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FORTY YEARS LATER. CHANGES IN RAINFALL-RUNOFF PARAMETERS IN THE GOČ MOUNTAINS, SERBIA: CLIMATE CHANGE OR SIMPLY THE EFFECT OF VEGETATION CHANGES?

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ABSTRACT

Aim of the study
This article presents the results of a comparative study of three mountain microwatersheds near the village of Brezna (Serbian Republic) focused on comparing rainfall-runoff process data between the 1980–1983 and 2022–2025 periods.

Material and methods
Two of the studied catchments are forested, whereas the third catchment has no forest vegetation. This study aimed to compare historical data from individual microwatersheds from the 1980s with data from the 2020s, and to analyse differences between individual catchments. Changes in runoff characteristics were correlated with the development of vegetation cover in the studied watersheds as well as with changes in climatic parameters due to global climate change.

Results and conclusions
The results of this study revealed a significant decrease in the total runoff from the microwatersheds between the two periods (with annual average values of approximately 40% for the forested microwatersheds and 67% for the nonforested microwatershed). Moreover, while a close correlation between rainfall-runoff process parameters and the ability of tree vegetation (forest) to actively influence this process was observed in the studied microwatersheds during the 1980s, this ability disappeared during the 2000s, when the rainfall-runoff process parameters became more closely correlated with the total precipitation in the microwatersheds. Notably, this correlation was stronger in the nonforested microwatershed than in the forested microwatersheds.

Keywords: runoff coefficient, runoff-precipitation process, hydrological extremes, mountain forested microwatersheds

INTRODUCTION

This article presents significant changes in rainfall-runoff process parameters in three forested microwatersheds in the central mountain massif of Serbia near the village of Brezna. In this study, historical measurement data from these watersheds for the 1980s was compared with more recent data (early 2020s). The evident changes in rainfall-runoff process parameters were related to both changes in climatic conditions and changes in vegetation at each site, and the comparative influence of these drivers on these changes were characterized.

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The influence of forest stands on water cycle was examined as early as the 19th century, with an emphasis on the possibility of influencing hydrological extremes in watercourses. However, the positive effects of forests were considered so obvious that experimental research was not considered necessary for a long time. Thus, long after the initial general analyses of the relationship between forest stands and extreme water conditions in rivers, research focused on small river basins began in Switzerland in 1900. Thereafter, numerous experimental comparative studies emerged worldwide (Kantor, 2003). The monitoring of flows at the microbasin level is important when evaluating changes in the water balance, so that the results can be applied at the system level. Microwatersheds (with an individual area of a few dozen hectares) are especially suitable for this purpose because of the elimination of systematic errors and other effects that cannot be ignored in larger watersheds. Notably, the use of data from larger watersheds renders data interpretation more difficult and prevents the generalization of the results.

Today, owing to rapidly changing land use, global climate change and the increasing need for quality drinking water, the interest in better understanding valuable ecosystems (that forests undoubtedly are), and more effective use of them (Sun et al., 2008; Vörösmarty et al., 2010), is growing. For this reason, experimental watersheds are being established worldwide as a primary tool to assess the impact of forests and forestry interventions on the hydrological regime and the overall water balance (Hibbert, 1967; Bosch and Hewlett, 1982; Brown et al., 2005; Varhola et al., 2010; Hrachowitz et al., 2013). The results have revealed significant differences in the development of rainfall-runoff processes between treeless and forested catchment areas (not only in small catchment areas), demonstrating the fundamentally positive role of forests in regulating rainwater runoff. However, the reduction of flood peaks in small catchments depends not only on the forest cover and the distribution of stands in catchments but also on the age, vitality, and spatial and species composition characteristics of trees (Krešl, 2001).

Climate change is intensifying and constitutes one of the greatest challenges of the 21st century (IPCC, 2022). Across the European continent, the temperature has increased by 1.2°C on average over the 20th century, including an increase of 0.45°C over the past three decades alone. Over the last century, the increase rate of the average temperature in Europe has reached approximately 0.1°C per 10 years. However, this trend has more than doubled over the last 30 years. On the basis of model predictions of future climate change, global temperatures are projected to increase by 1.1–6.4°C by the end of the 21st century, depending on the scenario considered. If these predictions are correct, this increase will represent the fastest and most significant temperature increase in the last 10,000 years (CHMI, n.d.; IPCC, 2022). For example, over the last 150 years, the 10 hottest months of July have occurred over the past 10 years. Furthermore, the average daily global temperature of 17.16°C on 22 July 2024 was the highest since 1940 (ECMWF, 2023).

Serbia is already experiencing significant adverse effects of climate change. Between 2011 and 2020, the average temperature increased by 1.8°C compared with that during the reference period of 1961–1990, with an even greater increase of up to 2.8°C in the summer months. This change has led to increases in the frequency, duration, and intensity of heat waves (Republic of Serbia, 2023). These changes have altered the precipitation regime. Although the total annual precipitation has not notably changed thus far, seasonal redistribution has occurred. Precipitation in summer is decreasing (a decrease of 10–20%), whereas intense rainfall episodes are increasing beyond the summer season (Republic of Serbia, 2025). While most of Serbia has experienced an average increase in precipitation of +10 mm per decade (from 1991–2019 to 1961–1990), in mountainous areas such as Crni Vrh or Kopaonik, precipitation totals have increased by up to 70 or 85 mm per decade, respectively (Popov and Svetozarevich, 2021). Long-term projections have indicated continued warming. Notably, by the middle of the century (2041–2060), temperatures are projected to increase by 3.1°C, and precipitation during the summer season is projected to decrease by more than 20% (Republic of Serbia, 2025). By the end of the century, warming of up to 4.4°C is expected (according to the high-emission RCP8.5 scenario), with an even further decrease in precipitation in the summer months and higher pre-

cipitation extremes (Vuković et al., 2018). Climate change has also influenced hydrology: long-term studies have revealed that a 1°C increase in temperature corresponds to an approximately 20% decrease in the average annual river flow (for the 1949–2006 period). Over the past 100 years, the flow of rivers in Serbia has decreased by up to 30% (Dimkić, 2017). The closest to the study location is the research by Đurđević et al. (2018), who, on the basis of E-OBS gridded climate data, reported that while the average temperature increase in Serbia is 1.8°C (between 2011–2020 and the reference period of 1961–1990), this trend is even more significant in the southern part of the country, with an increase of 2 to 2.5°C (between 1998–2017 and the same reference period). In the case of precipitation, the authors reported changes in the summer months, namely, precipitation decreased by 20–30% in the mountainous parts of southern Serbia during the same period.

One of the main consequences of global climate change is the disruption of hydrological systems. The most severe impact will be the change in the hydrological regime, i.e., the distribution and amount of precipitation, as well as the presence of water in the landscape, will change. Precipitation totals will most likely remain unchanged, but their distribution throughout the year will significantly change. Decreases in runoff and average and minimum flows, as well as intense localized rainfall events, can yield increased incidence of drought, reduced soil moisture, and lower groundwater levels. In general, heat stress affects all species and ecosystems, whereas drought and extreme hydrometeorological events affect some ecosystems (Stejskal, 2012; CHMI, n.d.; IPCC, 2022).

MATERIALS AND METHODS

Location

Three microwatersheds in the mountains of central Serbia were utilized in this research. These microwatersheds are part of the training forest enterprise of the Faculty of Forestry of the University of Belgrade (FF Belgrade) (for their locations, please refer to Figure 1).

These forest microwatersheds were investigated between 1980 and 1983 by academics from FF Belgrad, and all historical data (except E-OBS precipitation and temperature data) were obtained from the literature (Macan, 1985). The names of the microwatersheds, MI, MII, and MIII, were derived from the original study. MI is a catchment covered with a mixture of coniferous trees, primarily Norway spruce (*Picea abies* (L.) H. Karst.); MII is a forestless catchment with solitary trees in the upper part; and MIII is a forested catchment with a predominance of black pine (*Pinus nigra* J.F. Arnold). A detailed description of vegetation changes is provided in the next section of the article (Results, b), and the morphological characteristics of the catchment areas are detailed in Table 1. The soil type in the microwatersheds area is ranker on peridotite and serpentinite (slightly to moderately eroded) with soil depth ranging from shallow to moderately deep (mostly 0–40 cm). The humus layer is poorly to moderately developed (University of Belgrade, Faculty of Forestry, 2021).

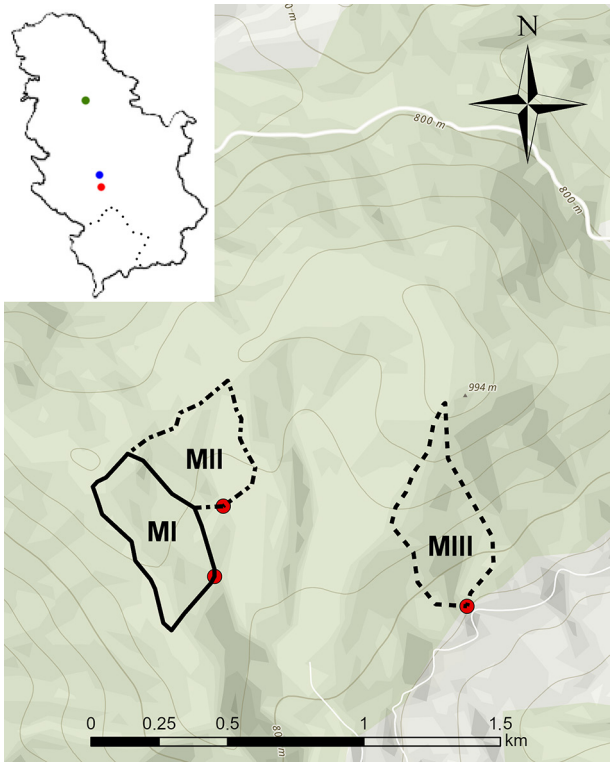


Fig. 1. Map of the experimental microwatersheds MI–III (the locations of the hydrological stations in Serbia are indicated by red dots, the city of Kraljevo is indicated by a blue dot, and Belgrade is indicated by a green dot) (Source: Authors' own elaboration)

Table 1. Basic morphological characteristics of the research catchment areas

	MI	MII	MIII
Surface area, km^2	0.076	0.064	0.084
Length of the river basin, m	400	325	625
Lowest elevation, m ASL	835	862	780
Highest elevation, m ASL	925	922	982
Elevation difference, $_{\Delta}$H	90	60	202
Average elevation, m ASL	880	892	881
Average elevation difference, m	45	30	110
River basin average slope, m/km	271	149	330
River basin relative slope, %	22.5	18.5	32.3
Length of the main stream, m	375	250	410
Length of all streams, m	475	530	570
River network density, km/m^2	6.25	8.35	6.76
Main stream height difference, $_{\Delta}$H	80	48	135
Main stream relative slope, %	21.3	19.2	32.9

Data acquisition

In order to acquire data, three established hydrological stations were utilized (their locations in the head areas of the microwatersheds are marked with red dots in Figure 1). The hydrological stations are equipped with a combined Thomson–Cipolletti spillway (for a detailed drawing, please refer to Figure 2). To determine basic hydrological parameters, submerged hydrostatic TSH22 probes (Fiedler Automatic Monitoring Systems (AMS), České Budějovice, Czech Republic) were used to collect hydrological information, especially water level data. All the data were collected using MOST software (V 2.30.92, 21.12.2022), in which the collected field data were also calibrated and verified. The individual heights were automatically converted by a datalogger into flow rates at 15-minute intervals and registered. A calibration check was also conducted during each field inspection using manual check measurements. Climate data (daily precipitation and temperature data) were obtained from the E-OBS gridded dataset (version 31.0e, 0.1-degree regular grid, grids 43,55–20,65) for 1980–1983 and 2022–2025 (Cornes et al., 2018).

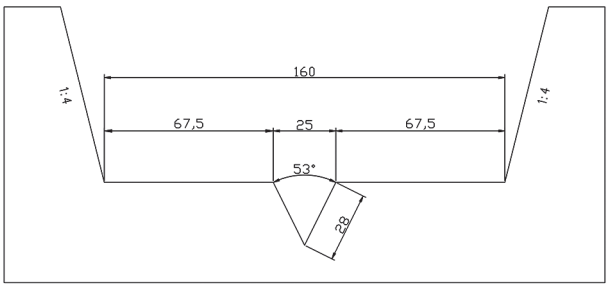


Fig. 2. A combined Thomson–Cipolletti weir (Source: Authors' own elaboration)

Data processing

On the basis of the 15-minute registered data, streamflow data were obtained, compiled and cleaned to establish the final working database. Because the spillway masks usually do not overflow, and the measured data are defined as inflows (not outflows), it was necessary to work with the data differently than with normal flow data. Therefore, the original methodology (Macan, 1985) was employed. Notably, the values for pool filling (water level fluctuations in the pool) and overflow of individual spillway masks (Thompson and Cipolletti) were separated. On the basis of the pool-filling values, possible pool leakage, pool evaporation, and other losses were considered negligible (up to 1% of the values). The amount of pool filling was calculated by multiplying the sum of water level additions by the pool area over the investigation period.

The spillway flow rates for individual overflow masks were calculated as follows:

$$Q = 1.3546 \cdot \textit{water level}^{2,48515} \quad (1)$$

or

$$Q = 1.859 \cdot \textit{length of the over flow edge} \cdot \textit{water level}^{3/2} \quad (2)$$

using the equation provided by the sensor manufacturer (Fiedler Automatic Monitoring Systems (AMS), České Budějovice, Czech Republic) for the Thomson part of the combined weir and by Environmental Management Bureau (2008) for the Cipolletti part of the combined weir. The calculated values were then multiplied by the flow duration. These values (pool filling, flow through the Thompson and Cipolletti spillways) were then added, and tabular data for runoff from the watershed were created. Hourly and daily average values were subsequently calculated. The average streamflow values listed in Table 3 were calculated from average monthly runoff totals, but they do not represent actual measured flow data. This maintains continuity with the methodology employed in previous research.

Data evaluation

To compare basic hydrological parameters, hydrographs were created from data for both the entire study period (2022–2025) and for individual years (Supplements). To evaluate changes in hydrological or rainfall-runoff process parameters, we determined the runoff coefficient (*RC*) as follows:

$$RC = \text{runoff/precipitation} \quad (3)$$

To evaluate changes in climatic conditions, the differences in average monthly temperatures and precipitation totals over the investigation periods were analyzed. To evaluate changes in vegetation and its impact on the rainfall-runoff process, data from the forest management plan (FMP) of Goč (University of Belgrade, Faculty of Forestry, 2021) (for the MI and MII catchments) and our own field surveys were used. This was accomplished by listing species along a transect across the MIII basin. To determine the influence of tree age on the rainfall-runoff process (water consumption from the catchment through transpiration), the methods of Deutscher et al. (2016) and Deutscher et al. (2019) were applied. Temperature was adopted as a proxy for the influence of vegetation on water consumption from the catchment through transpiration (Lofgren et al., 2011). To parameterize climate change, the temporal changes in temperature and precipitation (over the period between the two studies) were considered. Standard correlation analysis was conducted to determine the level of influence of vegetation or climate change on changes in hydrological processes in the studied microwatersheds.

Results

a. Changes in climate

The monthly total precipitation and monthly average temperatures during the monitored periods are shown in Figure 3. The values reveal that while the total annual precipitation remains relatively stable (with a slight increase), precipitation significantly fluctuates throughout the year. Except for short periods of potential moisture sufficiency, this process mainly results in significantly drier summers. The data below the graph (↑ °C) also

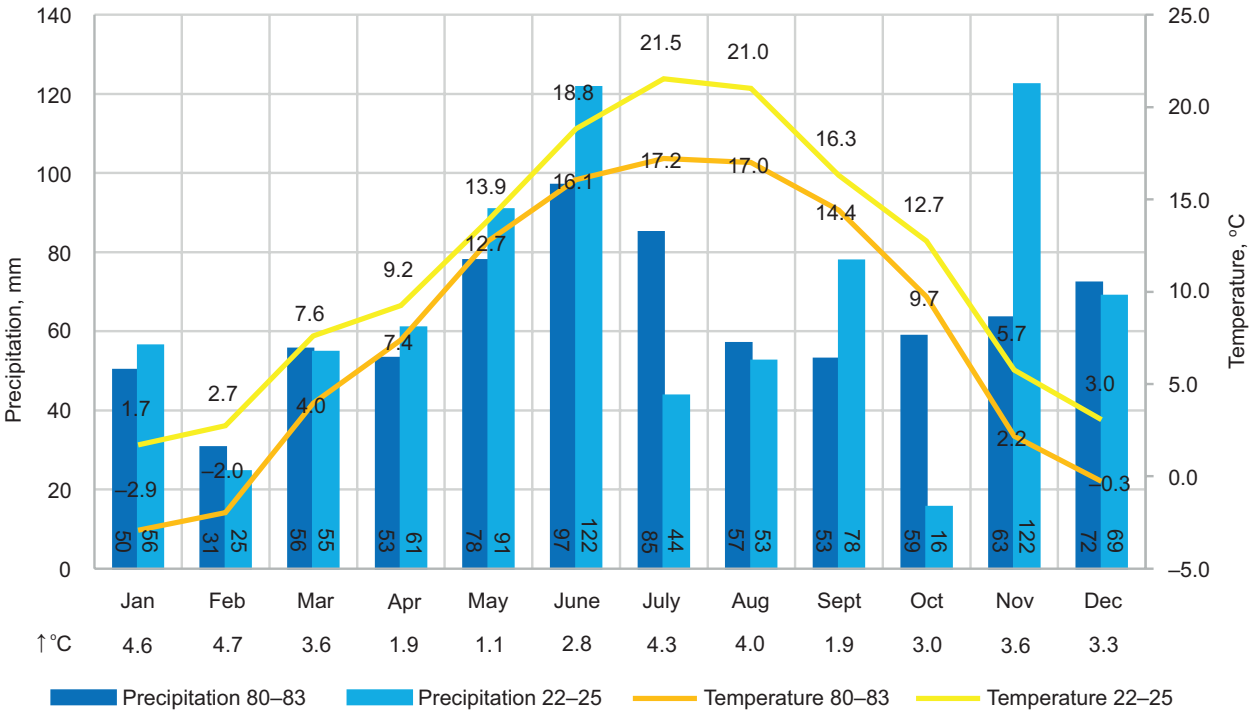


Fig. 3. Monthly average precipitation and temperatures, 1980–1983 vs. 2022–2025. ↑ °C denotes values calculated as temperature 22–25 minus temperature 80–83, which represents the increase in individual monthly average values

indicate that average monthly temperatures have increased significantly over the last 40 years. In general, while the increases in average temperatures are below average in spring (March, April, and May) and autumn (September, October, and November), the increases are above average in summer (June, July, and August) and winter (December, January, and February).

b. Changes in vegetation

During the 1960s, black pine (*Pinus nigra* J.F. Arnold; 73%) and white pine (*Pinus strobus* L.; 6%) were planted in the MI microwatershed, while spruce (*Picea abies* (L.) H. Karst.; 12%) was planted near the watercourse. The remainder of the area was covered by self-seeding sessile oak (*Quercus petraea* (Matt.) Liebl.; 9%). The undergrowth comprised Japanese pagoda trees (*Sophora japonica* L.) and rowan trees (*Sorbus aucuparia* L.). At the time of the initial research, these stands were about 20 years old. Recent data from the FMP (University of Belgrade, Faculty of Forestry 2021) indicate an even-aged stand (55 and 60 years old) with a very dense canopy cover and the following species composition: Norway spruce (*Picea abies* (L.) H. Karst.; 50%), black pine (*Pinus nigra* J.F. Arnold; 35%), sessile oak (*Quercus petraea* (Matt.) Liebl.; 7%), silver fir (*Abies alba* Mill.; 7%), and wild cherry (*Prunus avium* L.) and narrow-leaved ash (*Fraxinus angustifolia* Vahl; jointly up to 1%). The same vegetation, or rather its pine part, partially extends toward the edge of the MII microwatershed, and the remainder of this microwatershed is covered by a meadow with representative species, including mainly forest-steppe danthonia (*Danthonia alpina* DC.), mountain clover (*Trifolium montanum* L.), mountain buttercup (*Ranunculus montanus* Willd.), thyme (*Thymus* sp.) and red clover (*Trifolium pratense* L.).

In the MIII microwatershed, the surviving specimens of Japanese pagoda trees (*Sophora japonica* L.), rowan trees (*Sorbus aucuparia* L.) and mahaleb cherries (*Prunus mahaleb* L.) have developed into very dense stands. Black pine (*Pinus nigra* J.F. Arnold), which accounted for 25% of the surrounding vegetation, was supplemented by self-seeding common hornbeam (*Carpinus betulus* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.) at a level up to 3%. This created a mixture of locally native species, including Japanese pagoda tree (*Sophora japonica* L.), rowan trees (*Sorbus aucuparia* L.) and mahaleb cherry trees (*Prunus mahaleb* L.) (approx. 24% each).

c. Comparison of the conditions 40 years ago and today

Hydrographs for individual years, compiled from the database of daily average flows from 2022–2025 and supplemented with precipitation data from the E-OBS database, are provided in the Supplements. For comparison purposes, the data were evaluated in terms of monthly average values (as in the original study). The data represent the monthly averages of the RCs for each month of the year. The three-year measurement data are therefore grouped into twelve categories, with each month represented by the average of three monthly values (except April, May, and June, when data were not available).

The data revealed a significant decrease in the RCs, at 17% in MI and 7% in MIII (forested catchments), while the decrease in the nonforested MII catchment reached 42% (Table 2). Furthermore, runoff ratio between winter and summer months decreased. Specifically, the duration of the runoff-free period doubled in the summer months, interrupted only by significant hydrological extremes in the MIII catchment area. The lower RC values in the winter months suggest a) lower water reserves in the snow cover and

Table 2. Monthly average runoff coefficients for the historical (1980–1983) and current (2022–2025) research periods

Monthly ø runoff coefficient 80–83				Monthly ø runoff coefficient 22–25		
Month	ø MI	ø MII	ø MIII	ø MI	ø MII	ø MIII
Jan	0.80	1.04	1.02	0.72	0.18	1.75
Feb	1.43	2.06	1.61	0.09	0.11	0.37
Mar	0.90	1.14	1.15	0.07	0.05	0.05
Apr	0.14	0.28	0.33	0.40	0.42	0.40
May	0.15	0.52	0.53	0.20	0.19	0.12
June	0.23	0.38	0.41	0.22	0.27	0.31
July	0.40	0.44	0.69	0.00	0.00	0.01
Aug	0.00	0.00	0.00	0.00	0.00	0.00
Sept	0.00	0.00	0.00	0.01	0.01	0.08
Oct	0.16	0.37	0.50	0.00	0.00	2.24
Nov	1.00	1.15	1.16	0.18	0.33	0.11
Dec	0.70	0.76	0.84	1.37	0.80	1.07
ø year	0.44	0.61	0.64	0.27	0.19	0.57

b) a shortening of the winter season. This is evident in a significant decrease in RC in February, which in the 1980s did not occur until April. The reason for the slightly different values at the MIII weir compared with those at the other two weirs may be due to its location, where even a small distance can be very significant in terms of precipitation differences in a mountainous environment (Buytaert et al., 2006; Barry and Chorley, 2010). This discrepancy is also reflected in Table 3, which indicates that the MIII basin exhibits the highest water runoff levels and highest average flows. The total runoff is currently almost double as in the treeless MII basin; and these differences are increasing compared with those during earlier research periods. Notably, the difference in the RC is even greater, and owing to the influence of both

Table 3. Monthly ø Streamflow [l/s] (calculated from ∑ Runoff), ∑ Runoff for a given month [l], and Δ Runoff = changes in total runoff amounts calculated from data for 1980–1983 and 2022–2025

	MI	1980–1983		MII	1980–1983		MIII	1980–1983	
Month	ø Streamflow	∑ Runoff		ø Streamflow	∑ Runoff		ø Streamflow	∑ Runoff	
Jan	1.54	3,023,234		2.00	3,288,480		1.96	4,287,147	
Feb	1.72	3,379,651		2.47	4,063,017		1.93	4,215,719	
Mar	1.95	3,825,477		2.47	4,060,792		2.49	5,446,859	
Apr	0.28	548,963		0.56	929,155		0.67	1,472,584	
May	0.45	885,780		1.56	2,573,698		1.59	3,476,724	
June	0.87	1,703,194		1.41	2,328,724		1.54	3,365,211	
July	1.33	2,604,828		1.46	2,395,384		2.28	4,976,145	
Aug	0.00	3,600		0.00	50		0.00	0	
Sept	0.00	0		0.00	850		0.00	4,047	
Oct	0.37	724,853		0.84	1,382,385		1.14	2,487,040	
Nov	2.44	4,775,315		2.80	4,615,608		2.82	6,156,792	
Dec	1.94	3,803,328		2.12	3,488,425		2.32	5,069,347	
Year*	1.08	25,278,223		1.47	29,126,568		1.56	40,957,615	

	MI	2022–2025		MII	2022–2025		MIII	2022–2025	
Month	ø Streamflow	∑ Runoff	Δ Runoff	ø Streamflow	∑ Runoff	Δ Runoff	ø Streamflow	∑ Runoff	Δ Runoff
Jan	1.15	2,263,822	75%	0.71	1,162,980	35%	2.38	5,189,205	121%
Feb	0.13	258,366	8%	0.15	244,894	6%	0.49	1,073,163	25%
Mar	0.14	274,177	7%	0.10	172,286	4%	0.11	237,713	4%
Apr	0.97	1,917,655	349%	1.10	1,810,303	195%	1.04	2,280,736	155%
May	0.72	1,418,632	160%	0.67	1,098,543	43%	0.44	961,522	28%
June	1.51	2,974,072	175%	1.87	3,080,909	132%	2.10	4,591,960	136%
July	0.01	25,149	1%	0.01	22,690	1%	0.03	55,602	1%
Aug	0.00	1,150	32%	0.00	760	1,520%	0.00	9,893	0%
Sept	0.02	40,722	0%	0.03	44,300	5,212%	0.26	571,447	14,120%
Oct	0.00	148	0%	0.00	12	0%	0.61	1,338,859	54%
Nov	1.03	2,029,893	43%	1.54	2,538,176	55%	0.64	1,391,819	23%
Dec	2.53	4,990,926	131%	1.48	2,439,167	70%	2.26	4,930,293	97%
Year*	0.69	16,194,712	64%	0.64	12,615,021	43%	0.86	22,632,211	55%

components (precipitation and runoff), the RC is now twice as large as that in the MI basin and even three times as large as that in the MII basin. In contrast, these values were almost identical in the past.

The aggregated RC data of the studied watersheds are supported by the total monthly runoff and flow data (Table 3, Figure 4). In addition to revealing a significant decrease in water flow from the catchment area (with annual averages of 36% in MI, 67% in MII, and 45% in MIII in the studied years), the data also show a significant reduction in runoff in the winter period as well as an extension of the summer drought, a period with no or minimal runoff (Figure 4). Moreover, the percentages in the last columns at the bottom of Table 3 indicate significant variability in runoff for individual months compared to the historical measurement period. Values above 100% indicate increased runoff in the given months compared to the historical period, while values below 100% indicate decreased runoff. However, as the current differences in temperature, precipitation, and runoff still exceed the estimated and modeled climate change-related values, it is possible that the influence of extreme weather in the Goč Mountains has exceeded the gradual effects of climate change.

The correlations between the RCs and temperatures are detailed in Table 4. The results revealed that while the correlation between the RC and temperature was significant during the earlier research period (1980–1983), the relationship between these two variables has decreased significantly during the recent period (2022–2025). Table 5 summarizes the correlations between temperature, precipitation and total runoff. The upper part of each table contains data from 1980–1983, and the lower part provides data from 2022–2025. The results clearly indicate that the correlations between the individual variables were insignificant.

The results (Table 5) demonstrated that, while the influence of vegetation (with the temperature employed as a proxy) on runoff generation under standard precipitation conditions was notable, this influence significantly decreased under the current climatic conditions in the mountains of central Serbia. In contrast, the correlation between the precipitation totals and RCs increased significantly, confirming the hypothesis that long-term stressed forest stands in the area can utilize precipitation water less effectively. This phenomenon (limited water retention and utilization capacity) is even more notable in the treeless MII catchment area.

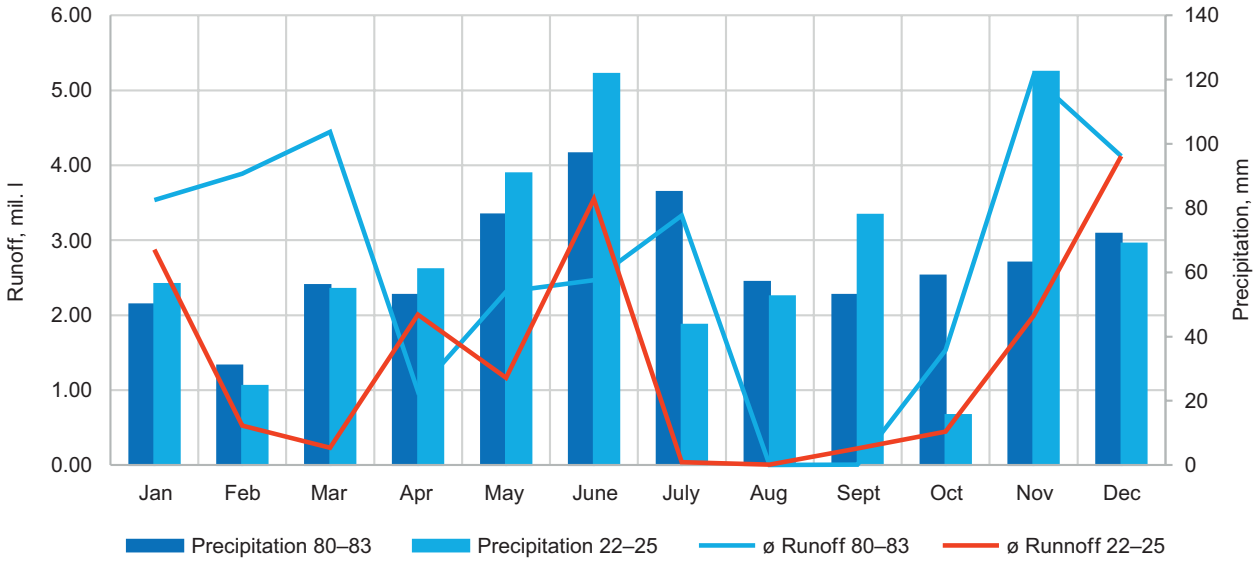


Fig. 4. Monthly average runoff amounts, 1980–1983 vs. 2022–2025

Table 4. ø MI 80–83 = correlation of runoff coefficients vs. temperature, 1980–1983; ø MI 22–25 = correlation of runoff coefficients vs. temperature, 2022–2025

	ø MI 80–83	ø MII 80–83	ø MIII 80–83	ø MI 22–25	ø MII 22–25	ø MIII 22–25
Runoff coefficients vs temperature	–0.82	–0.79	–0.79	**–0.58**	**–0.49**	**–0.40**

Table 5. Comparison of correlations between runoff and precipitation, resp. temperatures in historical (1980–1983) and current period (2022–2025)

Runoff	MI 80–83	MII 80–83	MIII 80–83	MI 22–25	MII 22–25	MIII 22–25
Precipitation	–0.05	–0.03	0.19	0.50	**0.76**	0.29
Temperature	–0.70	–0.70	–0.55	–0.43	**–0.26**	–0.45

DISCUSSION

In this study, rainfall-runoff process data for the 1980–1983 and 2022–2025 periods were compared with E-OBS grid data. The first two years of the first period (1980 and 1981) were wet, whereas 1982 and 1983 were dry. During the second period, compared with the wet year of 2023 (with an annual precipitation total of 681 mm), the year 2024 was significantly drier (with an annual precipitation total of 927 mm). Although the authors acknowledge the limited sample size within each period, they note that the occurrence of an equal number of dry and wet years with a similar deviation from the long-term normal during both periods mitigates the impact of any extremes.

With respect to the E-OBS grid data, one possible limitation for this research is that they do not effectively represent extreme hydrological conditions due to the method employed to compile the data (approximation of data from surrounding stations). However, this generalization method excludes local extremes that are not captured at standard climatological stations (Deutscher et al., 2021). Overall, there is no issue with the amount of recorded precipitation, as demonstrated by Deutscher et al. (2021), who compared data from the E-OBS dataset with their own network of climate station measurements and found a high correlation (an R2 value of 0.99). For these reasons, and to enable comparison with recent data, E-OBS data were also chosen for the historical period.

Water consumption in forest ecosystems is a key factor influencing the hydrological cycle and the adaptation of forests to climate change. Understanding the differences in water consumption between coniferous and deciduous forests of different ages is essential for ensuring sustainable water resource management and predicting the effects of drought (Du et al., 2024; Komatsu et al., 2011; Jia et al., 2022). The differences in water consumption between coniferous and deciduous forests are influenced by various factors, including physiological structure, climatic conditions, soil types, and seasonal changes. Seasonal changes can lead to distinct water consumption patterns. For example, deciduous forests can experience higher evapotranspiration rates in summer months when the leaf area is at maximum, whereas coniferous forests may exhibit more stable but lower evapotranspiration rates throughout the year, even in winter (Young-Robertson et al., 2016; Siddiq et al., 2017; Deb Burman et al., 2021; Trueba et al., 2022; Azuma et al., 2024).

Water management has been compared among stands of various ages; for example, in the study of Deutscher et al. (2016), who, using the methodology of Allen et al. (1998) reported that the type (coniferous, deciduous, or mixed) and age of stands are not important, and thus, the resulting amount of water consumed for evapotranspiration in an average year is approximately identical. Although deciduous stands can experience 20–30% more evapotranspiration during the day, than coniferous stands can (Deutscher et al., 2016), owing to increasingly mild winters, when there is a high proportion of liquid precipitation and the soil does not freeze, coniferous vegetation can also experi-

ence evapotranspiration in winter, thus compensating for this difference (Clausnitzer et al., 2011).

The influence of vegetation on the hydrological cycle in river basins has been examined by Ruiz-García et al. (2023). The authors reported that, under the conditions of advancing climate change, the hydrological balance in this area would also change, with a particular increase in evapotranspiration caused mainly by rising temperatures and seasonal precipitation. This would have a markedly negative impact on flow. Higher transpiration rates, together with higher interception rates, suggest that trees exhibit higher evapotranspiration rates than other types of vegetation do (Verstraeten et al., 2005). However, as there was no increase in precipitation at the research site, the potential evapotranspiration did not increase. Therefore the potential driver of change in these catchments is climate change itself, rather than the state of vegetation. A similar phenomenon was also reported by Li et al. (2025), who demonstrated that changes in climatic parameters affect the water balance more notably than structural changes in vegetation, and that vegetation modulates rather than controls this effect.

In regard to the impact of climate change, it is useful to compare the expected changes in this part of the Balkans with the changes that have already been registered. A report by the European Centre for Medium-Range Weather Forecasts (2023) indicated that the 10 warmest months of July over the last 150 years have occurred during the past 10 years. This finding is consistent with the data from this location, as July is the month with the greatest increase in the average temperature (except for the winter months) compared with the earlier research period (1980–1983). Long-term projections assuming continued warming have already been exceeded at this location, with an increase of 3.2°C, compared to the expected increase of 3.1°C by mid-century (2041–2060) in the study by the Republic of Serbia (2025) (compared to the reference period 1961–1990).

The above changes also affect precipitation patterns, as supported by the obtained values. While the total annual precipitation remains relatively unchanged (with only a slight increase), there is significant fluctuation in precipitation throughout the year. This finding is consistent with, among other studies, the report issued by the Republic of Serbia (2025). With regards to changes in the precipitation regime, the data from this study are also consistent with the findings reported by Popov and Svetozarevich (2021), who indicated that most of Serbia experienced an average increase in precipitation of +10 mm per decade (comparing the 1991–2019 period to the 1961–1990 period). In our case, there was an increase of 36 mm over four decades.

Climate change also influences hydrology. Notably, long-term studies have revealed that a 1°C increase in temperature corresponds to a decrease in the average annual river flow of approximately 20% in Serbia (for the 1949–2006 period) (Dimkić, 2017). This finding is consistent with the data from the treeless MII basin, where the total runoff decreased by 67%. The decreases in runoff in the MI and MII basins (36% and 45%, respectively) are consistent with the data from Đurđević et al. (2018), who also analyzed E-OBS data in the mountainous environment of southern Serbia, where the forest vegetation can be similar to that at our research site. The positive effect of forest vegetation on runoff from watersheds, in which more water flows out of forests, has long been acknowledged (Riedl and Zachar, 1974; Křovák and Kuřík, 2001), with various authors demonstrating this fact in mountainous environments. However, Deutscher and Kupec (2014) found the opposite effect, but their research was conducted in a highland area. Li et al. (2025), who conducted their research in both mountainous and highland areas, observed a similar effect (higher runoff from forests than from nonforested areas) in the upstream areas of forested landscapes, as in our study. The differences between the microwatersheds in terms of runoff or RC were eliminated by converting runoff values to specific runoff levels. Here, the decreases in runoff in individual catchments were 70%, 78%, and 83%, indicating that the problem of this area is not due to older vegetation, and thus greater evapotranspiration at the site, but rather significant increases in average temperatures.

CONCLUSIONS

This study demonstrated significant changes to the rainfall-runoff process in the mountains of central Serbia by comparing climate and runoff data from

the 1980s with data from the 2020s. The significant decrease in total runoff (with annual average decreases of 36% in the MI basin, 67% in the MII basin, and 45% in the MIII basin) was mainly due to the lengthening of the summer season, which constitutes a period with no or minimal runoff, and a decrease in runoff during the winter season. In combination with temperature data, which revealed above-average temperature increases in summer (June, July, and August) and winter (December, January, and February), the data indicate a) lower water reserves in the snow cover and b) a shortening of the winter period. The correlation results indicated that while the correlation between the RC and temperature was significant from 1980–1983, the relationship between these two variables decreased significantly from 2022–2025, regardless of vegetation type in the microwatershed area. Together with the results of other studies, these findings indicate that increasing temperature is a significant driver of the observed changes and has a secondary impact on other processes within the catchment area.

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SUPPLEMENTS

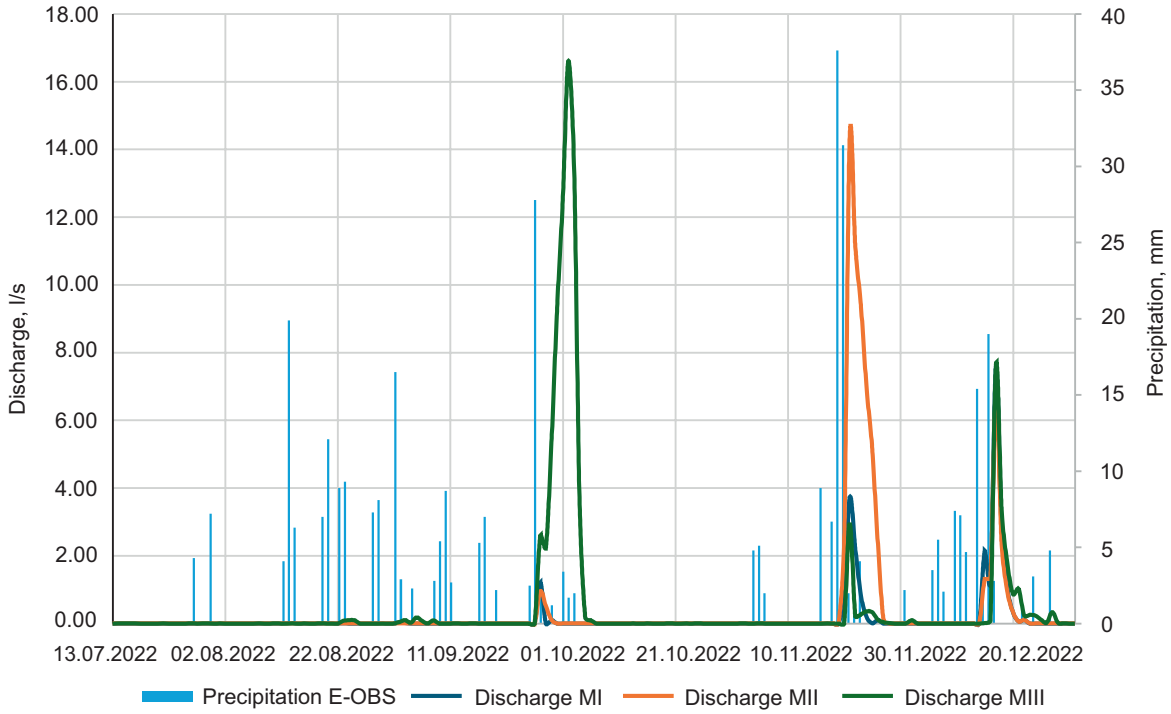


Fig. 5. Discharge (measured) and precipitation data (E-OBS) for 2022

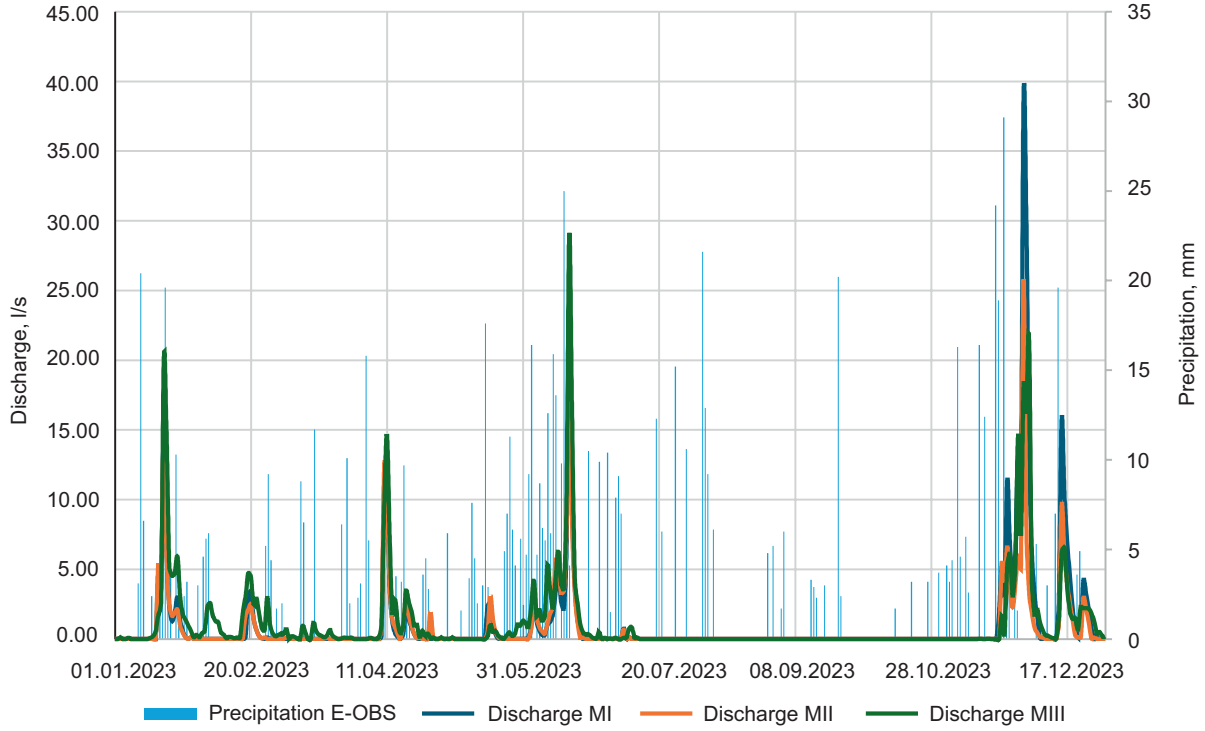


Fig. 6. Discharge (measured) and precipitation data (E-OBS) for 2023

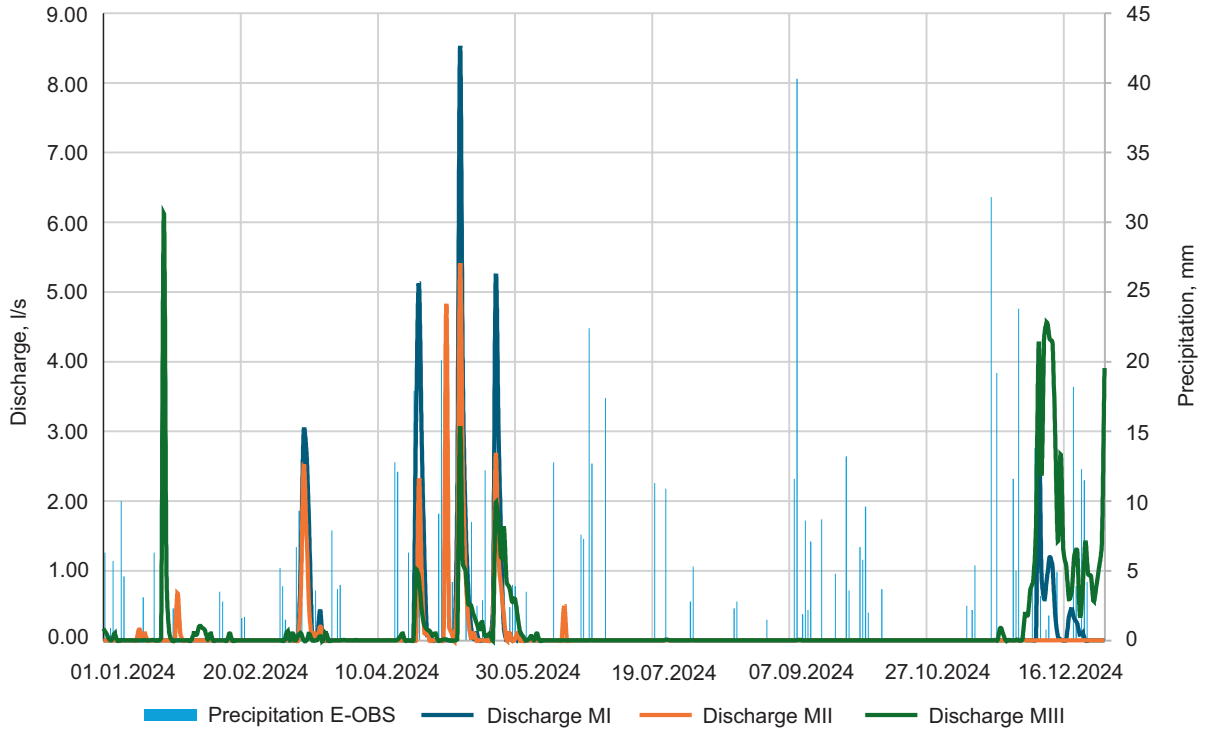


Fig. 7. Discharge (measured) and precipitation data (E-OBS) for 2024

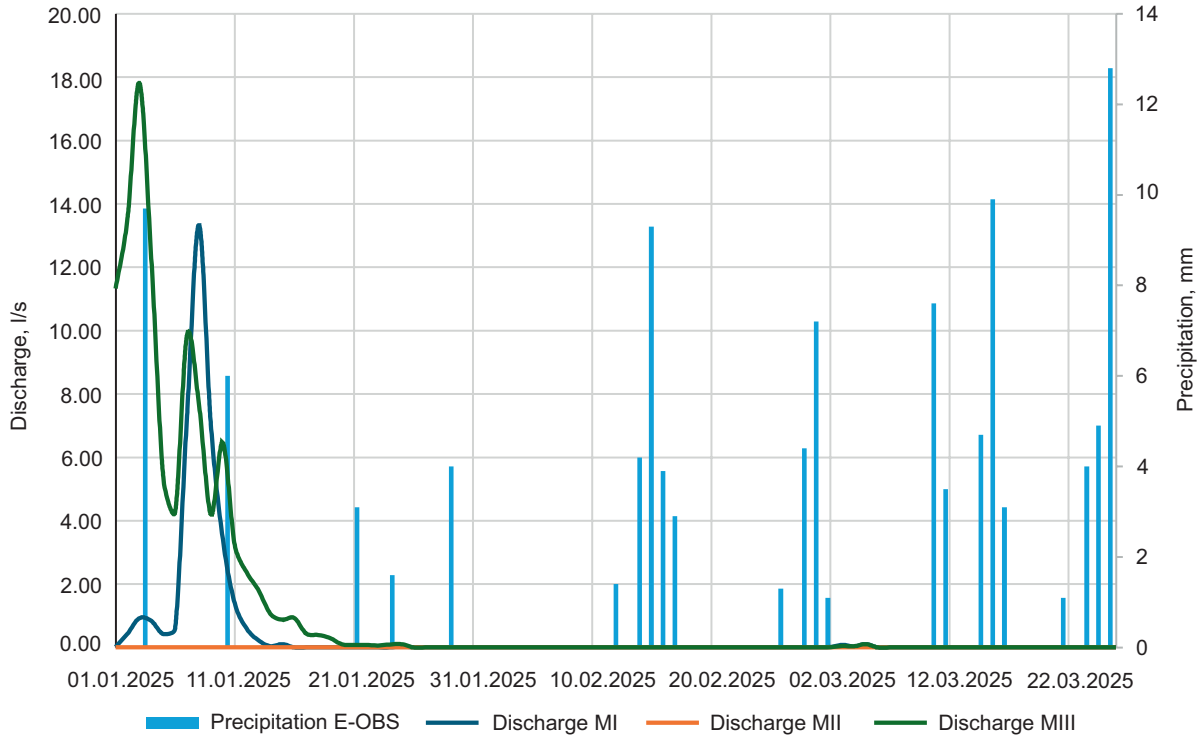


Fig. 8. Discharge (measured) and precipitation data (E-OBS) for 2025

CZTERDZIEŚCI LAT PÓŹNIEJ. ZMIANY WSPÓŁCZYNNIKÓW OPADÓW I SPŁYWU W GÓRACH GOČ W SERBII: EFEKT ZMIAN KLIMATU CZY TYLKO WPŁYWU POKRYWY ROŚLINNEJ?

ABSTRAKT

Cel badania

W niniejszym artykule przedstawiono wyniki przeglądu trzech górskich mikrozlewni w pobliżu miejscowości Brezna (Republika Serbii), którego celem było porównanie danych dotyczących procesów opadowo-spływowych w latach 1980–1983 i 2022–2025.

Materiały i metody

Dwie z badanych zlewni pokryte są lasami, natomiast w trzeciej zlewni nie występuje roślinność leśna. Celem niniejszego badania było porównanie danych historycznych z poszczególnych mikrozlewni z lat 80. z danymi z lat 20. XXI wieku oraz analiza różnic między poszczególnymi zlewniami. Zmiany charakterystyki spływu zostały skorelowane z rozwojem pokrywy roślinnej w badanych zlewniach, a także ze zmianami parametrów klimatycznych wynikającymi z globalnych zmian klimatu.

Wyniki i wnioski

Wyniki analizy wykazały znaczny spadek całkowitego spływu z mikrozlewni w obu okresach (przy średnich rocznych wartościach wynoszących około 40% dla mikrozlewni zalesionych i 67% dla mikrozlewni niezalesionych). Ponadto, podczas gdy w latach 80. XX wieku w badanych mikrozlewniach zaobserwowano ścisłą korelację między parametrami procesu opadów i spływu a zdolnością roślinności drzewnej

(lasu) do aktywnego wpływu na ten proces, zdolność ta zanikła w pierwszej dekadzie XXI wieku, kiedy to parametry procesu opadów i spływu uległy silniejszej korelacji z całkowitą ilością opadów w mikrozlewniach. Co istotne, korelacja ta była silniejsza w mikrozlewni niezalesionej niż w mikrozlewniach zalesionych.

Słowa kluczowe: współczynnik spływu, proces opadów i spływu, ekstremalne zjawiska hydrologiczne, górskie zalesione mikrozlewnie