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The impact of climate change on the dynamics of the water level of Lake Skadar

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Abstract

Lake Skadar is the largest freshwater body on the Balkan Peninsula. It is recognized as a wetland of international importance under the Ramsar Convention and holds the status of a national park in Montenegro. The results presented in this study indicate a significant downward trend in monthly water levels during the period 1948-2021, ranging from -14.9 cm in September to -24.0 cm per decade in May. Water levels show significant variation both seasonally and annually (cm per decade): from -16.8 (autumn) to -21.7 (spring), *i.e.*, -19.3 (year). Standardized deviations suggest that the most pronounced decline began in 1981, a pattern further confirmed by the Rescaled Adjusted Partial Sums. Total precipitation in Lake Skadar's drainage basin has shown little to no change. However, there has been a significant increase in air temperature, and thus increased evaporation. According to ERA5-Land data, the annual total evaporation trend in the lake basin reaches up to 10.0 mm per decade. The substantial increase in evaporation has probably resulted in a significant reduction in runoff (Y) derived from precipitation contributing to stream flow. The trend of the mean annual runoff (Y) from 1 m^2 is -45 mm per decade, and the flow of the Morača River, the main tributary of the lake, -2.5% per decade. Notably, over the past 14 years, Lake Skadar recorded both its highest water level (2010) and its lowest (2017). We appreciate that the long-term trend of falling water levels is influenced by significant warming of the atmosphere, which has led to increased water evaporation. Short-term fluctuations in lake water levels are primarily driven by variations in precipitation within the catchment area, which are likely linked to atmospheric oscillation patterns. In addition, human impact is evident near the confluence of the Morača River and Lake Skadar, particularly due to the intensive extraction of gravel and sand. To preserve the ecology and economy of Lake Skadar, its natural and cultural heritage, urgent measures are necessary by the countries (Montenegro and Albania) within whose territories this natural gem is located.

Key words: water level; evaporation; ERA5-Land; temperature; precipitation; Lake Skadar; Montenegro.

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Introduction

The fact that human life and the overall existence of society depend on water has made water resource management a primary concern throughout history (Hering, 2019). However, clean water is becoming increasingly scarce, as freshwater resources are often exploited and polluted without adequate planning (Dobričić and Marjanović, 2017). Following energy challenges, water-related issues are regarded as the most serious threat to human society (Dong *et al.*, 2013). Among freshwater resources, natural lakes and artificial reservoirs have special significance and represent essential components of terrestrial hydrological systems (Yücel *et al.*, 2022). As dynamic water bodies, lakes are highly sensitive to both climate variability and human activities, making them valuable indicators of climate and environmental change (Li *et al.*, 2020).

Some lakes show an increase in water level, while others show a decreasing trend. For example, by analyzing water level trends in 200 large lakes worldwide between 1992 and 2019, Kraemer *et al.* (2020) found that, while global lake levels generally show an increasing trend, there are substantial variations from one lake to another. In recent years, the Great Lakes of North America have shown an increase in water levels, despite significant fluctuations (around 2 meters) since the 1970s (Gronewold and Rood, 2019). Under future hydroclimate conditions, further increases in the water levels of this largest freshwater system in the world are predicted (Kayastha *et al.*, 2022). Of particular note is the recent study by Yao *et al.* (2023), where the authors utilized 250,000 satellite images from 1992 to 2020 to investigate water level changes for the 1,972 largest lakes globally. Their findings indicate that 53% of the world's largest lakes are experiencing declining water levels, primarily due to global warming and unsustainable anthropogenic water consumption. The authors estimate that approximately 25% of the global population -around 2 billion people- reside in lake basins experiencing declining water levels, whereas lakes with increasing water levels are predominantly located in sparsely populated regions.

The study suggests that excessive human water consumption can be mitigated through regulatory measures, citing Lake Sevan in Armenia as an example. Human activities can have a direct impact on water levels in lakes (Rodell *et al.*, 2018). A striking example of human impact is the sharp reduction in the Aral Sea's water level. This reduction is primarily attributed to the extensive use of its main tributaries (Syr Darya and Amu Darya) since the 1970s for irrigating cotton plantations in the deserts of Central Asia (Aladin *et al.*, 2009). On the other hand, data for the period 1971-1990 indicate a retreat in the water level of the world's largest artificial lake, Lake Volta in Ghana (8,502 km^2). The decline in water level is attributed mainly to climatic changes, specifically to a significant reduction in precipitation within its catchment area, which has consequently led to decreased inflow from the rivers feeding the lake (Gyau-Boakye and Tumbulto, 2000). Estimates suggest that, throughout the Volta Basin, the reduction in average seasonal precipitation will continue until the end of the 21st century, and that the basin will become warmer and drier (Yeboah *et al.*, 2022).

The Mediterranean region and Southeast Europe, including the Balkan Peninsula, are classified among the most vulnerable areas to contemporary climate change (Blauhut *et al.*, 2022). For instance, Lake Eğirdir is one of the largest and most important lakes in Turkey, serving as a vital source of drinking water. Research covering the period from 1988 to 2019 has documented a decline in both the lake's water level and volume. These reductions are primarily attributed to climate change within the lake basin and a decrease in the availability of water from its contributing sources (Yücel *et al.*, 2022).

Montenegro, positioned at the intersection of the Mediterranean and Balkan regions, has experienced growing impacts from climate variability and change over recent decades. The country has experienced significant warming, extreme heat, floods, droughts, intense rainfall, and frequent heatwaves (Burić *et al.*, 2021; Luković *et al.*, 2024; Burić *et al.*, 2024a). Projections through the end of the 21st century indicate a continued significant rise in temperature (Burić, 2024). While no substantial changes are expected in total annual or seasonal precipitation, Projections through the end of the 21st century indicate a continued significant rise in temperature (Burić, 2024). Although no significant changes are projected in total annual or seasonal precipitation, marked interannual variability and a reduction in the number of rainy days are anticipated (Doderović *et al.*, 2020).

This research focuses on fluctuations in Lake Skadar's hydrometric levels during the instrumental period, spanning the past seven decades and beyond. The study also evaluates how temperature and rainfall patterns influence lake levels within the lake's catchment area. It is located on the border between Montenegro and Albania, with approximately two-thirds of its surface area owned by Montenegro and one-third by Albania. The Montenegrin portion of the lake was designated as a national park in 1983 and included in the Ramsar List in 1995 as an exceptionally important wetland area covering approximately 20,000 hectares (Doderović *et al.*, 2018). Due to the Mediterranean climate, particularly the precipitation regime, Lake Skadar's surface area varies markedly across seasons: during low water levels, it can decrease to 370 km^2, while during high water levels, it can expand to 540 km^2. The water quality of this freshwater lake is still considered to be good (Burić *et al.*, 2023a). Beyond its hydrological role, Lake Skadar is valued for its importance in tourism, ecology, agriculture, and cultural history.

Methods

Study area

As mentioned earlier, this is the largest lake in the Balkan Peninsula (Fig. 1), and its watershed is located in a Mediterranean climate zone, with only a small part, characterized by the headwaters of its tributaries, having mountainous climate features (Burić *et al.*, 2023b). The largest part of the basin belongs to Montenegro (81.3%), and a smaller part to Albania (18.7%). The entire watershed, covering approximately 5,490 km^2, is characterized by a Mediterranean precipitation regime. The region experiences hot, arid summers and mild, rainy winters. For example, in Podgorica, the capital of Montenegro located approximately 20 km from the lake, the annual average precipitation is 1,675 mm for the period 1948–2021, with 34% occurring in winter and only 10% in summer. The rainiest month is November, accounting for 15% of the annual average, which, along with the three winter months (December to February), constitutes 49% of the total annual precipitation. For the same period, the average annual air temperature in Podgorica is 15.8°C, in January 5.5°C, and in July 26.9°C. In summer, temperatures in Podgorica and the surrounding areas (the Zetska and Bjelopavlićka plains) can exceed 40°C.

The "zero" water level reference for Lake Skadar at the Plavnica HS is 456 cm above the sea level. The average depth of the lake is around 5 m, and in certain underwater sinkholes, it reaches up to 60 m (Raduško Oko). At the average water level of 650 cm above sea level, the lake spans approximately 475 km^2. Lake Skadar has several tributaries, with the river Morača contributing the largest volume of water to the lake - around 62%. Most of the lake's outflow occurs via the Bojana River, which discharges into the Adriatic Sea, while approximately 20% is lost through evaporation, primarily during the summer (Doderović *et al.*, 2018).

Data

On the Montenegrin side of the lake, there are 7 hydrological stations (HS), but the most extended series of water measurements at Lake Skadar was recorded at the Plavnica HS. Data on the flow of the Morača River from the Podgorica HS were also used, because the water level of the lake largely depends on the inflow of water from this river. The Bojana River, which flows into the Adriatic Sea, is the sole outflow of Lake Skadar. The only hydrological station (HS) on the Bojana River is Fraskanjel, located in the middle course of the river, approximately 20 km from its mouth. However, since the Fraskanjel HS only records water level, these data were used for the analysis. To assess the long-term effects of temperature and precipitation on the variations in the water level of Lake Skadar, we analyzed data from four meteorological stations (MS) situated within its basin (Fig. 1): Podgorica, Nikšić, Golubovci, and Cetinje (Tab. 1). All data were obtained from the Institute for Hydrometeorology and Seismology of Montenegro (2024). The monthly datasets obtained from IHMSM were almost complete: data gaps amounted to 3.2% for the Plavnica HS, 2.7% for the Fraskanjel HS and 2.5% for the Podgorica HS, while the MS in Podgorica, Nikšić, Cetinje, and Golubovci had missing data rates of approximately 0.9-1.3%, respectively. Missing values were estimated based on available (measured) data from neighboring HS and MS using the MASH method (Multiple Analysis of Series for Homogenization). This method, recommended by the WMO

(Szentimrey, 2003), was also employed to assess the relative homogeneity of the time series.

Data on evaporation from the IHMSM network of stations are quite limited. Therefore, total (actual) evaporation data from the ERA5-Land database (Muñoz Sabater, 2019), with a horizontal resolution of 0.1°x0.1° (native resolution is 9 km) were used. Evaporation data were obtained from the ERA5-Land database for five points (grid cells) in the Skadar Lake basin. ERA5-Land data have been available since 1950, and were produced by the European Center for Medium-Range Weather Forecasts (ECMWF), as part of the Copernicus Climate Change Service (C3S). This dataset represents the cutting–edge global reanalysis for land applications (Muñoz–Sabater *et al.*, 2021) and has been extensively utilized in recent research (*e.g.*, Kaissi *et al.*, 2024; Dalla Torre *et al.*, 2024). The data sets were downloaded using the *Python* program, using *cdsapi* scripts written in python obtained on the Copernicus platform.

Methodology

The following methods were employed in this study: trend analysis, 10-year moving averages, standardized deviations (SD), and Rescaled Adjusted Partial Sums (RAPS). To determine the significance and magnitude of trends, the nonparametric methods of the Mann-Kendall test and Sen's method are used (Helsel *et al.*, 2020), respectively. Common significance levels $p<0.001$, 0.01, 0.05, and 0.1 correspond to confidence levels of 99.9%, 99%, 95%,

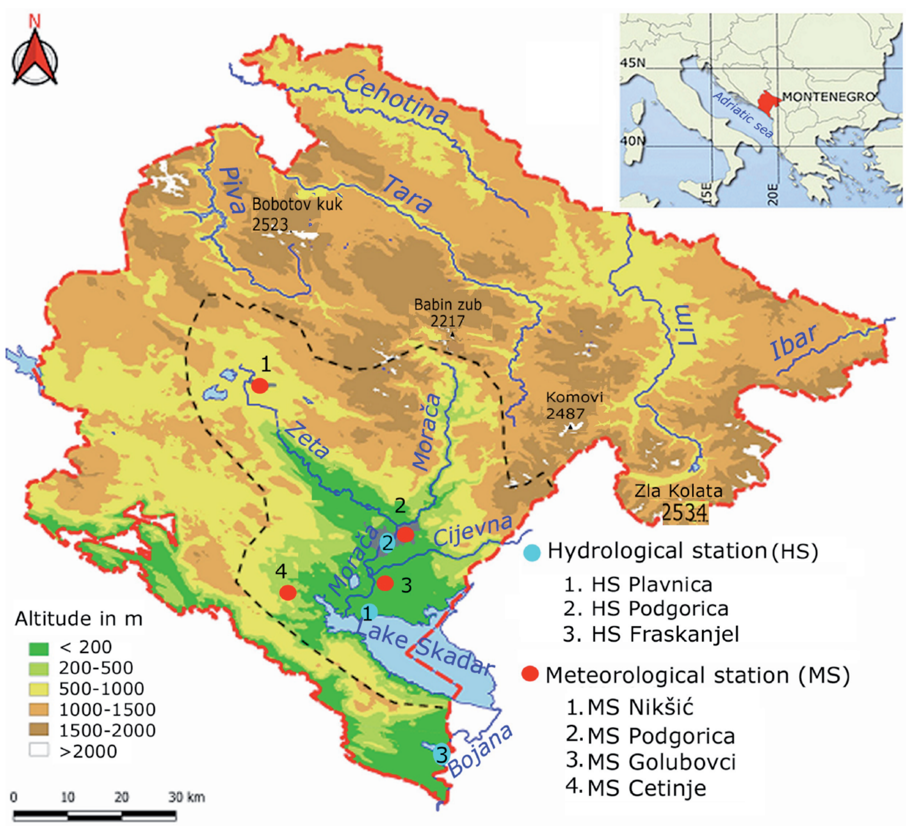

Fig. 1. Position of Montenegro and Lake Skadar on the Balkan Peninsula with the location of the Plavnica and Podgorica Hydrological Station, and Meteorological Stations in the basin.

Tab. 1. List of the stations.

Station name	WMO No.	Period	Latitude (N)	Longitude (E)	Elevation (m)
HS Plavnica	/	1948-2021	42°27′	19°20′	4.56
HS Podgorica	/	1948-2021	42°45′	19°26′	24.6
HS Fraskanjel	/	1960-2021	41°58′	19°23′	0.07
MS Podgorica	13463	1948-2021	42°26′	19°17′	49
MS Cetinje	13460	1948-2021	42°23′	18°55′	640
MS Nikšić	13459	1949-2021	42°46′	18°57′	647
MS Golubovci	13462	1978-2021	42°22′	19°15′	33

and 90%, respectively. The 10-year moving averages method helps reduce short-term fluctuations and identify potential decadal variations over a longer time span. The standardized deviations method quantifies how much water levels deviate from the hydrological norm. The standard deviation (STDEV) was first calculated according to the following equation:

$$STDEV = \sqrt{\frac{\sum (x-\bar{x})^2}{n-1}} \quad \text{(Eq. 1)}$$

x – the value of individual water levels in the series;
$\bar{x}$ – the average value of the entire series (hydrological normal);
n – the total number of elements in the series.

In the subsequent step, the standardized deviation (SD) for each element in the series was calculated according to the following equation:

$$SD = \frac{x-\bar{x}}{STDEV} \quad \text{(Eq. 2)}$$

Finally, the resulting SD values were assigned to the predefined classes (Tab. 2).

For this study, the specific discharge (q) was determined for the portion of the Skadar Lake basin contributing to the Podgorica HS profile, which encompasses an area of 2,628 km² (F). The specific discharge was calculated from the Moraca River flow (Q) using the following formula (Doderović *et al.*, 2018):

$$q = Q \cdot 1000 / F(l/s/km^2) \quad \text{(Eq. 3)}$$

Using q, the average annual discharge depth (Y) was subsequently calculated according to the following equation (Doderović *et al.*, 2018):

$$Y = q \cdot 31.56 \cdot 10^6 (mm) \quad \text{(Eq. 4)}$$

For the assessment of the main components of the water balance, a simplified equation was employed, in which precipitation (P) is assumed to equal the sum of evaporation (E) and runoff (Y):

$$P = E + Y(mm) \quad \text{(Eq. 5)}$$

Finally, the RAPS method is frequently employed to determine the tipping point (year) after which abrupt changes hydroclimatic variables (such as lake water levels, precipitation, river discharge, temperature, and other elements) occur (Đurin *et al.*, 2022; Šrajbek *et al.*, 2023). This method utilizes the mean and standard deviation of the original time series, and through the application of specific equations, a new or transformed series is generated. Essentially, the application of the RAPS method is based on the "highest peak" and "lowest valley" principle (Đurin *et al.*, 2022). When the transformed (RAPS) values are graphically displayed, the tipping point(s) become evident, representing peaks of subperiods within the entire time series.

Results

Dynamics of the water level of Lake Skadar

During the study period (1948-2021), Lake Skadar maintained an average annual level of 194.3 cm above the zero point. On a monthly basis, the average water level fluctuates from 84.2 cm in September to 270.4 cm in December (Fig. 2). Lake Skadar's typical annual fluctuation, or normal (standard) deviation (STDEV), is 52.5 cm. STDEV is highest in November, at 91.2 cm, and lowest in August, at 40.1 cm. The ratio between the average highest and lowest monthly water level fluctuations is 1:2.3, indicating that the typical fluctuation in Lake Skadar's water level is more than twice as great in November as it is in August. Average seasonal water level values align with the monthly water level. The highest average water level of Lake Skadar is in winter (260.8 cm), followed by spring (238.0 cm), then autumn (142.6 cm), with the lowest in summer (134.9 cm). Such a water level regime during an average year is a direct consequence of climatic characteristics, primarily the rainfall regime in its watershed area.

The classification of mean water levels (monthly, seasonal, and annual) was conducted using standardized deviations (SD). Mean water levels with SD values between –1 and +1 are classified as normal fluctuations (Fig. 3). Positive SD values indicate higher water levels than the average, while negative values indicate lower levels. For example, in the observed period (1948-2021), so-called normal deviations in the month of January occurred in 52 years or 70.3% of cases. During the observation period, 13.5% of January averages (10 years) were categorized as high water levels, and only twice (2.7%) as very high. In contrast, low levels occurred in nine cases, with a single instance of very low level recorded in January 2020. According to this indicator, no January had an average water level >3 SD or <–3 SD, *i.e.*, there were no significantly large and

Tab. 2. Categorization of water level anomalies based on standardized deviations.

Water level regime	Range of SD values
Extremely large water	>3
Very big water	2 - 3
Big water	1 - 2
Normally	–1 - 1
Little water	–1 - –2
Very little water	–2 - –3
Extremely little water	<–3

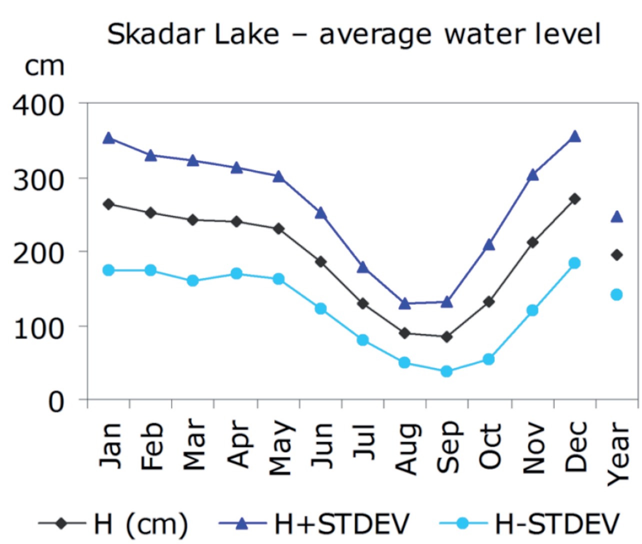

Fig. 2. Average monthly/annual water level values (H) and standard deviation (STDEV) water levels of Skadar Lake (HS Plavnica) for the period 1948-2021.

significantly small waters. The 10-year sliding averages had a positive value in the first half of the period and a negative value in the second half, but there is an obvious tendency towards a decrease in the water level of Lake Skadar. The same interpretation can be applied to other months.

In accordance with the monthly data, the results of the categorization at the seasonal and annual levels are also available (not shown here for the sake of brevity). A common characteristic for all time units (months, seasons, and the year) is that two periods with dominant positive and negative deviations of average water

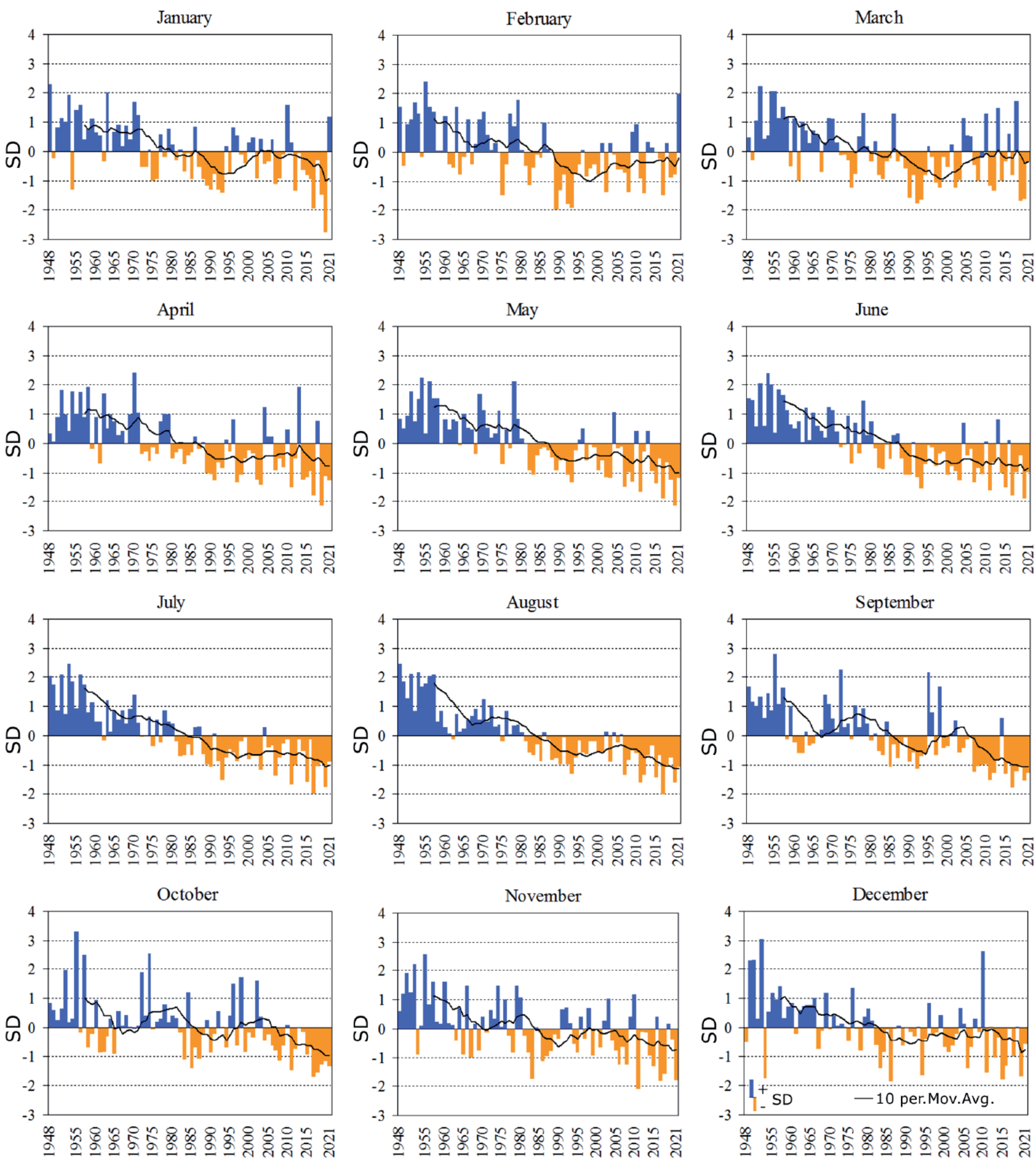

Fig. 3. Monthly values of standardized deviations (SD) and 10-year sliding averages of Lake Skadar's water levels (1948-2021).

levels can be distinguished. Namely, during the first (shorter) period, there is an absolute dominance of positive, while in the second (longer) period, negative deviations prevail. This is supported by the values of 10-year moving averages SD, which have a positive value until the 1980s and then become negative, generally.

The trend values of the water levels in Lake Skadar for the period 1948–2021 are concerning because all months show a statistically significant negative trend (Tab. 3), at the highest level of risk ($p<0.001$). September exhibits the smallest decrease in the water level of Lake Skadar (-14.9 cm/decade), while May shows the greatest decrease (-24.0 cm/decade). In line with the results of the monthly water level trend, negative trends are evident at the seasonal and annual levels. The rates of decrease in average water levels are relatively uniform in the winter and summer seasons, with trends of -19.2 and 19.0 cm per decade. The most significant reduction in the water level of Lake Skadar occurs during the spring season (-21.7 cm per decade), while the least reduction happens in the autumn (-16.8 cm per decade). Naturally, the trend was negative on an annual basis (-19.3 cm per decade). Both the seasonal and annual trends were found to be statistically significant at $p<0.001$.

The impact of climate change on the water level of Lake Skadar

The decline in Lake Skadar's water level can be attributed to several factors: changes in precipitation, variations in temperature (affecting evaporation), alterations in the flow of the Morača River that feeds the lake, changes in the Bojana River, through which the lake empties into the Adriatic Sea, and anthropogenic impacts. Regarding precipitation and temperature, we used available measurement data from 4 MS in the Lake Skadar basin, namely MS: Podgorica, Nikšić, Golubovci, and Cetinje (Fig. 1). The average annual precipitation at the observed meteorological stations (Golubovci, Podgorica, Nikšić, and Cetinje) is 1,573 mm, 1,675 mm, 1,943 mm, and 3,327 mm, respectively. The trend in changes in monthly precipitation is insignificant for all months. Moreover, a greater number of months in the year show a slight increase in precipitation. For example, at the Podgorica meteorological station, seven months of the year exhibit a slight increase in precipitation. Annual precipitation trends at the four meteorological stations men-

Tab. 3. Trend and significance of average water levels in Lake Skadar (1948-2021).

	Trend (cm/decade)	*p*
Jan	-23.3	<0.001
Feb	-16.2	<0.001
Mar	-19.3	<0.001
Apr	-21.1	<0.001
May	-24.0	<0.001
Jun	-23.5	<0.001
Jul	-18.6	<0.001
Aug	-15.2	<0.001
Sep	-14.9	<0.001
Oct	-16.2	<0.001
Nov	-22.1	<0.001
Dec	-20.2	<0.001
Year	-19.3	<0.001
Winter	-19.2	<0.001
Spring	-21.7	<0.001
Summer	-19.0	<0.001
Autumn	-16.8	<0.001

Tab. 4. Trend and significance of annual precipitation and mean annual temperatures in the Skadar Lake basin.

	Precipitation (%/decade)				Temperature (°C/decade)[a]			
	MS Nikšić	MS Podgorica	MS Cetinje	MS Golubovci	MS Nikšić	MS Podgorica	MS Cetinje	MS Golubovci
Jan	-1.7	-0.2	-1.4	-1.0	0.16#	0.17#	0.09	0.15#
Feb	1.2	0.4	0.4	-0.1	0.21#	0.25*	0.13#	0.23*
Mar	2.0	4.6	1.7	3.0	0.25*	0.28**	0.20*	0.27**
Apr	1.6	0.3	-1.0	0.0	0.17#	0.25**	0.14#	0.27**
May	0.9	-0.3	-1.1	2.9	0.18*	0.25**	0.16#	0.30***
Jun	-1.9	0.3	-0.8	1.3	0.30***	0.39***	0.21*	0.33***
Jul	-0.2	-2.8	-3.7	-3.6	0.33***	0.40***	0.28**	0.45***
Aug	0.3	-3.8	-0.3	-3.8	0.31**	0.41***	0.27**	0.41***
Sep	1.3	2.1	0.6	1.9	0.02	0.11	0.01	0.08
Oct	0.6	0.4	-1.0	0.3	0.12#	0.14*	0.07	0.16*
Nov	-1.3	2.4	-1.8	-1.1	0.10	0.15#	0.04	0.11
Dec	-2.2	-0.1	0.6	1.7	0.01	0.03	0.00	0.01
Year	-0.2	0.6	-0.3	0.3	0.20***	0.26***	0.17*	0.24***
Winter	-1.7	-1.4	0.9	-1.1	0.11	0.16*	0.02	0.13#
Spring	2.4	2.4	1.3	1.7	0.20***	0.28***	0.19*	0.27***
Summer	-0.7	-1.3	-0.2	-2.3	0.31***	0.39***	0.27**	0.39***
Autumn	-0.1	1.7	-2.1	1.8	0.07	0.12*	0.01	0.11#

[a]Period: MS Podgorica 1948-2021; MS Cetinje 1948-2021; MS Nikšić 1949-2021; MS Golubovci 1978-2021; ***$p<0.001$; **$p<0.01$; *$p<0.05$; #$p<0.1$.

tioned above range from -0.3% to 0.6% per decade (Tab. 4). Regarding temperature, all months exhibit a positive trend, predominantly significant, with the most intense warming occurring during the summer months. At certain meteorological stations, the average monthly temperature in June, July, and August increases at a trend rate of up to 0.45°C per decade. There is evidence that this significant warming, particularly during summer, has led to increased water evaporation.

To verify this assumption, evaporation data from the ERA5-Land dataset were used for the grid cells covering the basin and the water surface of Lake Skadar. Four of these grid cells were provisionally named after the corresponding MS, while a fifth grid represents the central part of the lake's water body. ERA5-Land data show that total annual evaporation in the lake basin is increasing at a trend rate of up to 10.0 mm per decade. For the ERA5-Land grid cell corresponding to the Podgorica meteorological station, the average annual total evaporation (TotE) was estimated at 628.6 mm (Tab. 5). ERA5-Land data indicate a positive trend TotE across all five grid points within the Lake Skadar basin (Fig. 4), consistent with the significant rise in air temperature recorded at all meteorological stations. For example, the grid containing the Podgorica MS shows an increase of 7.0 mm per decade in TotE. In all cases, the upward trend is statistically significant at the highest level (p<0.001). The substantial increase in evaporation from Lake Skadar's surface is most likely a consequence of rising water temperatures, rather than air temperature alone, given the lake's relatively shallow depth (average of 5 m). According to data from the IHMSM covering the past 4-5 years, surface water temperatures at the Plavnica HS average around 6-8°C in January and 27-30°C in July and August.

It has been mentioned that the largest amount of water entering Lake Skadar comes from the Morača River. For the period 1948-2021, the trend of mean monthly flows of the Morača River is negative and statistically significant from May to August. The most

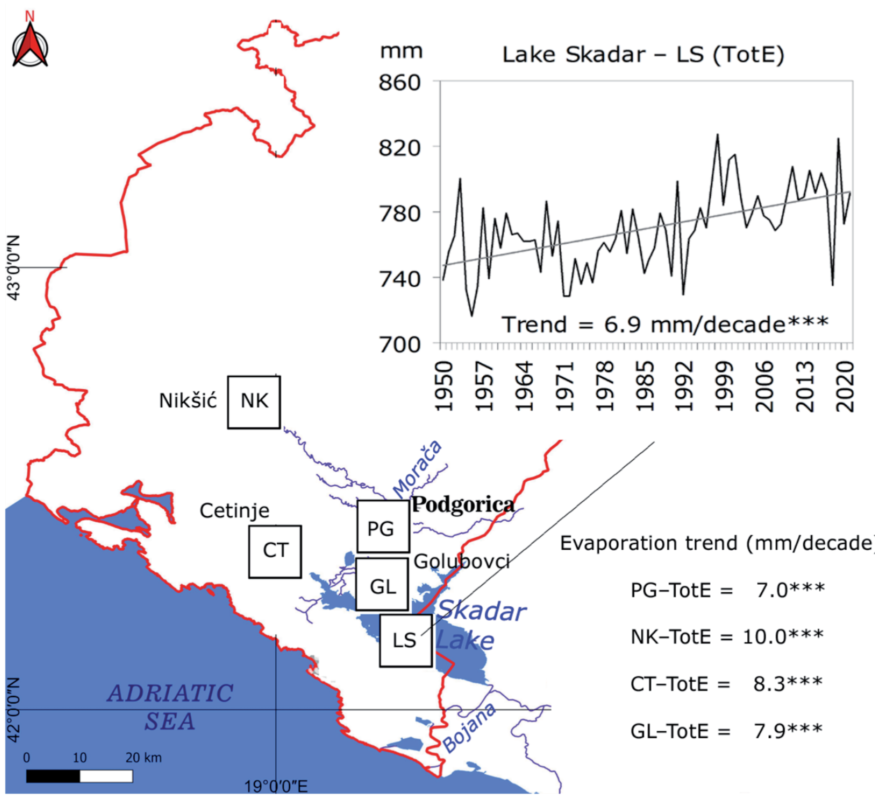

Fig. 4. Trend of annual total (TotE) evaporation based on ERA5-Land data for the period 1950-2021 for grids of 0.1°x0.1° containing: the center of Lake Skadar (LS), Podgorica (PG), Nikšić (NK), Cetinje (CT), and Golubovci (GL). ***p<0.001.

Tab. 5. Average, minimum, and maximum values of annual total (really) evaporation based on ERA5-Land data from 1950-2021 for grids of 0.1°x0.1°.

	Total evaporation (mm)				
	Lake Skadar	Podgorica	Nikšić	Cetinje	Golubovci
Average	771.3	628.6	556.8	541.5	641.1
Min	716.1	560.1	468.8	439.6	595.0
Max	829.9	690.3	659.2	665.8	735.8

intense decrease in flow was recorded for May and June (-5.7 and -8.9%/decade). The trend of mean annual flows for the observed 74-year period is -4.0 m^3/s/decade -2.5%/decade), and it is significant at the risk level of $p<0.1$. The Bojana River is the only outflow of the lake, and only water level data were available (flow was never measured). For the period 1960-2021, the trend in the mean annual water level of the Bojana River at the Fraskanjel HS profile is -8.4 cm per decade (-4.7% per decade). In any case, the Morača River shows a decreasing trend in water input to the lake, and judging by the water level, the Bojana River also exhibits a trend of reduced lake discharge through this river (Fig. 5).

The southern half of Montenegro (Adriatic basin) receives much higher precipitation than the northern half (Black Sea basin). For example, the Crkvice meteorological station, located at approximately 1,000 m above sea level on the Orjen mountain slope in the Bay of Kotor, has an annual average precipitation of 4,600 mm, making it probably the wettest place in Europe (Burić *et al.*, 2024b). Considering the above, the specific discharge was calculated for the portion of the Skadar Lake basin draining to the Podgorica HS profile. Based on the data on mean annual discharge (Q) and the basin area (F = 2,628 km^2) upstream of the Podgorica HS profile on the Morača River, the mean annual specific discharge is q = 59.7 l/s/km^2. Using q, the average annual runoff depth (Y) was also calculated. At the observed profile, the average annual runoff depth is Y = 1,884.0 mm per square meter. The Skadar Lake basin receives abundant precipitation, but its effective utilization is reduced because rainfall is unevenly distributed throughout the year. For the purposes of this study, based on data from eight precipitation–measuring stations and using the Thiessen polygon method along with precipitation gradients, it was determined that the average annual precipitation in the Skadar Lake basin upstream of the Podgorica HS profile is approximately 2,450 mm. Applying the simplified water balance equation for an average year (P = E + Y), the average runoff at the observed profile corresponds to an average evaporation of E = 566 mm in the basin. For comparison, according to ERA5-Land data, the total evaporation (TotE) for the Podgorica grid cell is 628.6 mm, and for the Nikšić grid cell it is 556.8 mm. The differences between evaporation values obtained via the water balance equation and the ERA5-Land dataset are small and arise from the use of different methodologies for estimating evaporation. The pronounced relief variability in the basin is an additional factor that complicates not only the estimation of evaporation but also precipitation, runoff, and other hydrometric parameters.

Runoff depth (Y) is an important component of the basin, as it represents the average amount of precipitation evenly distributed over the basin that contributes to the river flow. For this reason, the Y trend was calculated for the Skadar Lake basin upstream of the Podgorica HS profile. For the 74-year period studied (1948-2021), the results show that the average annual Y per square meter is decreasing at a trend rate of -45 mm per decade. This trend is statistically significant at the 10% significance level ($p<0.1$). Therefore, the decrease in runoff in the basin is most likely the result of increased evaporation and may be a key factor contributing to the observed trends of decreasing Morača River flow and Skadar Lake water level.

RAPS values for water level, precipitation and temperature

In order to accurately determine the breakpoint (year) of changes, the RAPS transformation of mean annual water levels, temperature, and precipitation was performed for the period 1948-2021. The obtained RAPS values of mean annual water levels for the Plavnica HS showed that two distinct time subseries could be distinguished: 1948-1981 and 1982-2021. Over the 74-year observation period, RAPS values indicate that significant changes in the water level of Lake Skadar occurred after 1981. These changes are primarily characterized by the more frequent occurrence of lower annual mean water levels. Previous research for the entire Montenegro for the period 1961-2020 (Burić *et al.*, 2024b) showed that the turning point of sudden changes in precipitation and temperature in most of the country was 1981 and 1997, respectively. Of course, the same results were obtained for a longer period (1948-2021), but they need to be commented on in the context of explaining the worrying decrease in the lake's water level.

The key tipping point (the highest peak) after which abrupt changes in annual precipitation totals are observed is also the year 1981. The second key tipping point is the year 2003, after which higher annual precipitation totals have been recorded more fre-

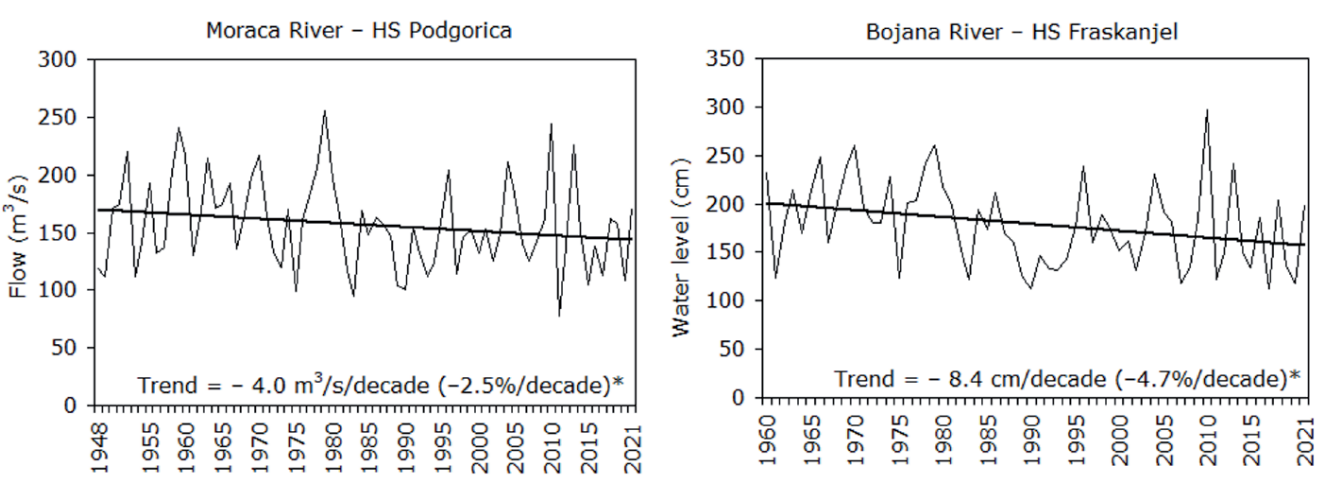

Fig. 5. Trend of the average annual flow of the Morača River (HS Podgorica: 1948-2021) and the average annual water level of the Bojana River (HS Fraskanj: 1960-2021). *$p<0.05$.

quently. In other words, the annual precipitation data can be divided into at least three main subperiods: 1948-1981, 1982-2003, and 2004-2021, within which several shorter subseries can also be identified. This underscores the marked interannual variability in precipitation patterns. However, despite the more frequent occurrence of higher annual precipitation totals after 2003, RAPS values for Lake Skadar's water level continue to show a declining trend. Finally, in regard to the mean annual temperature within the Lake Skadar basin, two distinct subperiods can be identified. The tipping point does not coincide with 1981, as observed for lake water levels and precipitation, but rather occurs in 1997. Specifically, the two main subperiods for mean annual temperature are 1948-1997 and 1998-2021. The Podgorica meteorological station serves as a representative case for illustrating RAPS transformations due to its central location and long data record (Fig. 6).

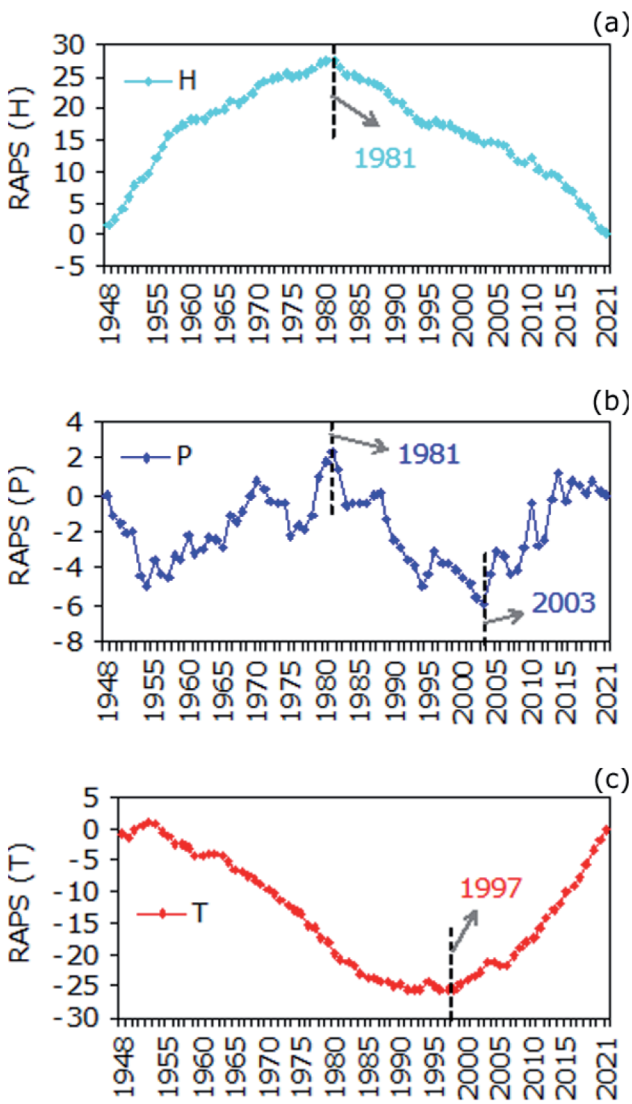

Fig. 6. RAPS-transformed values of mean annual: a) water levels of Lake Skadar (H) at the Plavnica Hydrological Station; b) precipitation (P); c) temperature (T) at the Podgorica Meteorological Station (1948-2021).

Although RAPS values indicate increased precipitation after 2003, lake water levels continue to decline, highlighting the dominant effect of rising temperatures This indicates that the continued occurrence of lower water levels in Lake Skadar after 2003 is attributable to rising air temperatures, which have undoubtedly led to increased evaporation from both the catchment area and the lake's surface, which was proved in the previous subsection.

Discussion

It is worth mentioning that the core of medieval Montenegro is closely tied to Lake Skadar, and its shores, numerous islands, and peninsulas bear traces of history and a rich cultural heritage: remnants of old towns, numerous fortresses, churches, and monasteries. It should be emphasized that the lake is home to a rich avian (ornithofauna) and fish (ichthyofauna) world, as well as lush swamp vegetation.

Due to the multifaceted importance of Lake Skadar -not only for Montenegro and neighboring Albania but also for the wider Balkan region and Europe- this study aimed, for the first time, to examine changes in water levels over the past seven decades (1948-2021). Additionally, the study aimed to assess the overall effects of changes in precipitation and air temperature (evaporation) within the lake's catchment on its water level, as well as the potential impacts of anthropogenic activities and runoff within the basin. The statistically significant decline in monthly, seasonal, and annual water levels is strongly associated with contemporary climate change, particularly the pronounced regional warming. For the period 1961-2020, Burić (2024) highlights that the increase in temperature is evident throughout Montenegro. Comparing the last two standard climate periods, the mean summer temperature in Podgorica for 1991-2020 was 26.8°C, which is 2.0°C higher than in the period 1961-1990 (24.8°C). There is no doubt that this pronounced warming has led to increased evaporation from the lake's basin, as confirmed by the analysis of evaporation data from the ERA5-Land network for five grid cells within the catchment area. The precipitation trend in the Lake Skadar catchment is stationary. Thus, changes in precipitation are unlikely to be the primary driver of the significant downward trend in Lake Skadar's water levels. For the somewhat shorter period 1961-2020, Burić *et al.* (2025) examined the trend and the influence of atmospheric and oceanic oscillations on the flow of the Morača River. Similar results were obtained when considering the longer period analyzed in this study. For the period 1948-2021, a significant downward trend in the flow of the Morača River, the main tributary of Lake Skadar, was observed. Furthermore, it is highly likely that increased evaporation, resulting from substantial warming, has caused a reduction in runoff from precipitation feeding the river, and consequently, the lake.

Lake Skadar drains into the Adriatic Sea via the Bojana River, and results indicate that the water level of this river has decreased significantly along the trend line. Therefore, the water level of Lake Skadar is declining primarily due to increased evaporation, which reduces the volume of water supplied to the lake by the Morača River. Additionally, the decreasing trend in Lake Skadar's water level also leads to reduced outflow through the Bojana River, which in turn contributes to the overall decline in the river's water level. However, the downward trend in the Bojana River cannot be considered a driving factor in the reduction of Lake Skadar's water level. The Bojana is a border river between Montenegro and Albania, and as such, its channel has not experienced significant anthropogenic degradation. In fact, the river has been facing sediment deposition in its bed and at its mouth in the Adriatic Sea for years, often causing flooding of surrounding areas during high water events. Paradoxically, even under conditions of bed elevation due to sediment and silt transported into the Bojana by the Albanian rivers Drin and Kir (raising the riverbed), the water level of the Bojana continues to decline. With a high degree of confidence, we can assert that changes in the Bojana's water level are not the cause of Lake Skadar's declining levels, as the riverbed is not lowering; on the contrary, it is rising. This further underscores the dominant influence of climate change, particularly the substantial increase in evaporation within the lake's catchment.

Also, the results obtained allow us to assert with a high degree of confidence that changes in precipitation could not have had a dominant influence on the long-term component -the overall trend of decreasing water levels. However, changes in daily precipitation extremes have been observed over the past 2-3 decades (Burić and Doderović, 2022), specifically in terms of an increase in the number of days with heavy rainfall, as well as an increase in the number of days without precipitation. Supporting this assertion is the fact that during the entire period of instrumental measurements (from 1948 to the present), Lake Skadar recorded its highest and lowest water levels within the past 14 years: the absolute maximum on December 4, 2010 (588 cm above the zero point), and the absolute minimum on October 4, 2017 (-12 cm). Thus, the long–term component of the declining water level in Lake Skadar is likely influenced by significant warming (resulting in increased evaporation from both the catchment area and the lake itself). From a short-term perspective, the reasons for the pronounced interannual fluctuations in water levels should primarily be sought in the variations in precipitation within its basin, which are affected and by atmospheric oscillation variations (Burić *et al.*, 2025).

Similar changes in surface freshwater bodies (lake water levels and river discharge) are also observed in neighboring countries of Montenegro and the surrounding region. Based on flow data from 94 hydrological stations in neighboring Serbia for the period 1961-2010, the results indicate that most rivers show a negative trend (Kovačević-Majkić and Urošev, 2014). From 1956 to the early 1990s, Plitvice Lakes in Croatia displayed a slight increasing trend in water levels, while for the period 2001-2019, a negative tendency in the mean annual water level was observed (Radišić *et al.*, 2021). Lake Prespa, located in the border region of North Macedonia, Albania, and Greece, has experienced a significant decrease in water levels from 1984 to 2020 (Soria and Apostolova, 2022). Over the past decades, Lakes Koronia and Volvi in the Mygdonia Basin in northern Greece have exhibited a declining trend in water levels, likely due to a combined effect of anthropogenic and climatic factors (Kolokytha *et al.*, 2017). Studies of surface hydrological processes in the Mygdonia Basin indicate that a continuous decrease in average annual surface runoff into Lakes Koronia and Volvi can be expected until the end of the 21st century (Malamataris *et al.*, 2020). In neighboring Bosnia and Herzegovina, there is a trend of decreasing river flows from 1961 to 2020, particularly in the summer period (Gnjato *et al.*, 2023). During the period 1917-2014, the water level of Lake Orta in northern Italy decreased during the winter and summer seasons (Saidi *et al.*, 2016). Over the past three decades, the impact of climate change on the water balance of Lake Garda, the largest lake in Italy, has become increasingly evident (Hinegk *et al.*, 2023). Research covering the period 1845-2016 indicates a significant reduction in both inflow and outflow in Lake Como in the Italian Alps. However, this reduction in outflow can only partially be attributed to climatic variations, as it is largely driven by anthropogenic factors, including water withdrawals for irrigation and increased evapotranspiration losses due to natural reforestation (Ranzi *et al.*, 2021).

In any case, the observed changes in the water level of Lake Skadar do not indicate that it will disappear in the near future, but the significant downward trend in water levels is concerning. The main cause of the decrease in the water level of Lake Skadar is climate change (significant warming - significant increase in evaporation), but human influence should not be ruled out. In recent decades, the amount of water used for irrigating arable land has significantly decreased, as land nationalized after World War II has been returned to its original owners and their descendants by law. This has led to the fragmentation of plots and a reduction in irrigation practices, as these parcels are now used for other purposes (further divided and sold for the construction of family homes). According to official data from the Government of Montenegro, the estimated volume of water used for irrigating arable land in the country was approximately 8.8 million m³ in 2006, which fell to only 1.7 million m³ of surface and groundwater used for irrigation by 2010 (Government of Montenegro, 2017). Nevertheless, the anthropogenic impact on the water level of Lake Skadar cannot be completely disregarded.

Three key spatial degradations that have certainly influenced the trend of falling water levels in the lake are: uncontrolled deforestation, frequent recent wildfires, and excessive gravel exploitation. The disappearance of forest complexes in the mountainous parts of the basin and the wildfires that have become a regular occurrence in summer in Mediterranean Montenegro (Pešić *et al.*, 2020) affect the runoff of precipitation by reducing its infiltration into the soil, thereby increasing surface runoff thereby intensifying erosive processes. Finally, the uncontrolled decades-long exploitation of gravel and sand, especially around and in the lower course of the Morača River (downstream of HS Podgorica), has likely caused a lowering of the water level in Lake Skadar. In the last two to three decades, enormous amounts of sand have been extracted from the Morača Riverbed and its coastal area. The water level of Lake Skadar largely depends on the amount of water (flow) brought into it by the Morača River, as well as the water level of this river. In fact, downstream of the HS Podgorica, the extensive exploitation of sand and gravel in the lower reaches of the Morača River, not far from its confluence with Lake Skadar, has led to a significant deepening of the riverbed, in some sections by more than 10 meters. It is possible that this deepening near the river's mouth contributed to a decline in groundwater levels, which may also have influenced the reduction in Lake Skadar's water levels. This hypothesis requires comprehensive geo-hydrological studies and hydrometric measurements, although such investigations are beyond the scope of the present study. It is important to emphasize that the degradation of the Morača Riverbed (sand and gravel extraction) occurred several kilometers downstream of the HS Podgorica. The significant reductionn in the flow of HS Podgorica, together with the marked decrease in runoff from precipitation within the catchment, supports the conclusion that climate change -specifically the substantial increase in evaporation due to intense warming- is the dominant factor driving the decline in Lake Skadar's water levels. It is likely that the lowering of the lake's water level is partly influenced by riverbed degradation near the Morača River's mouth, but the magnitude of this effect requires further investigation.

It should be emphasized that Montenegro is very rich in precipitation. According to data from the national Institute of Hydrometeorology and Seismology (IHMSM), the country ranks among the top 4% of the world's territory in terms of average runoff. The mean annual specific runoff (q) for the entire country is approximately 40 l/s/km^2, corresponding to a volumetric flow of around 19.5 km^3/year. Notably, 95.3% of the country's river flow is generated within national borders, with both the sources and catchments located entirely within Montenegro (http://www.meteo.co.me/page.php?id=136). For the Lake Skadar catchment, up to the Podgorica HS profile, the results indicate that the mean annual specific runoff is significantly higher (59.7 l/s/km^2) than the national average, while the mean annual runoff depth is 1,884.0 mm per m^2 of catchment area. Given the increasing demand for water, these findings highlight the need for decision–makers in Montenegro to develop strategies for the protection and sustainable management of the country's abundant water resources. This is particularly critical for the Lake Skadar catchment, which contains the largest arable areas and the highest population density in Montenegro.

Conclusions

The findings clearly indicate a serious and persistent decline in the water level of Lake Skadar. In the observed 74-year period (1948-2021), the average monthly water levels of Lake Skadar show a significant decreasing trend for all months, as well as at the seasonal and annual level (-19.3 cm per decade). Data from standardized deviations and 10-year averages reveal that low water levels have prevailed in Lake Skadar over the past four decades. The RAPS transformation indicates that the tipping point (year) from which abrupt changes in the water level of Lake Skadar begin is 1981, in terms of the increasingly frequent occurrence of low water levels. It is essential to highlight the increased frequency of extreme events. For instance, in the past 14 years, Lake Skadar experienced both its highest water level (early December 2010) and its lowest water level (September–early October 2017) in the entire period of water level measurements (from 1948 to the present). The impact of climate change is evident, and the alarming decline in Lake Skadar's water level can be attributed to several factors: a significant increase in evaporation within its basin and from its surface (6.9-10.0 mm per decade), a decrease in the flow of its main tributary, the Morača River (-2.5% per decade), and the anthropogenic degradation of the terrain along the river's lower course. To protect the water sources near Lake Skadar that supply water to the population along the Montenegrin coast, decision-makers have already implemented a ban on sand and gravel extraction from the Morača Riverbed. Namely, over the past few years, both electronic and print media in Montenegro, citing expert opinions, have rightly emphasized that the uncontrolled and extensive exploitation of sand and gravel along the lower reaches of the Morača Rive r-from downstream of Podgorica to the mouth of Lake Skadar- represents one of the country's most pressing environmental problems. The severity of the issue is further highlighted by the Government of Montenegro's 2022 decision to impose a complete ban on sand and gravel extraction from all watercourses in the country (https://me.ekapija.com/news/3795469/real-estate/investments). One of the measures that should be implemented as soon as possible is the protection of existing forests from logging and fires, as well as afforestation wherever feasible. Forests have a significant positive impact on terrestrial water resources and play an important role in mitigating climate change. A recent study by the Food and Agriculture Organization (FAO) highlights a range of innovative examples in the forestry sector aimed at a sustainable future (FAO, 2024). Montenegro and other Balkan countries should consult this study to support the development of policies for forest conservation, restoration, and sustainable management. In the upper part of the Lake Skadar catchment, catastrophic fires occurred in mid–August 2025. This underscores the urgent need for fire protection measures and the preservation of water resources.

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