CLIMATE AND HYDROLOGICAL CHANGES IN SLOVENIA'S MOUNTAIN REGIONS BETWEEN 1961 AND 2018

KLIMATSKE I HIDROLOŠKE PROMJENE U PLANINSKIM REGIJAMA SLOVENIJE IZMEĐU 1961. I 2018./PODNEBNE IN HIDROLOŠKE SPREMEMBE V GORSKEM SVETU SLOVENIJE MED LETOMA 1961 IN 2018

Mauro HRVATIN
Research Centre of the Slovenian
Academy of Sciences and Arts
Anton Melik Geographical Institute
Gosposka ulica 13
SI – 1000 Ljubljana, Slovenia
mauro.hrvatin@zrc-sazu.si

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Matija ZORN
Research Centre of the Slovenian
Academy of Sciences and Arts
Anton Melik Geographical Institute
Gosposka ulica 13
SI – 1000 Ljubljana, Slovenia
matija.zorn@zrc-sazu.si

Summary

This article examines various annual trends in climate and hydrological changes in Slovenia's mountain regions between 1961 and 2018. Climate changes are primarily reflected in the increase in average annual temperatures and significantly decreased duration of snow cover, and hydrological changes in the decrease in the minimum and mean annual discharge, whereas the maximum discharge is increasing in some places. Among the factors affecting the reduction in the annual water volume in rivers, land-use changes (i.e., increased forest cover) especially stand out. In addition to the water volume, rivers' discharge regimes are also changing. In nearly all locations, the autumn maximum discharge now exceeds the spring maximum discharge, which was once one of the basic characteristics of mountain snow-rain discharge regimes.

Keywords: climate geography, hydrogeography, climate changes, hydrological changes, discharge regimes, land-use changes, Alps

Ključne riječi: klimatska geografija, hidrogeografija, klimatske promjene, hidrološke promjene, pretočni režimi, promjene namjene tla, Alpe

Ključne besede: podnebna geografija, geografija voda, podnebne spremembe, hidrološke spremembe, pretočni režimi, spremembe rabe tal, Alpe

1 INTRODUCTION[1]

Many studies have shown that both climate changes[2] and hydrological changes[3] have occurred in recent decades. In this regard, Slovenia[4] and its mountains are no exception. In recent years, some observations were published on climate and hydrological trends in Slovenia's mountains[5] and parts of the pre-alpine hills[6] for the period from 1961 to 2010. The most obvious change has been an increase in average annual temperature, a decrease in the number of days with snow cover, and a decrease in the mean annual discharge. This article expands the period studied by nearly a decade, covering 1961 to 2018.

The area examined roughly corresponds with the Slovenian sub-macroregion of alpine mountains,[7] which comprises the mesoregions of the Julian Alps, Kamnik–Savinja Alps, Western Karawanks, and Eastern Karawanks. The first two are split by deep valleys shaped by glaciers, and on their margins are distinctly karstified and forested plateaus. The Karawanks are an elongated chain with high mountains only in their western and central parts, descending to hills to the east. The area corresponds to nearly a sixth of Slovenian territory with an average elevation of 1,054.5 m and an average inclination of 24.6°.[8] The climate is predominantly mountainous.[9] A common characteristic of the mountain climate is that average temperatures are below −3 °C in the coldest month and above 10 °C in the hottest month. Such conditions predominate above an elevation of about 1,600 m, which is also the upper limit of the alpine tree line. The precipitation regime can be divided into two parts: the mountainous area in western Slovenia with a sub-Mediterranean regime and annual precipitation between 1,600 and 3,000 mm, and the mountainous area in northern Slovenia with a moderate continental regime and annual precipitation between 1,100 and 1,700 mm.[10] With regard to lithology, limestone predominates (over 50% of the area), and over 70% is forested.[11]

2 METHODS

To determine the trend of change in selected climate and hydrological variables (Table 1) between 1961 and 2018, the Mann-Kendall test and Theil-Sen estimator (also known as Sen's slope estimator) were used at selected temperature, precipitation, and gauging stations (Tables 2 and 3, Figure 1). The Mann-Kendall test is a nonparametric test used to detect monotonic trends. It is not sensitive to outliers in the data and is based on the test statistics. A positive test statistic implies an increasing trend and a negative test statistic indicates a decreasing trend. Sen's slope estimator is the most frequent nonparametric test used for detecting linear time trends.[12] It is more accurate for asymmetric data distribution

1 Acknowledgments: This study was conducted as part of the research program The Geography of Slovenia (P6-0101), financed by the Slovenian Research Agency.

2 E.g.: ClimateChangePost; Ogrin, "Spreminjanje temperature zraka"; Sušnik, *Spremembe podnebja*; Kajfež-Bogataj, "Podnebne spremembe"; Dolinar, *Spremenljivost podnebja*; Dolinar and Vertačnik, "Spremenljivost temperaturnih"; Kajfež-Bogataj et al., "Spremembe agro-klimatskih spremenljivk"; Žiberna, "Podnebne spremembe"; Milošević et al., "Analysis of the climate … Part I; Milošević et al., "Analysis of the climate … Part II"; De Luis et al., "Trends in seasonal precipitation"; Gabrovec et al., *Triglavski ledenik*; Ogrin, "Tendence spreminjanja podnebja"; Tošić et al., "Annual and seasonal variability"; Milošević et al., "Maximum temperatures"; Vertačnik and Bertalanič, *Podnebna spremenljivost*; Dolinar, *Ocena podnebnih sprememb*.

3 E.g.: Uhan, "Trendi velikih"; Ulaga, "Trendi spreminjanja pretokov"; Kobold, "Vpliv podnebnih sprememb"; Frantar et al., "Trend pretokov"; Ulaga et al., "Trends of river discharges"; Ulaga et al., "Analiza časovnih sprememb"; Kobold et al., "Spremembe vodnega režima"; Janža, "Impact assessment"; Kovačič et al., "Vpliv podnebnih sprememb"; Makor, "Trendi spreminjanja pretokov"; Hrvatin and Zorn, "Trendi temperatur in padavin"; Hrvatin and Zorn, "Trendi pretokov rek"; Hrvatin and Zorn, "Recentne spremembe"; Hrvatin and Zorn, "Hidrološki odraz podnebnih."

4 See footnotes 2 and 3.

5 Hrvatin and Zorn, "Trendi pretokov rek"; Hrvatin and Zorn, "Recentne spremembe."

6 Hrvatin and Zorn, "Trendi temperatur in padavin."

7 Perko, "The regionalization."

8 Perko and Kladnik, "Nova regionalizacija."

9 Ogrin, "Podnebni tip", 47.

10 Ibid., 52.

11 Petek, *Spremembe rabe tal*.

12 Kraner Šumenjak and Šuštar, "Parametrični in neparametrični."

Climate variables	Average annual air temperature
	Annual precipitation
	Annual days with precipitation over 0.1 mm
	Annual days with snow cover
Hydrological variables	Minimum annual discharge
	Mean annual discharge
	Maximum annual discharge

Table 1: *Climate and hydrological variables examined.*

than linear regression, and for normal data distribution it yields results that are completely comparable to least squares.[13]

The free online software MAKESENS 1.0 (Mann-Kendall test for trend and Sen's slope estimates)[14] was used to calculate the Mann-Kendall test and Sen's slope estimator values.

In addition to the Mann-Kendall test and Sen's slope values, the tables with climate and hydrological variables also show the confidence levels, the (initial) 1961 trend value, the (final) 2018 trend value, and absolute and relative trend differences.

In statistics, the confidence level is the probability of the confidence interval calculated containing the true value of an estimated parameter. In this case, a higher confidence level indicates a higher probability that the increasing or decreasing trend of a selected variable detected actually exists.

The initial 1961 trend value represents the value of a selected variable in 1961 read from the trend line, and the final 2018 trend value is the value of a selected variable in 2018 read from the trend line.

The absolute trend difference is the difference between the final and initial trend values, and the relative trend difference is the difference between the final and initial trend values expressed in percentage.

The trend value per year can be calculated using the following equation:

trend value per year x = Sen's slope* (trend year x − initial trend year) + initial trend value.

3 DATA

3.1 Climate data

Climate data were obtained from the Slovenian Environment Agency.[15] The analysis included eight temperature and twelve precipitation stations in Slovenian Alps (Table 2, Figure 1) that had measured data spanning several decades.

3.2 Hydrological data

Hydrological data were obtained from the Slovenian Environment Agency.[16] The analysis included twelve stations in Slovenian Alps (Table 3, Figure 1) that had measurement data spanning several decades.

4 RESULTS

4.1 Climate variables

The following were analyzed in terms of climate variables (Table 1): 1) average annual air temperature trends, 2) annual precipitation trends, 3) trends in annual days with precipitation over 0.1 mm, and 4) trends in annual days with snow cover.

13 Kovačič, "Trendi pretokov rek"; Kovačič et al., "Vpliv podnebnih sprememb"; Hrvatin and Zorn, "Trendi temperatur in padavin", 11; Hrvatin and Zorn, "Trendi pretokov rek", 15.
14 Salmi et al., *Detecting trends*; Finnish, "MAKESENS."
15 Agencija, "Arhiv meteoroloških podatkov."
16 Agencija, "Arhiv hidroloških podatkov."

Table 2: *Weather stations with the time series analyzed.*

	Weather station	Municipality	Elevation (m)	Time series	No. of annual measurements
Temperature station	Bovec	Bovec	450	1961–2010	50
	Kredarica	Kranjska Gora	2,513	1961–2018	58
	Krvavec	Cerklje na Gorenjskem	1,740	1961–2018	55
	Lesce	Radovljica	515	1961–2018	56
	Mozirje	Mozirje	340	1961–2010	50
	Planina pod Golico	Jesenice	947	1961–2012	52
	Rateče	Kranjska Gora	864	1961–2018	58
	Šmartno pri Slovenj Gradcu	Slovenj Gradec	444	1961–2018	58
Precipitation station	Bohinjska Bistrica	Bohinj	507	1961–2018	57
	Javorniški Rovt	Jesenice	940	1961–2018	58
	Kamniška Bistrica	Kamnik	610	1961–2018	56
	Koprivna	Črna na Koroškem	840	1961–2017	57
	Kredarica	Kranjska Gora	2,513	1961–2018	58
	Mislinja	Mislinja	589	1961–2018	58
	Podljubelj	Tržič	679	1961–2018	57
	Podpeca	Črna na Koroškem	950	1961–2018	57
	Rateče	Kranjska Gora	864	1961–2018	58
	Šmartno pri Slovenj Gradcu	Slovenj Gradec	444	1961–2018	58
	Soča	Bovec	487	1961–2018	58
	Solčava	Solčava	658	1961–2018	58

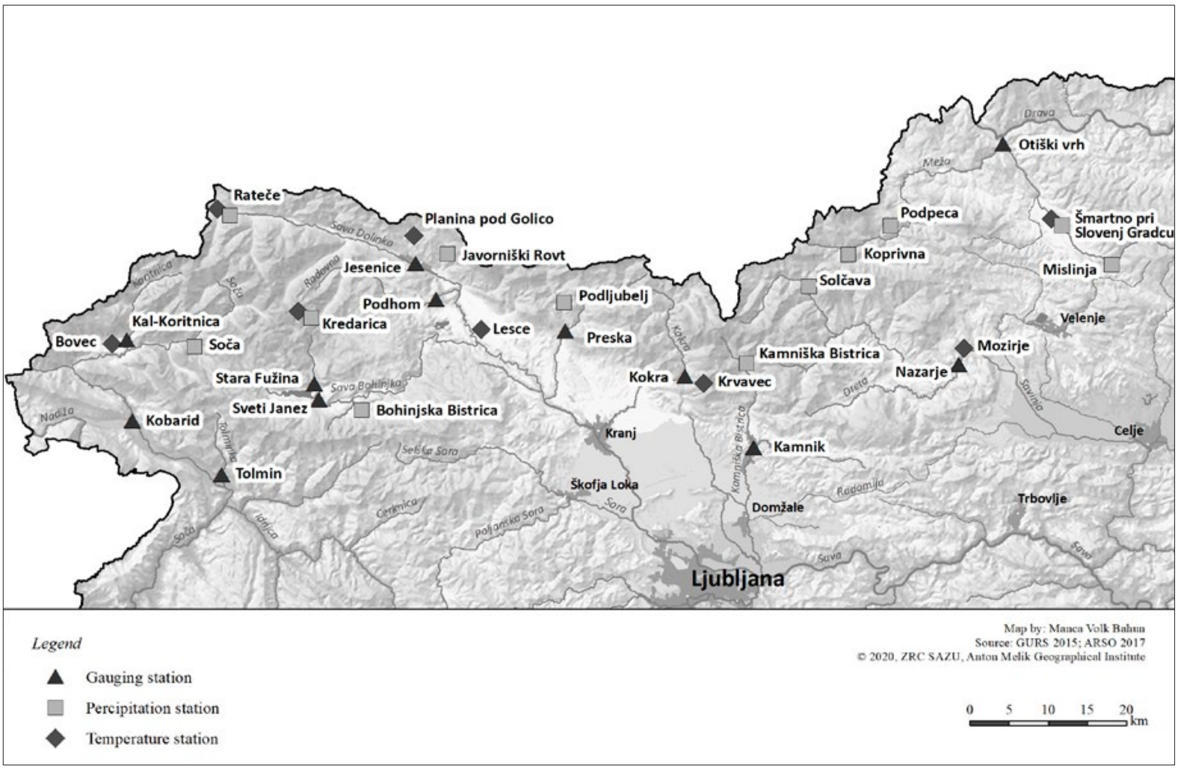

Figure 1: *Locations of temperature, precipitation, and gauging stations included in the analysis.*

Table 3: *Rivers with the time series analyzed.*

River	Gauging station	Municipality	Elevation (m)	Time series	No. of annual measurements	Drainage area (km²)	Mean annual discharge (1961–2018) (m³/s)
Kamniška Bistrica	Kamnik	Kamnik	371	1961–2018	54	194.79	7.33
Kokra	Kokra	Preddvor	523	1961–2018	56	112.34	4.28
Koritnica	Kal-Koritnica	Bovec	405	1961–2017	56	86.04	7.18
Meža	Otiški Vrh	Dravograd	334	1961–2018	58	550.89	12.38
Mostnica	Stara Fužina	Bohinj	527	1961–2018	49	74.26	3.19
Radovna	Podhom	Gorje	566	1961–2018	56	166.79	7.96
Sava Bohinjka	Sveti Janez	Bohinj	525	1961–2018	58	93.99	7.94
Sava Dolinka	Jesenice	Jesenice	566	1961–2013	51	257.56	10.59
Savinja	Nazarje	Nazarje	337	1961–2018	58	457.30	16.60
Soča	Kobarid	Kobarid	195	1961–2018	58	437.02	33.75
Tolminka	Tolmin	Tolmin	168	1961–2018	53	73.08	7.90
Tržiška Bistrica	Preska	Tržič	489	1961–2018	56	121.00	4.95

Table 4: *Average annual air temperature trends, 1961–2018. The trend difference in percentage is calculated based on the absolute (Kelvin) temperature scale.*

Temperature station	Mann-Kendall test	Confidence level	Sen's slope	1961 trend value	2018 trend value	1961–2018 trend difference	1961–2018 trend difference
	Z	%	*Q*	°C	°C	°C	%
Bovec	4.63	99.9	0.032	8.83	10.65	1.82	0.65
Kredarica	5.59	99.9	0.036	–2.22	–0.19	2.03	0.75
Krvavec	4.27	99.9	0.029	2.60	4.26	1.66	0.60
Lesce (Figure 2)	6.11	99.9	0.042	7.38	9.78	2.40	0.85
Mozirje	4.53	99.9	0.036	8.54	10.59	2.05	0.73
Planina pod Golico	4.85	99.9	0.032	5.60	7.42	1.82	0.65
Rateče	6.43	99.9	0.041	5.22	7.55	2.33	0.84
Šmartno pri Slovenj Gradcu	6.64	99.9	0.044	7.07	9.57	2.50	0.89

4.1.1 Average annual air temperature

The average annual air temperature trends from 1961 to 2018 were similar at all eight temperature stations examined, and they indicate a clear increasing trend (Table 4, Figure 2). There is also an exceptionally high confidence level, which is 99.9% at all temperature stations.

During the period studied, the temperature at the Bovec, Kredarica, and Lesce stations (Figure 2) and at the Mozirje, Planina pod Golico, and Rateče stations annually rose by an average of 0.032 to 0.042 °C, which means that in the last half century temperatures at these stations have increased by 1.82 to 2.40 °C. The absolute temperature difference from 1961 to 2018 was greatest at the Šmartno pri Slovenj Gradcu station, where the temperature rose by 2.50 °C (annually by 0.044 °C), and the least at the Krvavec station, where the temperature rose by 1.66 °C (annually by 0.029 °C).

4.1.2 Annual precipitation

In contrast to the increasing temperature trends, the annual precipitation trends from 1961 to 2018 indicate a decreasing trend at nine of the twelve precipitation stations studied (Table 5, Figure 3). The

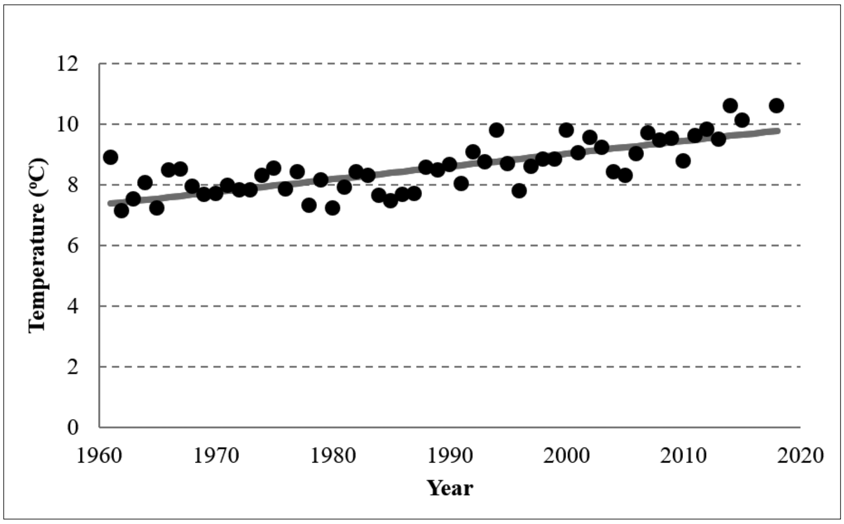

Figure 2: *Average annual temperature trend at the Lesce temperature station, 1961–2018.*

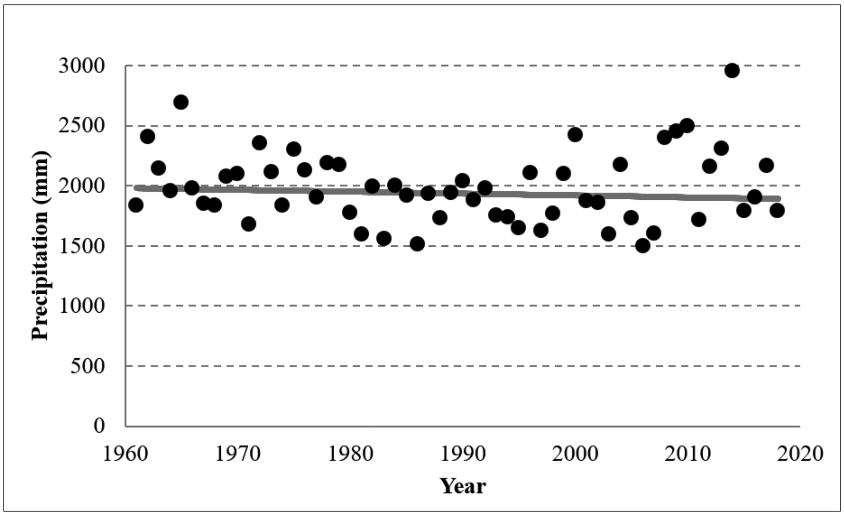

Figure 3: *Annual precipitation trend at the Javorniški Rovt precipitation station, 1961–2018.*

Table 5: *Annual precipitation trends, 1961–2018.*

Precipitation station	Mann-Kendall test	Confidence level	Sen's slope	1961 trend value	2018 trend value	1961–2018 trend difference	1961–2018 trend difference
	Z	%	*Q*	mm	mm	mm	%
Bohinjska Bistrica	–1.66	90.0	–5.730	2200.81	1874.18	–326.63	–14.84
Javorniški Rovt (Figure 3)	–0.59	< 90.0	–1.568	1979.99	1890.61	–89.38	–4.51
Kamniška Bistrica	–0.59	< 90.0	–1.854	2150.82	2045.15	–105.66	–4.91
Koprivna	–0.23	< 90.0	–0.370	1506.04	1484.95	–21.09	–1.40
Kredarica	1.36	< 90.0	3.370	1957.96	2150.08	192.12	9.81
Mislinja	–0.80	< 90.0	–1.014	1248.93	1191.14	–57.80	–4.63
Podljubelj	–3.56	99.9	–7.192	1976.88	1566.96	–409.92	–20.74
Podpeca	0.34	< 90.0	0.536	1429.73	1460.26	30.53	2.14
Rateče	–1.03	< 90.0	–1.624	1567.89	1475.32	–92.57	–5.90
Soča	0.89	< 90.0	3.870	2309.42	2530.04	220.62	9.55
Solčava	–1.80	90.0	–2.822	1619.07	1458.21	–160.87	–9.94
Šmartno pri Slovenj Gradcu	–0.36	< 90.0	–0.482	1179.12	1151.63	–27.49	–2.33

confidence level is very modest because at nine stations it does not even reach 90%. It is 90% at the Bohinjska Bistrica and Solčava stations, and 99.9% at the Podljubelj station.

During the period studied, annual precipitation at the Bohinjska Bistrica, Podljubelj, and Solčava stations decreased annually by an average of 3 to 7 mm, which means that at these stations precipitation decreased by 161 to 410 mm or by 10 to 21%. The absolute difference in precipitation was the greatest at the Podljubelj station, where precipitation fell by 409.92 mm or 20.7%.

An approximately 5% decrease in annual precipitation was recorded at the Javorniški Rovt (Figure 3), Kamniška Bistrica, Mislinja, and Rateče stations, whereas at the Koprivna, Podpeca, and Šmartno pri Slovenj Gradcu stations there were only mild trend deviations in a negative or positive direction.

An increasing trend in annual precipitation from 1961 to 2018 was recorded at the Kredarica (+192.12 mm) and Soča (+220.62 mm) stations. At both stations precipitation increased by nearly 10%.

4.1.3 Annual days with precipitation over 0.1 mm

From 1961 to 2018, the annual number of days with precipitation over 0.1 mm increased at five precipitation stations, decreased at five, and remained the same at two (Table 6, Figure 4). The confidence level varies greatly: at eight of the stations it does not even reach 90%, at the Bohinjska Bistrica station it reaches 95%, and at the Kamniška Bistrica, Koprivna, and Podpeca stations 99.9%.

At the majority of precipitation stations–Javorniški Rovt, Kredarica, Mislinja, Podljubelj (Figure 4), Rateče, Soča, Solčava, and Šmartno pri Slovenj Gradcu–the negative or positive trends of deviation were smaller and do not reach 10%. A decrease in the annual number of days with precipitation greater than 0.1 mm is clearly evident only at the Podpeca station (–27.22 days or –17.36%), and the increase in the annual number of days with precipitation exceeding 0.1 mm is greatest at the stations at Kamniška Bistrica (35.01 days or 26.43%), Koprivna (27.14 days or 23.08%), and Bohinjska Bistrica (18.04 days or 15.29%).

4.1.4 Annual days with snow cover

The number of days with snow cover greatly decreased at eleven of the twelve precipitation stations between 1961 and 2018 (Table 7, Figure 5). The only exception is the high mountain precipitation station on Mount Kredarica, which registered a slight decrease. With the exception of the Kredarica station, the confidence level is very high everywhere, reaching 99.0 or 99.9%.

Table 6: *Trends in annual days with precipitation, 1961–2018.*

Precipitation station	Mann-Kendall test	Confidence level	Sen's slope	1961 trend value	2018 trend value	1961–2018 trend difference	1961–2018 trend difference
	Z	%	*Q*	Days	Days	Days	%
Bohinjska Bistrica	2.32	95.0	0.316	118.00	136.04	18.04	15.29
Javorniški Rovt	–0.13	< 90.0	0.000	160.00	160.00	0.00	0.00
Kamniška Bistrica	3.38	99.9	0.614	132.43	167.43	35.01	26.43
Koprivna	3.37	99.9	0.476	117.62	144.76	27.14	23.08
Kredarica	0.75	< 90.0	0.114	171.04	177.56	6.51	3.81
Mislinja	–1.60	< 90.0	–0.200	139.10	127.70	–11.40	–8.20
Podljubelj (Figure 4)	0.07	< 90.0	0.000	154.00	154.00	0.00	0.00
Podpeca	–3.35	99.9	–0.478	156.82	129.60	–27.22	–17.36
Rateče	0.69	< 90.0	0.071	146.93	151.00	4.07	2.77
Soča	–1.53	< 90.0	–0.158	142.92	133.92	–9.00	–6.30
Solčava	–1.03	< 90.0	–0.111	152.94	146.61	–6.33	–4.14
Šmartno pri Slovenj Gradcu	–1.75	90.0	–0.250	150.38	136.13	–14.25	–9.48

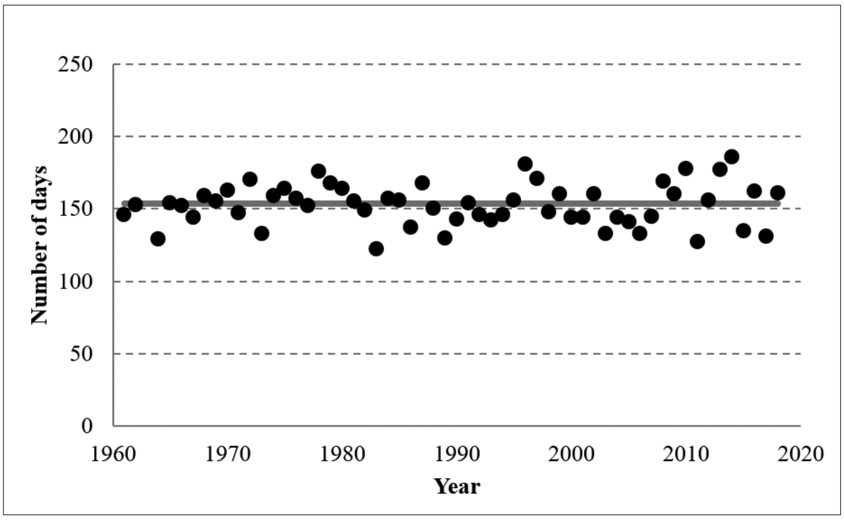

Figure 4: *Trends in annual days with precipitation at the Podljubelj precipitation station, 1961–2018.*

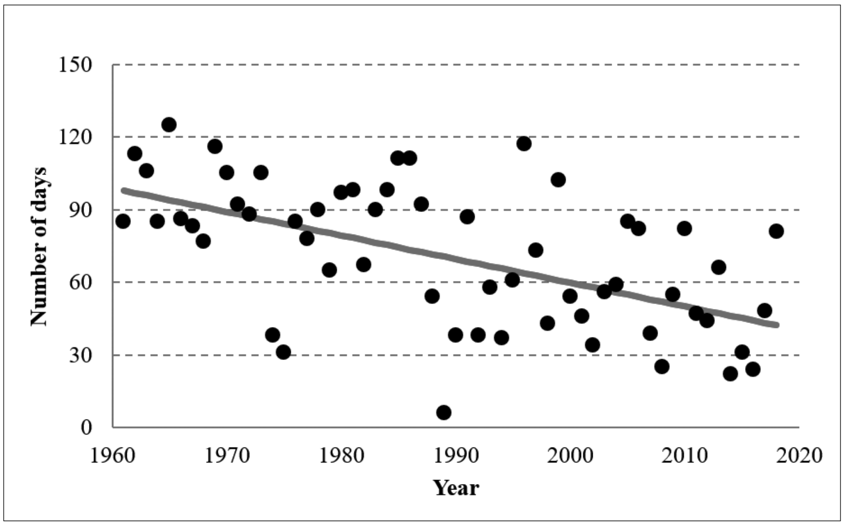

Figure 5: *Trend in annual days with snow cover at the Šmartno pri Slovenj Gradcu precipitation station, 1961–2018.*

Table 7: *Trends in the annual days with snow cover, 1961–2018.*

Precipitation station	Mann-Kendall test	Confidence level	Sen's slope	1961 trend value	2018 trend value	1961–2018 trend difference	1961–2018 trend difference
	Z	%	Q	Days	Days	Days	%
Bohinjska Bistrica	–2.62	99.0	–0.781	98.37	53.86	–44.50	–45.24
Javorniški Rovt	–3.83	99.9	–0.792	133.77	88.65	–45.13	–33.73
Kamniška Bistrica	–3.77	99.9	–0.975	83.60	28.03	–55.58	–66.48
Koprivna	–2.70	99.0	–0.549	139.57	108.82	–30.75	–22.03
Kredarica	–0.83	< 90.0	–0.125	267.38	260.25	–7.13	–2.66
Mislinja	–3.44	99.9	–0.758	111.05	67.86	–43.18	–38.89
Podljubelj	–3.25	99.0	–0.875	94.99	45.13	–49.86	–52.49
Podpeca	–3.50	99.9	–0.733	123.70	81.94	–41.75	–33.76
Rateče	–3.13	99.0	–0.643	143.50	106.86	–36.64	–25.54
Soča	–3.05	99.0	–0.813	91.84	45.53	–46.31	–50.43
Solčava	–3.87	99.9	–0.958	103.65	49.02	–54.63	–52.70
Šmartno pri Slovenj Gradcu (Figure 5)	–4.19	99.9	–0.975	97.84	42.26	–55.58	–56.80

Table 8: *Minimum annual discharge trends, 1961–2018.*

River	Gauging station	Mann-Kendall test	Confidence level	Sen's slope	1961 trend value	2018 trend value	1961–2018 trend difference	1961–2018 trend difference
		Z	%	*Q*	m³/s	m³/s	m³/s	%
Kamniška Bistrica	Kamnik	–2.11	95.0	–0.008	2.02	1.54	–0.48	–23.54
Kokra	Kokra	–1.39	< 90.0	–0.005	1.41	1.14	–0.27	–19.41
Koritnica	Kal-Koritnica	–1.21	< 90.0	–0.005	2.28	2.01	–0.27	–11.93
Meža (Figure 6)	Otiški Vrh	–3.42	99.9	–0.028	4.57	2.99	–1.58	–34.56
Mostnica	Stara Fužina	–0.25	< 90.0	–0.001	0.40	0.37	–0.03	–7.45
Radovna	Podhom	–0.47	< 90.0	–0.002	1.68	1.55	–0.12	–7.41
Sava Bohinjka	Sveti Janez	0.40	< 90.0	0.001	0.80	0.84	0.04	5.48
Sava Dolinka	Jesenice	–3.69	99.9	–0.035	4.69	2.70	–1.98	–42.32
Savinja	Nazarje	–3.31	99.9	–0.017	3.63	2.68	–0.94	–25.96
Soča	Kobarid	–0.12	< 90.0	–0.002	7.78	7.67	–0.11	–1.46
Tolminka	Tolmin	–1.81	90.0	–0.008	1.45	0.99	–0.46	–31.74
Tržiška Bistrica	Preska	–4.03	99.9	–0.016	2.49	1.59	–0.91	–36.35

During the period studied, the number of days with snow cover at the eleven precipitation stations with a distinctly decreasing trend fell by 30.75 to 55.58 days, or by 22.03 to 66.48%. The period with snow cover decreased by more than thirty days per year at the Koprivna and Rateče stations, by more than forty days at the Bohinjska Bistrica, Javorniški Rovt, Mislinja, Podljubelj, Podpeca, and Soča stations, and by more than fifty days at the Kamniška Bistrica, Solčava, and Šmartno pri Slovenj Gradcu (Figure 5) stations. The absolute negative difference in the number of days with snow cover was greatest at the Kamniška Bistrica and Šmartno pri Slovenj Gradcu stations, where the number of days with snow cover fell by 55.58 days, and the relative negative difference was the greatest at the Kamniška Bistrica station, where the number of days with snow cover decreased by 66.48%

On Mount Kredarica, which is the only precipitation station with a moderate decreasing trend, the number of days with snow cover from 1961 to 2018 decreased by 7.13 days or 2.66%.

4.2 Hydrological variables

The following were examined in terms of hydrological variables (Table 1): 1) minimum annual discharge trends, 2) mean annual discharge trends, and 3) maximum annual discharge trends.

4.2.1 Minimum annual discharge

The minimum annual discharge trends from 1961 to 2018 were decreasing on eleven of the twelve mountain rivers (Table 8, Figure 6). The trend difference was moderate only on the Mostnica, Radovna, Sava Bohinjka, and Soča rivers, and for all others it exceeded at least 10%.

The confidence level varies greatly. On seven rivers (the Kokra, Koritnica, Mostnica, Radovna, Sava Bohinjka, Soča, and Tolminka) it does not reach 90%, on the Kamniška Bistrica it is 95%, and on the four remaining rivers (the Meža, Sava Dolinka, Savinja, and Tržiška Bistrica) it attains 99.9%.

In relative terms, the Kamniška Bistrica, Kokra, Koritnica, and Savinja registered a decrease of 10 to 30%, and for the Meža (Figure 6), Sava Dolinka, Tolminka, and Tržiška Bistrica the decrease was as much as 30 to 50%. The greatest decrease was recorded for the Sava Dolinka at the Jesenice gauging station, where the minimum discharge between 1961 and 2018 decreased by 1.98 m³/s or 42.32%.

4.2.2 Mean annual discharge

The mean annual discharge trends from 1961 to 2018 were decreasing on all twelve rivers (Table 9, Figure 7). The confidence level was variable. For the Kokra, Meža, and Mostnica rivers it reached 99%,

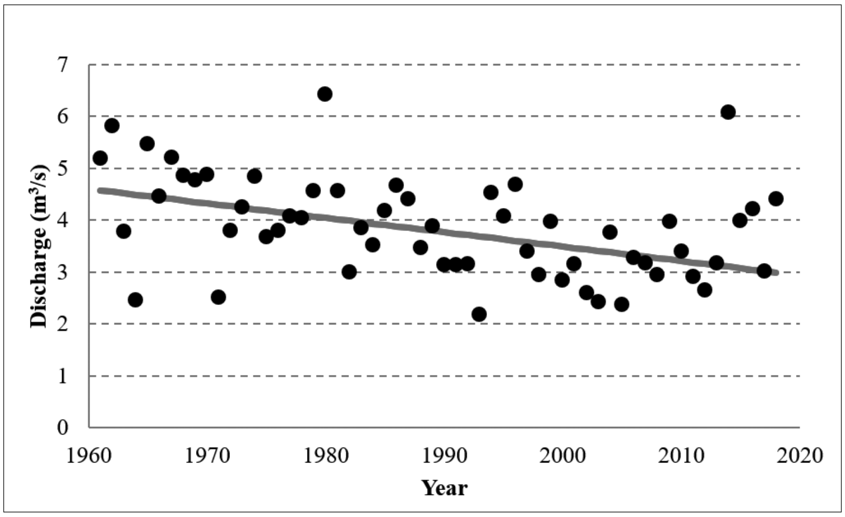

Figure 6: *Minimum annual discharge trend of the Meža at the Otiški Vrh gauging station, 1961–2018.*

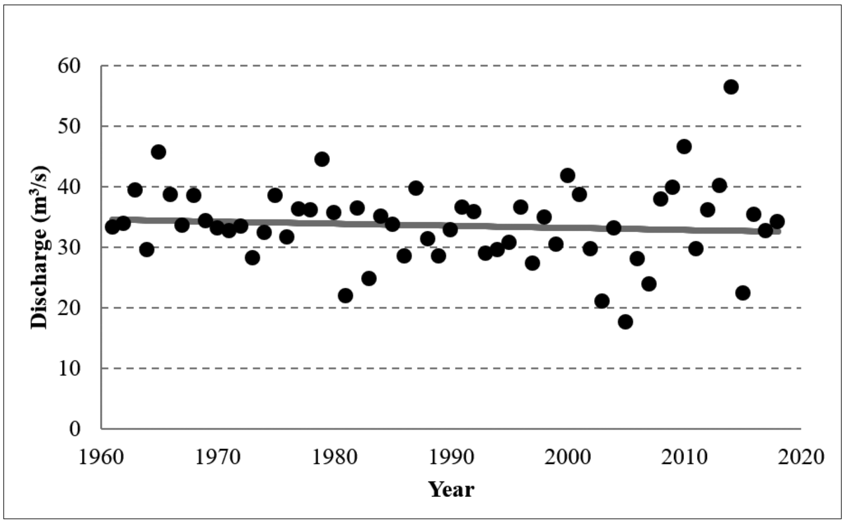

Figure 7: *Mean annual discharge trend of the Soča at the Kobarid gauging station, 1961–2018.*

Table 9: *Mean annual discharge trends, 1961–2018.*

River	Gauging station	Mann-Kendall test	Confidence level	Sen's slope	1961 trend value	2018 trend value	1961–2018 trend difference	1961–2018 trend difference
		Z	%	*Q*	m³/s	m³/s	m³/s	%
Kamniška Bistrica	Kamnik	–1.66	90.0	–0.018	7.75	6.74	–1.01	–13.06
Kokra	Kokra	–2.93	99.0	–0.020	4.85	3.73	–1.13	–23.26
Koritnica	Kal-Koritnica	–1.54	< 90.0	–0.018	7.58	6.53	–1.05	–13.85
Meža	Otiški Vrh	–2.84	99.0	–0.057	13.80	10.54	–3.26	–23.62
Mostnica	Stara Fužina	–2.64	99.0	–0.017	3.64	2.67	–0.97	–26.74
Radovna	Podhom	–1.56	< 90.0	–0.021	8.51	7.30	–1.20	–14.15
Sava Bohinjka	Sveti Janez	–2.35	95.0	–0.030	8.83	7.12	–1.72	–19.44
Sava Dolinka	Jesenice	–2.01	95.0	–0.045	11.79	9.23	–2.55	–21.66
Savinja	Nazarje	–1.11	< 90.0	–0.027	17.21	15.69	–1.52	–8.85
Soča (Figure 7)	Kobarid	–0.68	< 90.0	–0.035	34.54	32.58	–1.97	–5.69
Tolminka	Tolmin	–0.68	< 90.0	–0.006	7.74	7.39	–0.35	–4.54
Tržiška Bistrica	Preska	–1.75	90.0	–0.014	5.22	4.44	–0.78	–14.92

Table 10: *Maximum annual discharge trends, 1961–2018 (*until 2016 the station had only daily observations and is consequently less reliable for maximum annual discharge trend determination).*

River	Gauging station	Mann-Kendall test	Confidence level	Sen's slope	1961 trend value	2018 trend value	1961–2018 trend difference	1961–2018 trend difference
		Z	%	*Q*	m^3/s	m^3/s	m^3/s	%
Kamniška Bistrica	Kamnik	–2.06	95.0	–0.636	105.30	69.03	–36.27	–34.45
Kokra	Kokra	–1.15	< 90.0	–0.340	102.44	83.07	–19.38	–18.91
Koritnica	Kal-Koritnica	0.48	< 90.0	0.106	63.63	69.65	6.01	9.45
Meža	Otiški Vrh	–1.23	< 90.0	–0.501	143.27	114.69	–28.58	–19.95
Mostnica	Stara Fužina*	–2.18	95.0	–0.736	81.43	39.48	–41.95	–51.52
Radovna	Podhom	–0.43	< 90.0	–0.091	73.62	68.44	–5.18	–7.04
Sava Bohinjka	Sveti Janez	–0.44	< 90.0	–0.143	102.08	93.92	–8.15	–7.99
Sava Dolinka	Jesenice	0.80	< 90.0	0.262	70.81	85.72	14.91	21.05
Savinja	Nazarje	0.47	< 90.0	0.333	241.00	260.00	19.00	7.88
Soča	Kobarid	2.65	99.0	2.187	396.41	521.09	124.68	31.45
Tolminka	Tolmin*	0.51	< 90.0	0.109	74.17	80.40	6.24	8.41
Tržiška Bistrica (Figure 8)	Preska*	1.05	< 90.0	0.254	56.90	71.37	14.47	25.43

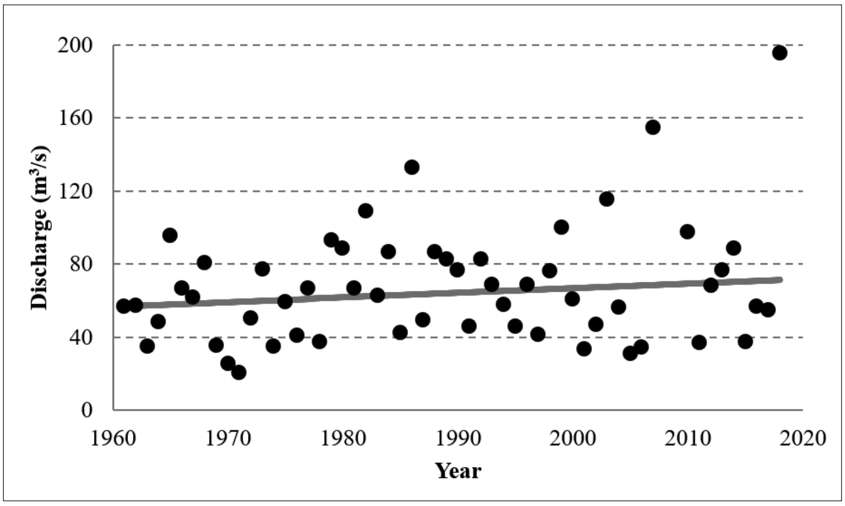

Figure 8: *Maximum annual discharge trend of the Tržiška Bistrica at the Preska gauging station, 1961–2018.*

for the Sava Bohinjka and Sava Dolinka it was 95%, and for the remaining rivers (the Kamniška Bistrica, Koritnica, Radovna, Savinja, Soča, Tolminka, and Tržiška Bistrica) it was less than 90%.

In relative terms the majority of watercourses recorded a decrease of 10 to 30%, and only for the Savinja, Soča, and Tolminka was this less than 10%. The absolute trend difference in the mean annual discharge from 1961 to 2018 was greatest for the Meža River at the Otiški Vrh gauging station, where the discharge decreased by 3.26 m^3/s, and the greatest relative trend difference was recorded for the Mostnica River at the Stara Fužina gauging station, where the discharge decreased by 26.74%.

4.2.3 Maximum annual discharge

The maximum annual discharge trends from 1961 to 2018 were decreasing on six rivers (the Kamniška Bistrica, Kokra, Meža, Mostnica, Radovna, and Sava Bohinjka), and there was an increasing trend for the remaining six (the Koritnica, Sava Dolinka, Savinja, Soča, Tolminka, and Tržiška Bistrica; Table 10, Figure 8). The confidence level is low because for ten of the rivers examined it does not reach

90%. Exceptions are the Mostnica at the Stara Fužina gauging station and the Kamniška Bistrica at the Kamnik gauging station with a 99% confidence level.

The maximum annual discharge during the period studied decreased the most on the Mostnica River (by 41.95 m^3/s or 51.52%) and the Kamniška Bistrica (by 36.27 m^3/s or 34.45%). A somewhat lower share of trend decrease was recorded for the Meža (−28.58 m^3/s or −19.95%), Kokra (−19.38 m^3/s or −18.91%), Sava Bohinjka (−8.15 m^3/s or −7.99%), and Radovna (−5.18 m^3/s or −7.04%).

A less than 10% relative increase in the maximum annual discharge was recorded for the Savinja (19.00 m^3/s or 7.88%), Tolminka (6.24 m^3/s or 8.41%), and Koritnica (6.01 m^3/s or 9.45%).

The maximum annual discharge increased the most for the Soča (124.68 m^3/s or 31.45%), Tržiška Bistrica (14.47 m^3/s or 25.43%; Figure 8), and Sava Dolinka (14.91 m^3/s or 21.05%).

4.3 Discharge regimes

Long-term changes in temperature and precipitation not only affect the volume of the minimum, mean, and maximum discharge, but also have a significant impact on changes in the discharge regime.[17] Among the climate indicators examined, changes in the number of days with snow cover seem especially important because they strongly affect all discharge regimes with an expressed snow share.

In classifying the discharge regimes based on the 1961–1990 data set,[18] the Sava Dolinka, Radovna, Sava Bohinjka, Mostnica, Kamniška Bistrica, Soča (at the Kobarid gauging station), Koritnica, and Tolminka ranked among the rivers with an alpine high mountain snow-rain regime, and the Meža, Tržiška Bistrica, Kokra, and Savinja (at the Nazarje gauging station) among the rivers with an alpine medium mountain snow-rain regime. For rivers with an alpine high mountain snow-rain regime, the main discharge maximum appeared in May or June, and the secondary discharge maximum in November. The main discharge minimum was in January or February, and the secondary discharge minimum in August. Rivers with an alpine medium mountain snow-rain regime had their main discharge maximum in April or exceptionally in May, and their secondary maximum in November. The winter (February or January) and summer (August) discharge minimums were equivalent.

A comparison of the discharge regimes based on the 1961–1990 data set with the discharge regimes based on the 1991–2018 data set primarily shows the following differences (Tables 11 and 12, Figure 9):

– For all rivers, except at the Bohinjska Bistrica gauging station, the main discharge maximum has shifted from spring to autumn;

– In many places, the summer (secondary) discharge minimum has already nearly approached the winter (main) minimum; for the Kokra and Meža rivers, the main discharge minimum already occurs in the summer, and for the Savinja this was already the case from 1961 to 1990;

– There is a strong increase in water in the autumn; December discharge is near the annual average or has even exceeded it, implying that winter is "running late."

The intensity of changes in the monthly discharge coefficients for individual rivers during the three-decade periods of 1961–1990 and 1991–2018 were also ascertained with the Pearson correlation coefficient (Table 11). The results indicate that the degree of correlation between both sets for the Meža, Savinja, and Sava Dolinka rivers are moderate (coefficients from 0.56 to 0.69), and high for the Tržiška Bistrica, Kokra, Radovna, Mostnica, Soča, Kamniška Bistrica, Koritnica, Tolminka, and Sava Bohinjka rivers (coefficients from 0.73 to 0.87). The lowest Pearson correlation coefficient values were found for the monthly discharge coefficients for the Meža (0.56) and Savinja (0.66), and the highest for the Sava Bohinjka (0.87) and Tolminka (0.86).

Changes in the monthly discharge regimes during the three-decade periods of 1961–1990 and 1991–2018 are shown in Table 12 (Figure 10). In the autumn months the amount of water in rivers is increasing. This is connected with rising temperatures and thus less snowfall and more rainfall in the mountains. Higher temperatures are also responsible that snowmelt in the mountains starts earlier causing e.g. the

[17] Hrvatin, "Pretočni režimi," 38; Frantar, "Pretočni režimi"; Frantar and Hrvatin, "Pretočni režimi"; Hrvatin and Zorn, "Trendi pretokov rek."
[18] Hrvatin, "Pretočni režimi," 86.

Table 11: *1961–1990 and 1991–2018 monthly discharge coefficients (white numbers in grey shading show the main (dark grey) and secondary minimums (light grey), and black numbers in grey shading show the main (dark grey) and secondary maximums (light grey)); the correlation between the two datasets is based on the Pearson correlation coefficient.*

River: Gauging station	Period	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Pearson
Kamniška Bistrica: Kamnik	1961–1990	0.70	0.69	0.76	1.12	1.45	1.46	1.08	0.76	0.86	1.06	1.22	0.84	0.78
	1991–2018	0.77	0.66	0.84	1.07	1.29	1.14	0.86	0.70	0.95	1.22	1.56	0.94	
Kokra: Kokra (Figure 9)	1961–1990	0.80	0.67	0.80	1.36	1.34	1.19	0.92	0.73	0.85	1.06	1.29	0.98	0.74
	1991–2018	0.81	0.66	0.89	1.20	1.07	0.94	0.80	0.65	0.88	1.13	1.71	1.26	
Koritnica: Kal-Koritnica	1961–1990	0.57	0.55	0.62	1.17	1.65	1.50	1.12	0.81	0.95	1.05	1.22	0.79	0.79
	1991–2018	0.72	0.58	0.70	1.02	1.31	1.15	0.99	0.74	1.00	1.36	1.52	0.92	
Meža: Otiški Vrh	1961–1990	0.66	0.73	1.07	1.53	1.20	1.10	1.01	0.75	0.93	1.00	1.17	0.86	0.56
	1991–2018	0.87	0.81	1.07	1.18	0.97	0.86	0.83	0.77	0.99	1.03	1.43	1.18	
Mostnica: Stara Fužina	1961–1990	0.54	0.48	0.75	1.50	1.80	1.32	0.77	0.73	1.00	1.04	1.38	0.69	0.77
	1991–2018	0.57	0.37	0.84	1.45	1.26	1.01	0.85	0.59	1.06	1.65	1.56	0.80	
Radovna: Podhom	1961–1990	0.51	0.44	0.60	1.35	1.80	1.42	1.01	0.81	1.03	1.11	1.18	0.74	0.76
	1991–2018	0.61	0.47	0.74	1.35	1.29	1.05	0.87	0.69	0.98	1.35	1.64	0.97	
Sava Bohinjka: Sveti Janez	1961–1990	0.39	0.30	0.40	1.09	2.27	1.85	1.02	0.78	1.09	1.03	1.20	0.58	0.87
	1991–2018	0.46	0.29	0.53	1.18	1.84	1.31	0.89	0.60	1.10	1.45	1.60	0.75	
Sava Dolinka: Jesenice	1961–1990	0.64	0.56	0.63	1.05	1.42	1.42	1.20	0.97	1.01	1.06	1.16	0.88	0.69
	1991–2018	0.80	0.61	0.69	0.97	1.12	1.10	1.04	0.87	0.91	1.26	1.54	1.10	
Savinja: Nazarje	1961–1990	0.72	0.70	0.96	1.48	1.40	1.18	0.86	0.66	0.83	1.03	1.25	0.92	0.66
	1991–2018	0.76	0.70	0.99	1.28	1.06	0.80	0.72	0.65	1.04	1.22	1.62	1.17	
Soča: Kobarid	1961–1990	0.58	0.52	0.66	1.20	1.69	1.48	0.98	0.75	0.99	1.10	1.28	0.79	0.78
	1991–2018	0.70	0.54	0.71	1.14	1.36	1.07	0.83	0.60	1.01	1.41	1.66	0.97	
Tolminka: Tolmin	1961–1990	0.58	0.52	0.66	1.14	1.84	1.60	0.89	0.64	0.90	1.13	1.33	0.77	0.86
	1991–2018	0.68	0.55	0.71	1.07	1.56	1.15	0.76	0.60	1.01	1.33	1.67	0.92	
Tržiška Bistrica: Preska	1961–1990	0.77	0.73	0.83	1.25	1.27	1.11	0.95	0.90	1.05	1.03	1.17	0.93	0.73

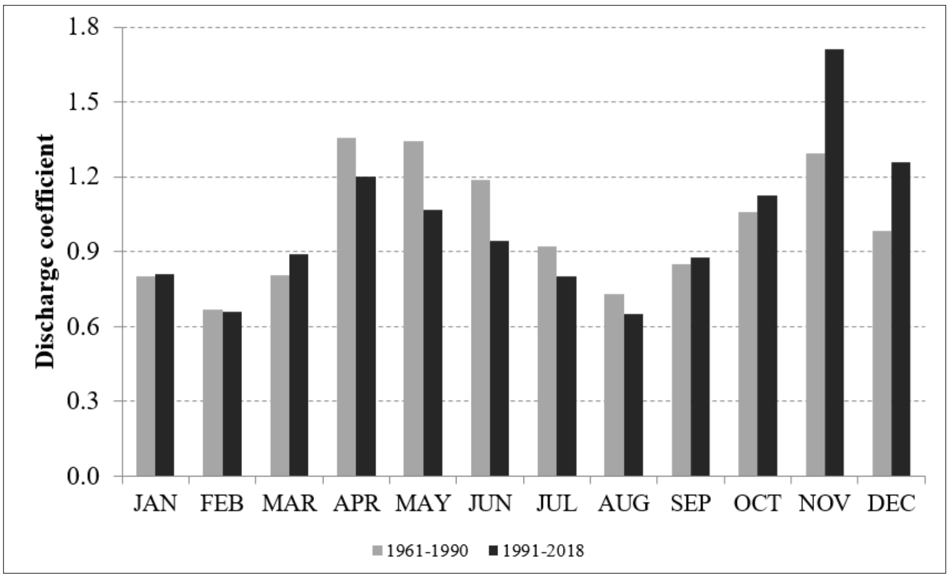

Figure 9: *Changes in the discharge regime of the Kokra at the Kokra gauging station between the 1961–1990 and 1991–2018 periods.*

Table 12: *Changes in the monthly discharge regimes between the 1961–1990 and 1991–2018 periods (white numbers indicate decreasing ratios and black numbers indicate increasing ratios; shading indicates the intensity – see legend).*

River: Gauging station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Kamniška Bistrica: Kamnik	0.07	−0.03	0.08	−0.05	−0.15	−0.32	−0.22	−0.06	0.09	0.16	0.34	0.11
Kokra: Kokra	0.01	−0.01	0.09	−0.16	−0.28	−0.25	−0.12	−0.08	0.03	0.07	0.42	0.28
Koritnica: Kal-Koritnica	0.14	0.04	0.07	−0.15	−0.33	−0.35	−0.13	−0.07	0.04	0.31	0.30	0.13
Meža: Otiški Vrh	0.20	0.09	0.00	−0.34	−0.23	−0.24	−0.18	0.02	0.06	0.03	0.26	0.32
Mostnica: Stara Fužina	0.03	−0.11	0.09	−0.06	−0.54	−0.30	0.08	−0.14	0.06	0.61	0.17	0.11
Radovna: Podhom	0.10	0.03	0.13	0.00	−0.51	−0.37	−0.14	−0.12	−0.05	0.24	0.46	0.23
Sava Bohinjka: Sveti Janez	0.06	−0.01	0.13	0.09	−0.43	−0.54	−0.13	−0.18	0.02	0.43	0.39	0.17
Sava Dolinka: Jesenice	0.16	0.04	0.06	−0.08	−0.30	−0.32	−0.17	−0.10	−0.10	0.20	0.38	0.22
Savinja: Nazarje	0.04	0.00	0.03	−0.21	−0.35	−0.37	−0.14	−0.01	0.21	0.19	0.36	0.24
Soča: Kobarid	0.12	0.02	0.06	−0.07	−0.33	−0.41	−0.15	−0.15	0.03	0.31	0.38	0.19
Tolminka: Tolmin	0.10	0.03	0.05	−0.06	−0.28	−0.45	−0.12	−0.04	0.10	0.19	0.34	0.15
Tržiška Bistrica: Preska	0.10	0.01	0.11	−0.07	−0.21	−0.14	−0.07	−0.13	−0.07	0.14	0.24	0.10

Legend:

> −0,50	−0,40 - −0,49	−0,30 - −0,39	−0,20 - −0,29	−0,10 - −0,19	−0,0 - −0,9	
0,0	0,05-0,09	0,10-0,19	0,20-0,29	0,30-0,39	0,40-0,49	< 0,5

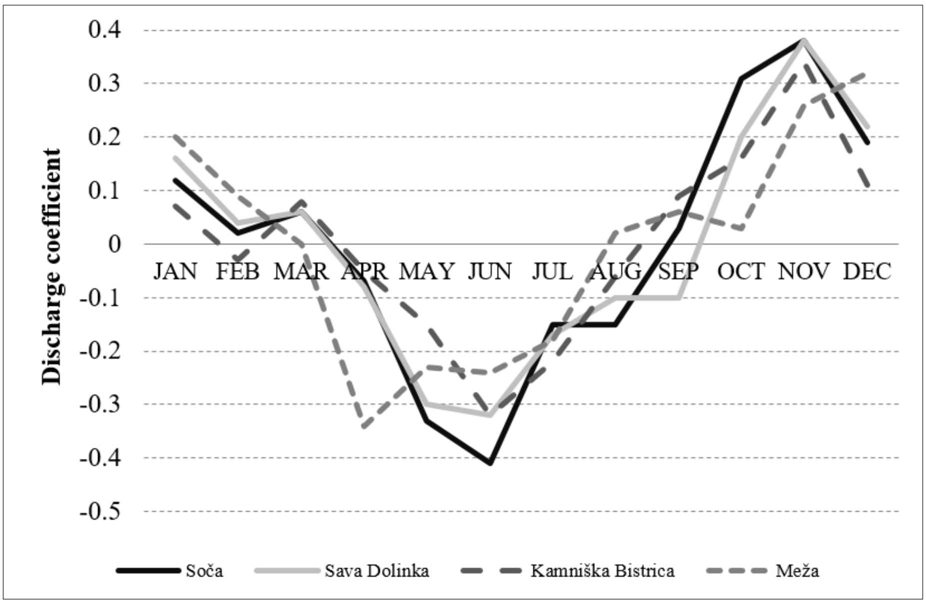

Figure 10: *Changes in the monthly discharge regimes between the 1961–1990 and 1991–2018 periods for selected rivers – from Soča River in the west to Meža River in the est.*

increasing amount of water in rivers in January. Consequently, as the snow mostly disappeared till late spring, there is less water in rivers during spring and summer.

4.4 Land use

In addition to a critical assessment of the hydrological changes presented, the factors that must be taken into account in a hydrological analysis of a selected area include analyses of changes in groundwater volume, the climate factors mentioned above, water use, and land use.[19] In recent decades land use has undergone rapid and extensive changes. In his study of land use in the Slovenian mountains, Petek[20] determined that conditions in 1953 were similar to those at the beginning of the twentieth century, but that in 1979 a considerable reduction in the share of tilled land, meadows, and pastures was already recorded in the land and property register, which was a consequence of industrialization and farms switching to market production.[21] Until 1999 the share of tilled land, meadows, and pastures decreased further, but less than in the previous period compared.[22]

Petek[23] drew attention to the fact that it is difficult to determine the actual reduction in area of agricultural land because the data in the land and property register were not regularly updated and were increasingly out of date. The data taken into account for 2020 are therefore no longer from the land and property register, but were obtained from records of actual use of agricultural and forest land at the Ministry of Agriculture, Forestry, and Food's geographical information system portal,[24] which is regularly updated every three months and thus regularly keeps records of changes in land use. The major difference in the share of forest between 1999 and 2020 (Table 13) is therefore not only a consequence of changes in land use but is also a consequence of a changed or improved methodology of gathering data.

Among the many changes in various land-use categories, the changes in the share of forested land stand out in particular (Table 13). Shortly after the Second World War, forest covered just under half of Slovenia's mountain territory, whereas today it covers over seven-tenths of the area. The most forested area is the Eastern Karawanks, where forest covers nearly nine-tenths of the land. More than three-quarters of the terrain is forested in the Savinja Alps, and more than seven-tenths in the Western Karawanks and the Sava area of the Julian Alps. The least forested is the Soča area of the Julian Alps, where the share of forest has just reached two-thirds.

The share of forested land is also very important from the perspective of hydrology because trees' interception of precipitation and their transpiration can significantly reduce the volume of water that reaches groundwater or surface watercourses. Coniferous trees intercept up to 20–40 %, and deciduous trees up to 20–25 % of precipitation; the higher the vegetation age, the higher the intercepted precipita-

Forest area	1953*	1979*	1999*	2020**
	%	%	%	%
Julian Alps, Soča area	28.7	34.4	39.8	66.7
Julian Alps, Sava area	51.1	54.5	57.0	72.4
Western Karawanks	54.4	58.8	60.7	73.8
Eastern Karawanks	52.7	76.4	77.3	88.9
Kamnik Alps	57.0	60.6	61.0	69.2
Savinja Alps	48.9	64.3	64.4	78.5
Mountain area, total	46.0	52.6	55.1	72.1

Table 13: *Change in share of forest by mountain unit in Slovenia, 1953–2020 (*per land and property register, **per records of actual use of agricultural and forest land*).*

* Ministrstvo, "Grafični podatki RABA."

19 Bat and Uhan, "Vode," 126.
20 Petek, *Spremembe rabe tal*, 113.
21 Ibid., 116.
22 Ibid., 119.
23 Ibid., 119.
24 Ministrstvo, "Grafični podatki RABA."

tion.[25] During the vegetation period it is necessary to take the influence of transpiration also into account in forested areas, due to which the annual loss of precipitation varies from 200 to 300 mm.[26]

5 CONCLUSION

The key findings about changes in the selected climate and hydrological variables between 1961 and 2018 largely overlap with the trends presented for Slovenia by other researchers.[27] They can be summarized as follows:

– The average annual air temperature at all eight temperature stations studied showed a statistically significant increase by an average of 2.0 °C. The smallest change was recorded at the Krvavec station, where the temperature rose by 1.7 °C, and the greatest at the Šmartno pri Slovenj Gradcu station, where the temperature rose by 2.5 °C.

– Annual precipitation decreased at nine precipitation stations, but the changes were mostly slight and did not exceed 10%. Statistical significance was only achieved at the Podljubelj station, with a decrease of 410 mm or 21%. An increasing trend in annual precipitation was observed at the Kredarica and Soča stations. At both of them precipitation increased by about 10%.

– The annual number of days with precipitation over 0.1 mm increased at five stations and decreased at five, and at Javorniški Rovt and Podljubelj it remained unchanged. There was a statistically significant increase in the number of days with precipitation in Bohinjska Bistrica, Kamniška Bistrica, and Koprivna, and a decrease in Podpeca.

– The annual number of days with snow cover saw a statistically significant decrease at eleven precipitation stations–by 31 to 56 days, or by 22 to 67% The only exception was the high-mountain station on Mount Kredarica, where the decrease was less than 3%.

– The minimum annual discharge trends were decreasing on eleven of the twelve mountain rivers. The trend difference was modest only for the Mostnica, Radovna, Sava Bohinjka, and Soča rivers, and for all the others it exceeded at least 10%.

– All of the mean annual discharge trends were decreasing, and in the majority of cases the rivers showed a discharge decrease between 10 and 25%. The trend difference was somewhat less pronounced only for the Savinja, Soča, and Tolminka rivers.

– The maximum annual discharge trends were decreasing on six rivers, and they also showed an increase on six rivers. There was a statistically significant decrease on the Kamniška Bistrica (−33%) and Mostnica (−44%) rivers, and an increase on the Soča (32%).

– In the period 1961–1990, mountain rivers had a distinctive snow-rain discharge regime. Because of snow retention, the discharge was the lowest in the winter and the main discharge maximum occurred in the spring due to melting snow. A secondary minimum followed in the summer and after that a secondary maximum due to autumn rain. In the period 1991–2018 the autumn maximum has exceeded the spring one on most mountain rivers, and the summer minimum has already become very close to the winter one.

– Because of the reduced volume and duration of snow cover and increasingly pronounced evapotranspiration there has been a perceptible decrease in the discharge in late spring and early summer, and a discharge increase between October and December, implying that because of the rising temperatures and thus less snowfall and more rainfall winter is “running late.”

– More than seven-tenths of Slovenia’s mountain territory is covered by forest, which through interception of precipitation and transpiration significantly reduces the volume of water that reaches groundwater and surface watercourses.

25 Šraj, “Določanje indeksa,” 106.
26 Smolej, *Gozdna hidrologija*, 198.
27 See footnotes 2 and 3.

POVZETEK

V prispevku obravnavamo različne letne trende podnebnih in hidroloških sprememb v gorskem svetu Slovenije med letoma 1961 in 2018. Prve se odražajo predvsem v rasti povprečne letne temperature in močno skrajšanem trajanju snežne odeje, pri drugih je opazno padanje minimalnih in srednjih letnih pretokov, maksimalni pretoki pa ponekod naraščajo. Med dejavniki, ki vplivajo na zmanjševanje letne količine vode v rekah posebej izpostavljamo spremembe rabe tal oziroma povečano gozdnatost. Poleg vodnih količin se pri rekah spreminjajo tudi pretočni režimi. Jesenski pretočni višek je že skoraj povsod presegel spomladanskega, ki je nekdaj spadal med temeljne značilnosti snežno-dežnih gorskih pretočnih režimov.

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Ivana Lučića 3, HR-10000 Zagreb
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Picture of Zadar from 1486 from the travelogue of Konrad von Grünemberg. View from the southwest. (From: Badische Landesbibliothek, Karlsruhe)

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