

ASSESSMENT OF FISH STOCK STATUS WITH A SPECIAL EMPHASIS ON REAL AND POTENTIAL PRODUCTION IN THE TERRITORY OF NATIONAL PARK KOPAONIK, SERBIA

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ABSTRACT. This study investigated the spatial and temporal dynamics of brown trout populations within Kopaonik National Park, Serbia, from 2010 to 2023. Population changes were evaluated through analysis of biomass, real production estimated using Chapman's method, and potential production calculated according to the Leger–Huet–Arrignon method. The results showed that *Salmo trutta* Linnaeus, 1758 biomass and production in the mountain rivers of NP Kopaonik were primarily constrained by cumulative habitat degradation driven by anthropogenic pressures. This resulted in pronounced spatial and temporal instability of populations, ranging from complete population loss in some rivers to strong interannual fluctuations in biomass and production in others. These findings highlight the need for continuous monitoring, habitat restoration, and targeted conservation measures to ensure the long-term stability of mountain river ecosystems and sustainable management of fish stocks in protected areas.

Keywords: Fish production, brown trout, protected areas, anthropogenic impact

INTRODUCTION

Although they cover only 1 % of the Earth's surface, freshwater ecosystems support as much as 50% of fish biodiversity and over 10% of the total biodiversity of our planet (DUDGEON *et al.*, 2006). The disproportion between their limited area and exceptional biological value highlights the crucial role of freshwater ecosystems in global biodiversity conservation

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(SAUNDERS *et al.*, 2002; STRAYER and DUDGEON, 2010; TICKNER *et al.*, 2020; SIMIĆ *et al.*, 2023). Located in the southeastern part of the European continent, formed under specific geotectonic, paleoclimatic, and paleogeological conditions, the Balkan Peninsula constitutes one of the most important hotspots of freshwater ecosystems in Europe (PERRIER *et al.*, 2013; SIMIĆ *et al.*, 2016; MARIĆ *et al.*, 2022; SIMIĆ *et al.*, 2023). The processes that shaped the Balkans resulted in numerous networks of mountain rivers and streams, karst areas, natural lakes, wetlands, and marshy zones, which today support the survival of multiple species (KOSTOSKI *et al.*, 2010; SIMIĆ *et al.*, 2023; VILENICA *et al.*, 2024). Located in the central part of the Balkan Peninsula, Kopaonik is one of the largest mountain massifs in Serbia. It belongs to the Dinaric mountain system (Dinarides) and is located on the eastern periphery, forming a transitional zone between the Dinaric Mountains and the Vlasina-Raska highlands, covering a total area of 2.758 km² (ANONYMOUS, 1981; SIMIĆ *et al.*, 2016; VUKOIČIĆ *et al.*, 2020; VUKOIČIĆ *et al.*, 2023). In 1981, Kopaonik was declared a National Park, under the Law on National Parks of the Republic of Serbia (ANONYMOUS, 1981). National Park Kopaonik has also been recognized as an Important Bird Area (IBA), an Important Plant Area (IPA) and a Prime Butterfly Area (PBA), and is classified as a Potential Emerald Site (RS0000002) under the Bern Convention (BIRDLIFE INTERNATIONAL, 2000; ANDERSON, 2005; JAKŠIĆ, 2008; COUNCIL OF EUROPE, 2008; SIMIĆ *et al.*, 2016). The rivers of NP Kopaonik provide important habitats for brown trout (*Salmo trutta* Linnaeus, 1758) and contribute to the conservation of the species in Serbia (SIMIĆ *et al.*, 2023). Their cold, well-oxygenated, fast-flowing waters, typical of rhithral river sections, create highly favorable conditions for sustaining native brown trout populations (SIMIĆ and SIMIĆ, 2012; ŠKRABA JURLINA *et al.*, 2020). However, over the past two decades, NP Kopaonik and its river ecosystems have been increasingly affected by a wide range of anthropogenic pressures. These include deforestation, mining, inappropriate stocking practices resulting in genetic introgression from non-native brown trout, untreated wastewater discharge, tourism development, construction of temporary recreational facilities and picnic areas, illegal fishing, and the construction of hydropower plants (SIMIĆ *et al.*, 2016; WEISS *et al.*, 2018; VELIČKOVIĆ *et al.*, 2024). Together, these pressures have altered the hydrological regime of rivers and streams, causing habitat fragmentation and the progressive decline of formerly stable brown trout populations. Moreover, their cumulative effects have contributed to the long-term decline of brown trout populations throughout Serbia (VELIČKOVIĆ *et al.*, 2024).

In addition, the increasingly pronounced effect of climate change significantly affects the general characteristics of mountain rivers (JAKOVLJEVIĆ *et al.*, 2023). The rise in average annual air temperature, and consequently in river water temperature, reduces the availability of dissolved oxygen, which is crucial for oxygen-loving species such as brown trout (NIEDRIST and FÜREDER, 2023; SOLÁR and TOMAŠKOVIČ, 2023). According to JONSSON (2024), salmonids are particularly sensitive to global warming, which negatively affects their overall biological productivity, reproductive success, and migration within river systems. Events such as floods, increasingly frequent annual droughts, and changes in precipitation patterns further reduce population resilience and amplify the impacts of existing anthropogenic pressures (JAKOVLJEVIĆ *et al.*, 2023; VELIČKOVIĆ *et al.*, 2024).

Cumulative anthropogenic stressors and progressive habitat deterioration impose a clear signature on the interannual variability of brown trout biomass, real and potential production in the mountain rivers of NP Kopaonik. This research aims to analyze the spatial and temporal dynamics of brown trout populations from 2010 to 2023, with particular attention to fish biomass, real and potential production. By adopting this approach, the study seeks to provide a clearer understanding of the current population status and to identify the principal threats to species survival. The findings will serve as a foundation for developing effective conservation measures and management strategies to preserve native salmonids.

MATERIALS AND METHODS

The Kopaonik mountain massif is located in the central part of Serbia. It extends in a northwest southeast direction, over approximately 75–82 km. The massif is separated from neighbouring mountains by rivers that surround it, namely the Ibar, Sitnica, Jošanica, Koznica, Rasina, Toplica, and Lab (GAVRILOVIĆ and DUKIĆ, 2014). These rivers belong to the Ibar watershed, within the West Morava River system (Black Sea basin) (GAVRILOVIĆ and DUKIĆ, 2014). All rivers and streams originate from the central parts of the National Park, flowing outward in all directions (Fig. 1) (JANKOVIĆ *et al.*, 2005). The northern part of the park is drained by the Gobeljska and Samokovska rivers, the latter being the longest watercourse on the mountain (JANKOVIĆ *et al.*, 2005; SIMIĆ *et al.*, 2010). The Barska and Lisinska rivers drain the western slopes of the massif and merge at its southwestern foothills to form the Rudnička River (Fig. 1). On the opposite side of these two rivers, to the east, lies the Brzečka River, which, after 20 km, flows into the Rasina River within the territory of Brus (JANKOVIĆ *et al.*, 2005).

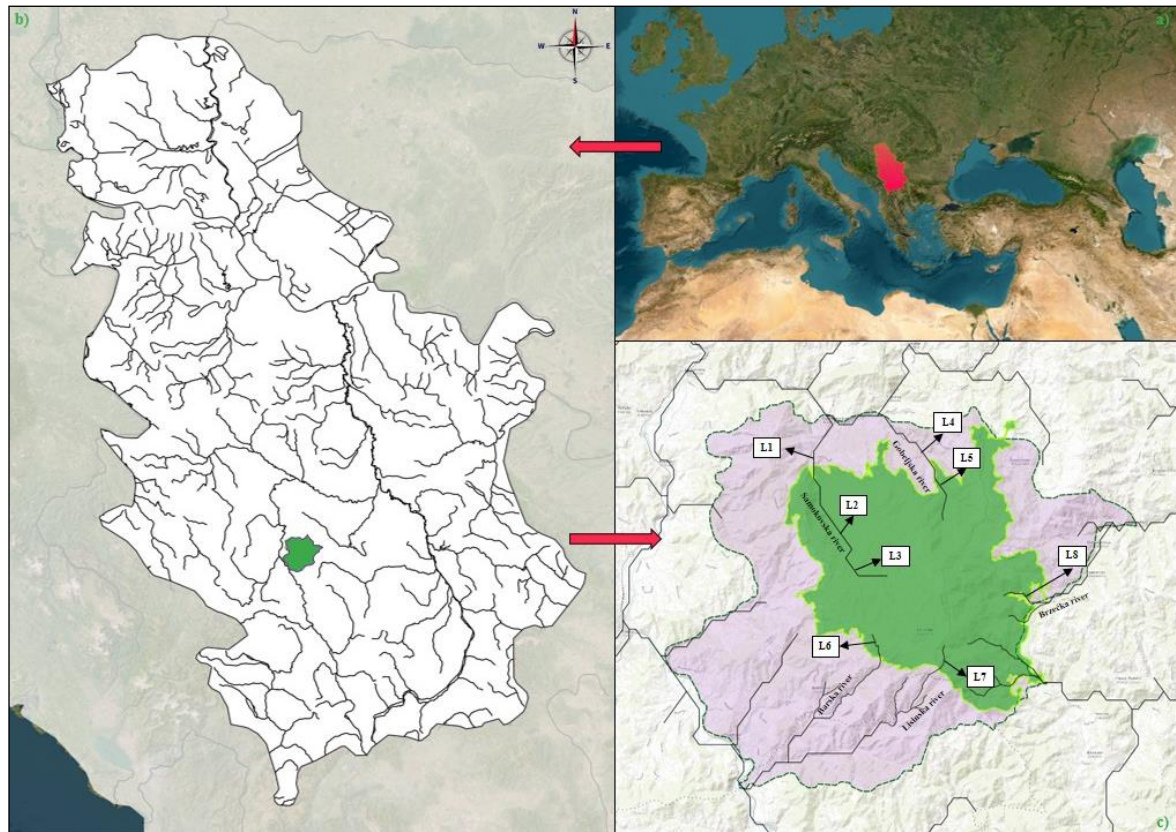


Figure 1. Study area: (a) Location of Serbia within the European continent. (b) Position of Serbia on the Balkan Peninsula, emphasizing its central location within the region. (c) Area of the Kopaonik mountain massif and the boundaries of NP Kopaonik within the study region. Rivers and sampling sites are marked on the map.

Sampling sites

The research was conducted at eight sites (Tab. 1) across five rivers (Fig. 2), within the NP Kopaonik, including Samokovska River (upper, middle, and lower courses), Gobeljska River (upper and lower courses), Brzečka River (middle course), Lisinska River (middle course), and Barska River (middle course). The GPS coordinates of the exact locations were georeferenced using the Garmin GPSMAP 64s device (Tab. 1).

Table 1. Investigated localities in the NP Kopaonik

Name of locality	Maped locality names	GIS coordinates	Altitude / Elevation
Samokovska River Upper course	L1	43.291817° N, 20.756183° E	1509 a.s.l.
Samokovska River Middle course	L2	43°19.617' N, 20°45.489' E	1386 a.s.l.
Samokovska River Lower course	L3	43°21.355' N, 20°44.612' E	786 a.s.l.
Gobeljska River Upper course	L4	43°20'20.19"N 20°49'22.63"E	1066 a.s.l.
Gobeljska River Lower course	L5	43°22.986' N, 20°47.201' E	717 a.s.l.
Barska River	L6	43°18'20.76"N 20°51'54.18"E	1346 a.s.l.
Lisinska River	L7	43°16'52.70"N 20°45'19.25"E	1176 a.s.l.
Brzečka River	L8	43°17'33.71"N 20°45'37.01"E	1078 a.s.l.



Figure 2. Representative sampling sites along the investigated rivers: (a) Gobeljska River, (b) Lisinska River, (c) Samokovska River, (d) Brzečka River, and (e) Barska River (photos by V. Simić and A. Cvetković, 2023).

Fish sampling

Fish samples were obtained using the electrofishing method (Aquatech IG 1300, AquaTech, Kitzbühel, Austria; SRPS EN 14011, 2008) along 50-meter-long sections from one side of the riverbank to the other during the summer period at the mentioned localities (Tab. 1).

To ensure consistency, the same sampling sites, section lengths, and sampling protocols were applied throughout the entire study period. The sampling frequency, duration, and intensity of electrofishing effort were standardized each year to maintain comparability of data across years. The collected fish were identified to the species level (KOTTELAT and FREYHOF, 2007), and their standard length (cm), total length (cm), weight (g), and total abundance (N) were measured, after which the fish were safely returned to the rivers (TREER, 2008). In addition to field collected data, the majority of the analyzed dataset was obtained from the database of the Center for Fisheries and Conservation of Inland Waters – Aquarium, Faculty of Science, University of Kragujevac (SIMIĆ *et al.*, 2006), established through continuous fish stock monitoring within the Fishery Management Programs of Kopaonik National Park during the period 2010-2023 (SIMIĆ *et al.*, 2010, 2016, 2020).

Quantitative Assessment of Fish Biomass, Real Production, and Estimation of Potential Production Using the LEGER, HUET, AND ARRIGNON (1970) Method

Fish biomass (B) was calculated as the product of the total number of individuals (N_i) and their average weight (W_i) for each species or class (CHAPMAN, 1966, 1971):

$$B = \sum(N_i \times W_i) \quad (1)$$

Estimation of real production (P) of fish was performed using Chapman's method (CHAPMAN, 1971), which provides a realistic indicator of fish mass increase per unit area or length (CHAPMAN, 1966, 1971). Real production is calculated using the formula $P = \sum(G \times B_t)$, where G represents the instantaneous growth rate (calculated as the difference in natural logarithms of mean individual weight between successive age classes: $G = \ln W_{t+1} - \ln W_t$), and B_t represents the total biomass of individuals within a given age class (calculated as $B_t = N_t \times W_t$) (CHAPMAN, 1966, 1971):

$$P = \sum(G \times B_t) \quad (2)$$

Potential production (PN) was calculated using the Leger-Huet-Arrignon method (Tab. 2) (HUET, 1949, 1964, 1970; ARRIGNON, 1976; NĂSTASE *et al.*, 2018). The formula $PN = L \times K \times B$ was applied, where L is the length of the watercourse (in km) for running waters, K is the productivity coefficient derived from the product of five factors ($K = K_1 \times K_2 \times K_3 \times K_4 \times K_5$; see Tab. 2), and B is the biogenic capacity (ranging from 1 to 10), reflecting the abundance of food source for fish (HUET, 1964; ARRIGNON, 1976; NĂSTASE *et al.*, 2018):

$$PN = L \times K \times B \quad (3)$$

Table 2. Calculation of the productivity coefficient (K) according to Leger, Huet, and Arrignon method (1970) (ARRIGNON, 1976; VOICAN *et al.*, 1981; STARAS, 1985; NĂSTASE *et al.*, 2018)

K1 The physical characteristics of the habitat (1)		K2 The chemical characteristics of the habitat (2)		K3 Fish type (3)		K4 Fish age (4)		K5 Characterize (5)	
<i>The temperate region</i> <i>(10 °C)</i>	1	<i>Acidic waters</i>	1	<i>Salmonids</i>	1	<i>More than 6 months</i>	1	<i>urban type continuous</i>	0.2 – 0.5

Table 2. continued

Table 27 continued									
K1 The physical characteristics of the habitat (1)		K2 The chemical characteristics of the habitat (2)		K3 Fish type (3)		K4 Fish age (4)		K5 Characterize (5)	
<i>The warm temperate region (16 °C)</i>	2	<i>Acidic waters</i>	1	<i>Cyprinids reophylous</i>	1.5	<i>More than 6 months</i>	1	<i>urban type diffuse</i>	0.5 – 1
<i>The intertropical region (22 °C)</i>	3	<i>Alkaline waters</i>	1.5	<i>Cyprinids limnophylous</i>	2	<i>Less than 6 months</i>	1.5	<i>Pastoral type</i>	
								<i>Valley 1b</i>	1.1
								<i>Valley 1c</i>	1.2
								<i>Valley 2</i>	1.3
<i>Equatorial region (24 °C)</i>	4	<i>Alkaline waters</i>	1.5	<i>Cyprinids limnophylous</i>	2	<i>Less than 6 months</i>	1.5	<i>Herbal type</i>	
								<i>Valley 1c</i>	1.4
								<i>Valley 2</i>	1.5
								<i>Valley 3</i>	1.6 – 1.8

(1) Average annual air temperature; (2) Acidity or alkalinity of water; (3) Dominant fish community type in the river section; (4) Coefficient involving individuals less than 6 months in nurseries and juvenile breeding pools; (5) Continuity type characteristic;

Statistical Analysis and Data Evaluation

Statistical analysis was performed using RStudio (R version 4.4.2) (R CORE TEAM, 2024; POSIT TEAM, 2024). Descriptive statistics were calculated for all variables. Prior to statistical testing, the normality of the data distribution was examined using the Shapiro-Wilk test (SHAPIRO and WILK, 1965). Since the data did not meet the assumption of normality, differences in real production, potential production, and biomass among the studied rivers were assessed using the Kruskal-Wallis H test (KRUSKAL and WALLIS, 1952). When significant differences were found, post-hoc pairwise comparisons were conducted using Mann–Whitney U (MANN and WHITNEY, 1947) tests with Bonferroni correction to control for multiple testing. Spearman's rank correlation (SPEARMAN, 1904) analysis was used to evaluate relationships among the examined parameters, with statistical significance defined at $p < 0.05$.

RESULTS AND DISCUSSION

Assessment of Fish Community Structure

During this study, only one fish species, the brown trout, was recorded. Compared with historical data from before 1995, JANKOVIĆ *et al.* (2005) confirmed greater ichthyofaunal diversity in the same rivers. During that period, the Lisinska River was dominated by brown trout, chub (*Squalius cephalus* Linnaeus, 1758), and Danube barbel (*Barbus balcanicus* Kotlík, Tsigenopoulos, Ráb and Berrebi, 2002), while the Barska River was characterized by the constant presence of European bullhead (*Cottus gobio* Linnaeus, 1758). Samokovska, Gobeljska, and Brzečka rivers were inhabited exclusively by brown trout.

Biomass Measurement and Evaluation of Real and Potential Fish Production.

The quantitative assessment of production parameters in the Samokovska River reveals a distinct pattern of interannual variability in real and potential production, as well as in fish biomass, for the time period from 2010 to 2023. The Kruskal-Wallis H test performed across all investigated rivers revealed statistically significant differences among the rivers for real production ($\chi^2 = 20.004$; $p < 0.001$), potential production ($\chi^2 = 10.245$; $p = 0.036$), and biomass ($\chi^2 = 26.551$; $p < 0.001$). Based on descriptive statistics and mean rank values, the Samokovska River consistently showed the highest values for all three parameters, indicating its position as the most productive river within the study area. Post-hoc pairwise comparisons using Mann–Whitney U tests with Bonferroni correction further revealed that the Samokovska River differed significantly from the Lisinska River in terms of real production ($p = 0.004$) and biomass ($p = 0.004$), while the difference in real production between Samokovska and Brzečka approached statistical significance ($p = 0.052$). Within the river itself, average real production amounted to 11.85 ± 5.21 kg/km, potential production to 14.96 ± 8.13 kg/km, while biomass reached 21.67 ± 10.81 kg/km. Real production peaked at 18.30 kg/km in 2016, then declined abruptly in 2019–2020 to 4.40 kg/km, before partially recovering to 9.77 kg/km in 2023. Biomass followed a nearly identical path, with a maximum of 41.26 kg/km in 2016, a marked decline in 2019, and a partial rebound (Fig. 3). In contrast, potential production displayed an inverse trend, reaching its highest value of 22.25 kg/km in the years when real production was at its minimum, illustrating a clear ecological mismatch between the river's biological capacity and its realized production. The slightly negative correlation between real and potential production ($\rho = -0.638$; $p = 0.089$), although not statistically significant, suggests that these parameters respond differently to environmental disturbances, reinforcing the interpretation that hydromorphological pressures affect real production more strongly. In contrast, the strong and statistically significant positive correlation between real production and biomass ($\rho = 0.854$; $p = 0.007$) provides solid evidence that increases in trout biomass are directly associated with increases in real production.

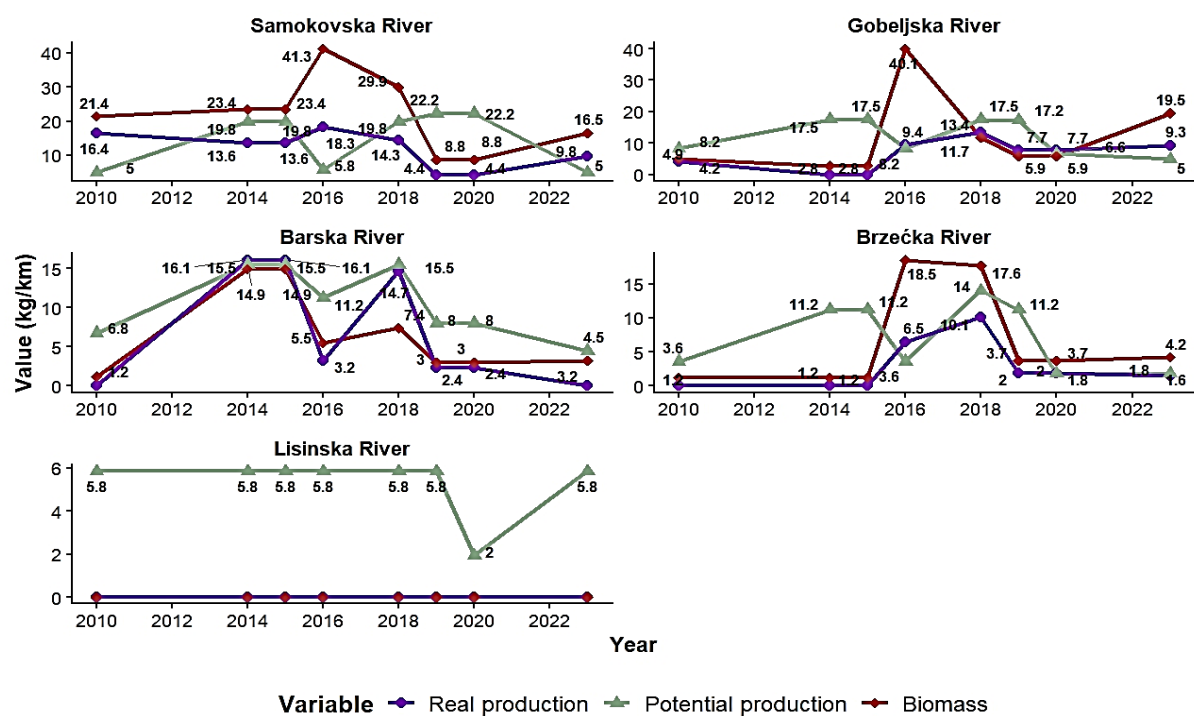


Figure 3. Temporal dynamics of real production, potential production, and fish biomass across five investigated rivers of NP Kopaonik from 2010 to 2023.

The production declines recorded in recent years in the Samokovska River can be linked to hydromorphological alterations associated with small hydropower plants (MHPs), which reduce habitat availability, fragment populations, and disrupt the river's longitudinal connectivity (FETTE *et al.*, 2007; ALMEIDA *et al.*, 2019; SIMONOVIĆ *et al.*, 2021). These impacts have been widely documented across European and North American rivers. Evidence from Norway demonstrates reduced connectivity and significant population declines in salmonids downstream of hydropower barriers (HEGGENES and RØED, 2006; JUNGE *et al.*, 2014; CARVAJAL-QUINTERO *et al.*, 2016). Additional changes in flow regime, dissolved oxygen, and water temperature, parameters critical for salmonid ecology, further contribute to reduced production and biomass (NILSSON *et al.*, 2005; CARVAJAL-QUINTERO *et al.*, 2016). KLÜTSCH *et al.* (2019) demonstrated that such fragmentation can lead to long-term genetic isolation of trout populations, a phenomenon particularly relevant to hydrologically regulated rivers such as the Samokovska and Gobeljska. (LIERMANN *et al.*, 2012; KLÜTSCH *et al.*, 2019). The efficiency of fish passes is crucial for mitigating habitat fragmentation, as their effectiveness depends on the river's hydromorphological characteristics, the fish pass's design, and the requirements of the target fish species (OVIDIO *et al.*, 2002).

In Portugal, results have indicated that only 44.40% of fish passes function effectively for the target species (SANTOS *et al.*, 2006). Considering that brown trout in Serbia do not exhibit a strongly pronounced migratory instinct like some other salmonid species, the efficiency of fish passes may be significantly reduced in rivers and streams of NP Kopaonik (LOIZEAU and DOMINIK, 2000; OVIDIO *et al.*, 2002; WÜEST, 2002; SCRUTON *et al.*, 2003; ARMSTRONG *et al.*, 2010). A comparable decline in biomass has been observed in the Aare, Rhone, Reuss, and Ticino rivers in Switzerland, where hydrological regime changes caused by flow diversions led to reduced fish biomass (LOIZEAU and DOMINIK, 2000; WÜEST, 2002; SCRUTON *et al.*, 2003). In the Samokovska River, however, the decline in biomass and real production was more pronounced in the upper reaches, as evidenced from 2019 and 2020 data, when both metrics in the upper and middle reaches dropped to 0 kg/km, while the lower reach retained measurable values of real production (7.84 kg/km) and biomass (23.9 kg/km). The main reason for this decline was likely the impact of organic pollution originating from municipal wastewater discharged directly into the river. As shown in Figure 3, the decline in biomass and production coincides with periods of increased organic pollution, suggesting that pollution caused mortality in part of the population, while another portion successfully migrated downstream (SIMIĆ *et al.*, 2021). Prior to this decline, the upper reaches were characterized by high biomass values, reaching 38,6 kg/km during 2014–2015, indicating that the observed reduction represents a sudden collapse. Following the construction of the mini-hydroelectric power plant in the middle reach of the river, individuals that migrated downstream were no longer able to return to the upper reaches due to newly created barriers and inadequate fish passes, which further contributed to the long-term reduction of real production and biomass in the upper reach. During this period, potential production in the upper reach remained relatively high (21–25 kg/km) compared to simultaneously low or absent values of biomass and real production, even after the original pollution source was no longer present, indicating that poaching likely represents an additional and significant threatening factor in this section of the river.

A similar trend is observed in the Gobeljska River, which, unlike the Samokovska, exhibits far more pronounced oscillations in production and biomass, reflecting the typical ecological consequences associated with the operation of small hydropower plants (FETTE *et al.*, 2007; POFF *et al.*, 2007). Descriptive statistics show that the average real production in Gobeljska is 6.46 ± 4.73 kg/km, whereas the potential production shows a higher average of 12.23 ± 5.67 kg/km. The examined period reveals substantial fluctuations in real production between 2014 and 2018, ranging from 0 to 13.43 kg/km, with the maximum recorded in 2018.

Biomass follows a comparable pattern, peaking in 2016 at 40.10 kg/km before sharply declining and exhibiting only partial recovery by 2023, as illustrated in Figure 3. In contrast, potential production remained relatively stable until 2019, after which a gradual decline occurred, indicating a long-term negative influence on the production capacity of the Gobeljska River.

The Spearman's correlation coefficient between real and potential production parameters is negative and statistically insignificant ($\rho = -0.311$; $p = 0.454$), suggesting that the temporal oscillations of real and potential production are not synchronized and are likely driven by different environmental influences. BARAN *et al.* (1995) demonstrated that flow reduction downstream of dams in the French Pyrenees results in reduced shallow marginal habitats for juvenile brown trout, leading to decreased production. The gradual decline in potential production in the Gobeljska River is closely associated with the observed reduction in macrozoobenthos biomass, a fundamental component of trout diet (WELCOMME, 1983; DWIRASTINA *et al.*, 2021; XIAOCHENG *et al.*, 2008, SIMIĆ *et al.*, 2021). According to SIMIĆ *et al.* (2022), macrozoobenthos biomass decreased from 26.6 g/m² in 2010 to 14.93 g/m² in 2023, indicating a continuous impoverishment of the trophic base. This decline directly reduces trout production potential, given their dependence on benthic resources (WELCOMME, 1983; DWIRASTINA *et al.*, 2021).

Somewhat different data were obtained for the Barska River, which shows moderate oscillations in the measured parameters, with occasional periods of extremely favorable environmental conditions and a gradual decline after 2016. Descriptive statistics show average values for real production of 6.86 ± 7.37 kg/km, potential 10.63 ± 4.44 kg/km, while average biomass is 6.65 ± 5.41 kg/km. In some years, Barska recorded high values of real production, with a maximum of 16.10 kg/km, which is similar to values comparable to those of the much larger Samokovska River. In same period potential production reached 15.50 kg/km, which indicates almost complete utilization of the ecological potential of the habitat. A similar pattern was observed in 2018, when the values for both productions nearly equalized (Figure 3), but after that period and until 2023, there was a gradual decline, so that by 2023 the values for real production were immeasurable and potential production had fallen to only 4.50 kg/km. Unlike the other analyzed watercourses, the Barska River was the only one to show a statistically significant positive correlation between real and potential production ($\rho = 0.975$; $p < 0.001$), confirming that changes in real production directly followed changes in potential production. This connection indicates a balanced relationship between available resources and realized production, whereby, in periods of stable conditions, the Barska River ecosystem functioned at its full capacity.

Due to the favorable hydrological regime, gravel-sandy substrate, and well-developed vegetation, the upper course of the Barska River is designated as a particularly special fish habitat (SFH) (SIMIĆ *et al.*, 2021) and represents an ideal site for brown trout spawning (POFF *et al.*, 2007; NAIMAN and LATTERELL, 2005). For a long time, its remoteness and natural isolation were largely spared from anthropogenic and fishing pressure. However, following the construction of picnic infrastructure and a forest recreation facility, the accessibility of this area increased considerably (SIMIĆ *et al.*, 2016). After 2016, a decline in the measured parameters became evident, coinciding closely with the period following the development of these infrastructures. Observed declines in production may be attributed to changes in the river's hydrological regime and reduced habitat quality, as riparian vegetation loss and increased sedimentation can hinder the spawning process (NAIMAN and LATTERELL, 2005; BILOTTA and BRAZIER, 2008). The natural isolation of local populations, caused by the presence of a large downstream waterfall (JANKOVIĆ *et al.*, 2005), together with increased human activity, illegal fishing, and the introduction of allochthonous alleles from historically inappropriate stocking, collectively contributed to the pronounced decline in the measured parameters during the studied period. Genetic contamination represents a major risk for brown trout populations in

the rivers of NP Kopaonik, as well as in other protected areas across Europe, where the problem of hybridization and the loss of native genetic diversity is becoming increasingly pronounced (PERRIER *et al.*, 2013; SNOJ *et al.*, 2021; MARIĆ *et al.*, 2022; RUPPERT *et al.*, 2024).

The Brzečka River is characterized by low average values of production parameters, with real production of 2.76 ± 3.66 kg/km, potential 7.30 ± 5.05 kg/km, and biomass of 6.43 ± 7.30 kg/km. During the period from 2010 to 2014, real production was very low, after which there was a sharp increase and reached a maximum of 10,12 kg/km in 2018, and then fell again until 2023. The potential production reaches its maximum in the same year (14.00 kg/km), and by 2023, it will decrease to only 1.80 kg/km, which indicates the loss of the production capacity of the river. Biomass showed an upward trend from 1.24 kg/km in 2010 to a peak of 18.54 kg/km in 2016, then declined to 4.20 kg/km by 2023.

The correlation between real and potential production is slightly positive but not statistically significant ($\rho = 0.121$; $p = 0.775$), indicating that changes in one parameter do not fully cause significant changes in the other. One of the reasons why the Brzečka River naturally has low fish production and biomass is due to its habitat uniformity (SIMIĆ *et al.*, 2019). In the work by JUTILA *et al.* (2001), it was shown that one important parameter directly affecting trout abundance is the number of pools. The Brzečka River is characterized by a uniformity of habitat, with many rapids and a substrate built of larger stones, lacking many microhabitats that would be favorable for brown trout to stay in this river (SIMONOVIC, 2010; SIMIĆ *et al.*, 2019).

Based on the obtained results, the Brzečka River can be classified as an ecosystem with low bioproductivity stability and weak production potential, in which fluctuations in production and biomass depend on short-term favorable conditions. This type of dynamics is typical for smaller mountain watercourses with limited flow and a large rocky substrate, where hydromorphological factors have a decisive influence on the sustainability of the fish stock (ELOSEGI *et al.*, 2010; SIMONOVIC *et al.*, 2020).

The Lisinska River exhibited the most degraded condition among all investigated rivers, there has been a complete absence of brown trout for the past 13 years, indicating serious problems the river has experienced in the previous period (SIMIĆ *et al.*, 2019). Consequently, real fish production could not be estimated, and potential production was inferred solely from macrozoobenthos data and associated environmental parameters (ARRIGNON, 1976; VOICAN *et al.*, 1981; STARAS, 1985; STACHEL *et al.*, 2005; NĀSTASE *et al.*, 2018; SIMIĆ *et al.*, 2019). Transaprobic and toxic pollution resulting from runoff from mining areas in the upper reaches of the Lisinska River has caused long-term consequences for the river ecosystem (SIMIĆ *et al.*, 2016). Chemical pollution, including the presence of heavy metals and organic contaminants, significantly affects the water chemistry and creates unfavorable conditions for the development and survival of fish population (JURAJDA *et al.*, 2020). Similar adverse effects have been observed in other European rivers, where mine runoff hinders the development of fish populations (STACHEL *et al.*, 2005; HEININGER *et al.*, 2004). Within protected areas like NP Kopaonik, conservation efforts have focused on habitat restoration, the establishment of fish refuges, and the implementation of sustainable stocking practices (SIMIĆ *et al.*, 2023; PLIBERŠEK and TAVČAR, 2023). Therefore, it is of utmost importance that hatchery reared brown trout used for supplemental stocking belong to the same mtDNA haplogroups or evolutionary lineage and even carry the same haplotypes as the recipient wild population. Furthermore, local differentiation in nuclear genes must also be considered (VELIČKOVIĆ *et al.*, 2024). Post-hoc pairwise comparisons confirmed the statistical distinctiveness of the Lisinska River, revealing that it differed significantly from the Samokovska, Gobeljska, and Barska rivers in terms of real production ($p = 0.004$, $p = 0.045$, and $p = 0.045$, respectively), and from all other rivers in terms of biomass ($p = 0.004$ for all pairwise comparisons). The Lisinska River thus remains an example of an extremely degraded watercourse, where biological production

is almost non-existent, and potential production, although minimally present, reflects only the residual function of the ecosystem in which the process of self-maintenance of the fish population has been interrupted.

CONCLUSION

Analyzing the results for the brown trout population in the rivers of NP Kopaonik for the period from 2010 to 2023 reveals a consistent decline in biomass, real production, and potential production across all studied watercourses. While individual rivers exhibited locally specific fluctuations, such as temporary production peaks in the Samokovska and Gobeljska rivers in 2016 and a period of relative stability in the Barska River until 2016, they all ultimately exhibited an overall negative trend. The Brzečka River maintained persistently low productivity throughout the study period due to its structurally simplified riverbed, whereas the Lisinska River became entirely devoid of fish as a consequence of prolonged ecological degradation. The decline is primarily attributed to cumulative anthropogenic pressures, including the discharge of municipal and mining wastewater, habitat fragmentation from the construction of mini-hydropower plants (MPAs), massive tourism development, poaching, and genetic introgression due to inadequate stocking practices. These factors, together with the intensifying effects of climate change, have substantially disrupted the natural dynamics and ecological stability of these river ecosystems.

Parameters such as real and potential production, as well as deviations between them, do not equally reflect the current state of the population. While real production is a direct indicator of the current population status, potential production reflects the productive capacity of the habitat, whereas the deviation between real and potential production indicates the degree to which this habitat potential has been utilized. These parameters serve as reliable, early, and indirect indicators of limiting environmental factors, providing a signal for timely improvements in habitat conditions. Such improvements can enhance spawning success, growth, and long-term population sustainability. Given the unfavorable status of the populations and the lack of opportunities for sustainable exploitation, continuous monitoring and targeted conservation measures are essential. These measures include controlling non-native genetic stocking and protecting designated fish habitats. The findings offer a practical foundation for managing and restoring river ecosystems by identifying key ecological constraints on brown trout production and the long-term viability of native salmonid populations in NP Kopaonik. Priority actions should focus on controlling non-native genetic introgression, protecting designated fish habitats, and fostering collaboration among researchers, park management, and the local community.

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