications of neighbouring countries (Čanjevac 2013; Čanjevac and Orešić 2018) and lacking true Mediterranean climatological and hydrological characteristics (Skoulikidis et al. 2022) – the name **sub-Mediterranean pluvial regime** (si. *obsredozemski dežni režim)*.

5 Conclusion

Given the need to fill the gap in consecutive discharge regime analyses of Slovenian rivers after the monitoring period of 1991–2020 ended, it was essential to check if the streams still resemble the discharge characteristics they once had and if they cluster similarly. Hence the literature review on the topic in this paper was followed by completing the major aims of analysing the discharge data, determining as well as describing the clusters, and briefly summarising the changes and reasons for them.

Physical geographical characteristics changed in Slovenia in the last three decades significantly. That has been observed for climate (Ogrin et al. 2023) as well as it can be confirmed for river discharge. Minimising the snow residence effect, movement of the Mediterranean precipitation influence eastward and for other factors, discharges of many rivers have lost their nival component being a result of extremely short winter snow residence period, rain being the sole and major factor affecting their peaks and lows. As a result, five spatially most homogenous groups are present, the first including two discharge regime types, and the rest one: Alpine rivers (Alpine nival-pluvial and Alpine pluvial nival regimes), pre-Alpine rivers of northern and western Slovenia (with pre-Alpine pluvial-nival regime), sub-Pannonian rivers of north-eastern and south-eastern Slovenia (with sub-Pannonian pluvial regime), Dinaric rivers of central and southern Slovenia (with Dinaric pluvial regime), and Rivers of south-western Slovenia (with sub-Mediterranean pluvial regime).

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