

Article

Water Quality Assessment of the Uvac River (Serbia) Using the Water Pollution Index (WPI): Relevance for Protected Area Sustainability and Tourism

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Abstract

Although water resources are very significant natural assets of protected areas, the increasingly intensive tourism development in national parks and nature reserves brings them under constant anthropogenic pressure. Therefore, the analysis of water quality and pollution in them is of great importance. This study evaluates the water quality of the Uvac River (Serbia) at the Priboj hydrological station using the Water Pollution Index (WPI), based on physicochemical data for the period 2021–2023. As part of the WPI methodology, C_i/S_i ratios between mean annual parameter concentrations and reference values for Class I (excellent water quality status) were analyzed. For seasonal analysis, C_i/S_i between seasonal parameter concentrations and reference values for Class I were calculated. Relationships between WPI and selected water-quality parameters were also analyzed. Annual WPI values ranged from 0.89 to 0.99, indicating stable Class II water quality throughout the study period. Seasonal analysis showed occasional shifts to Class III during autumn and winter, associated with increased organic matter and nutrient inputs. Correlation analysis revealed strong relationships between WPI and TOC, BOD₅, and COD_{Mn}, while moderate correlations with ammonium, suspended solids, and phosphorus compounds suggest the influence of nutrient inputs and hydrological conditions.

Keywords: water quality; Water Pollution Index (WPI); seasonal variability; protected area; tourism; Uvac River; Serbia



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1. Introduction

Surface waters are a fundamental component of natural ecosystems and represent an essential resource for drinking water supply, agriculture, industry, recreation, and tourism [1–4]. Consequently, river water quality is a key indicator of environmental sustainability and plays a central role in preserving the ecological integrity of river basins, as well as supporting various human activities that depend on them [5,6].

River water quality is shaped by both natural processes and human activities, and their interactions can significantly influence hydrological responses within river basins [7–10]. The natural chemical composition of river water is controlled by geology, climate, hydrology, and catchment characteristics. In contrast, anthropogenic pressures

such as urbanization, agriculture, industry, and tourism can modify these natural conditions by introducing nutrients, organic matter, oil, and trace metals into river systems. These inputs may alter ecological functioning and reduce the suitability of river water for drinking, irrigation, recreation, and other uses [7,11–13].

In protected areas, maintaining high water quality is particularly important, as aquatic ecosystems often represent key components of biodiversity conservation and overall landscape value [5]. Rivers and reservoirs within such areas frequently support sensitive habitats and provide essential resources for wildlife, while also serving as focal points for recreation and tourism. Clear and cold water frequently captivates people and often serves as a primary motivation for choosing a particular destination [14]. Water resources within protected areas can enhance tourism by offering cultural and recreational services and immersive physical and visual experiences, while also acting as a key driver of local economic development and biodiversity conservation [15–17]. Therefore, reliable assessment of water quality in these areas is essential for effective environmental protection and for the long-term sustainability of tourism activities that depend on clean and well-preserved natural environments.

The Uvac Special Nature Reserve (SNR), located in southwestern Serbia, represents one of the most important protected landscapes in the region. The Uvac River and its reservoirs are widely recognized for their exceptional geomorphological features, canyon landscapes, and habitats of rare and endangered species [18]. The area attracts an increasing number of visitors due to its scenic landscapes, boating opportunities, wildlife observation, and other forms of nature-based tourism [19].

At the same time, tourism development, as well as scientific and educational initiatives, stimulates nature conservation efforts within this SNR [20]. In such environments, maintaining high water quality is essential not only for ecological stability but also for preserving the attractiveness and sustainability of tourism activities. In addition, the karstic characteristics of the catchment and the presence of reservoir systems further influence hydrological and water-quality dynamics, making this area particularly relevant for integrated assessment.

Water quality is typically evaluated using numerous physicochemical, microbiological, and biological parameters. Because interpreting such large datasets can be challenging, water-quality indices are commonly used to integrate multiple indicators into a single value describing the overall condition of a water body. These indices, such as the Water Quality Index (WQI) and Water Pollution Index (WPI), facilitate comparisons between locations and monitoring periods and support water-resource management and decision-making [2,3].

The Water Pollution Index (WPI) is widely used in water quality assessment around the world: Birbhum District in India [21]; River Cihideung, River Ciapus and Anak Laut Lake in Indonesia [1,22]; Lake Xingyun, Xichao River Basin and Shanchong River in China [23–26]; Yelek River Basin in Kazakhstan [27]; Sinú River in Colombia [28]; and Chumbao River in Peru [29].

In Serbia, water-quality assessment has traditionally relied on interpreting individual physicochemical parameters in relation to national regulatory standards. In recent years, the Water Pollution Index (WPI) has been applied in several river systems and reservoirs, including the Danube, the Sava, the Drina, the Južna Morava and the Tamiš rivers [30–35], demonstrating its usefulness for summarizing monitoring data and providing an integrated overview of water-quality conditions across different locations and time periods.

Water quality in the Uvac Special Nature Reserve has been the subject of various studies. Vasiljević et al. [36] analyzed the physicochemical parameters of Zlatar Lake and the Marića River near the confluence with the Uvac River during August and October 2021,

reporting higher pH and temperature values and lower electrical conductivity in Zlatar Lake compared to the Marića River, as well as high dissolved oxygen and saturation levels, increased orthophosphate concentrations, higher ammonium concentrations in October compared to August, and generally low nitrate and nitrite values at both sampling sites. Kračun-Kolarević et al. [37] analyzed microbiological water quality at 14 sampling sites during the same period and recorded the highest fecal pollution at the Uvac River (Čedovo) and its tributary Vapa, where water quality was classified as Class III (moderate ecological status), while other sites were within Class I (good ecological status) and Class II (excellent ecological status). These sites, located near settlements, are exposed to stronger anthropogenic pressures due to insufficient wastewater collection and treatment. Andus et al. [38] evaluated the ecological status of water bodies at 17 sampling sites based on macroinvertebrates, phytobenthos, phytoplankton, physicochemical parameters, and chlorophyll, reporting moderate to poor ecological status at several locations associated with untreated wastewater, diffuse pollution, and nutrient inputs from erosion processes. Increased orthophosphate concentrations suggested organic matter inputs from agricultural land, while the presence of coliform bacteria indicated fecal and wastewater contamination. Earlier research by Sunjog et al. [39], based on data from 2009 to 2011, showed elevated concentrations of heavy metals (Zn, Cu, Cr, and Cd) in water, as well as increased Fe, Mn, Cr, and Ni concentrations in the sediments of Zlatar Lake, partly associated with the geological structure of the basin dominated by basic igneous rocks such as spilite, diabase, and gabbro. However, most previous studies in the Uvac River basin have focused on individual physicochemical, microbiological, ecological, or sediment-quality indicators. Integrated assessments that combine seasonal analysis, multiple physicochemical parameters, and water-quality indices remain limited, particularly for protected karst river systems exposed to increasing tourism pressure.

To address this gap, the aim of the present study is to assess the water quality of the Uvac River using the Water Pollution Index (WPI), based on physicochemical and trace-element data obtained from the national monitoring program. In addition, relationships between WPI and selected water-quality parameters were examined to identify the main factors influencing water-quality variability. Annual and seasonal analyses were performed to evaluate temporal patterns and potential pressures affecting the river system. The assessment is based on data from the Priboj hydrological station located in the lower course of the Uvac River. As this station is situated downstream of the Sjeničko, Zlatarsko, and Radoinjsko reservoirs, the results reflect water-quality conditions at the downstream outlet of the basin after the modifying effects of the reservoir cascade on upstream inputs.

The novelty of this study lies in the application of the Water Pollution Index (WPI) to assess seasonal water-quality dynamics in a karst-dominated protected river system, where groundwater–surface water interactions and rapid flow pathways can strongly influence the transport and seasonal variability of water-quality parameters. This approach contributes to a better understanding of water-quality variability in mountain river systems and supports more effective environmental management in protected areas.

2. Materials and Methods

2.1. Study Area

The Uvac River is located in southwestern Serbia, flowing between Nova Varoš and Sjenica through a predominantly mountainous landscape shaped by the northern slopes of Mt. Zlatar, the southern extensions of the Zlatibor massif, and the Javor range. The river rises on Mt. Ozren; it is 113 km long [40] and has a catchment area of 1334 km² [41]. The average annual discharge is approximately 13.2 m³/s at the confluence with the Lim [42].

Due to its abundant water resources and generally high water quality, the Uvac River basin is recognized in strategic and planning documents as a significant water-resource area [43].

The river is the longest tributary of the Lim River and drains a catchment characterized by complex geomorphological and hydrogeological conditions. The upper part of the basin includes the Sjenica Plateau (1000–1400 m a.s.l.), which is largely composed of karstified limestones. These conditions promote infiltration and limit surface runoff in this part of the basin.

Due to its favorable hydropower potential, the Uvac River has been extensively utilized for hydropower development. Consequently, three artificial reservoirs—Sjeničko, Zlatarsko, and Radoinjsko—have been constructed along the river, forming part of the Lim hydropower system [41]. These reservoirs significantly influence the hydrological regime by altering flow dynamics, sediment transport, and water retention.

For the purposes of this study, water-quality analysis was based on data from the Priboj hydrological station, located on the Uvac River (Figure 1). The station is situated at approximately 380 m a.s.l. (UTM 34T: 378,886 m E/4,830,197 m N) [44,45].

The 2023 Decree on Protection (Official Gazette of the Republic of Serbia, No. 27/2023) [46] introduced a three-level protection regime and expanded the total protected area to 118.45 km². Under national legislation, the Uvac SNR is classified as a Category I protected area of international, national, or exceptional importance. According to the International Union for Conservation of Nature's (IUCN) classification, it is designated as Category IV, corresponding to a habitat or species management area. In addition, parts of the SNR, or specific areas within it, are included in internationally recognized lists of important areas [47].

The waters of the Uvac River represent the fundamental value of the protected area of the Uvac SNR. The basin of the Uvac River is a peripheral mountainous area with relatively low population density and limited economic development. Through their erosional activity, these rivers have formed an exceptionally attractive canyon valley with incised meanders and large mountain systems, where sinkholes dominate the surface, while large cave systems are developed in the subsurface.

Together with the surrounding mountains and extensive plateaus, these valuable geo-heritage features provide habitat for a large number of relict, endemic, rare, and endangered species. The highly attractive landscapes, resulting from pronounced geological and geomorphological diversity, support 187 bird species (of which 163 are strictly protected), 18 species of amphibians and reptiles, 20 insect species, 47 mammal species, 23 fish species, and 655 plant taxa (many of which are relict, endemic, and protected at national and international levels) [48].

The Uvac Special Nature Reserve is one of the last and most important refuges of the griffon vulture (*Gyps fulvus*) in Serbia, the Balkan Peninsula and Southeast Europe. The population is estimated at over 400 individuals, which makes SNR the largest colony of this species on the Balkan Peninsula. The preservation of the habitat of this rare species of vulture was the reason for the initial protection of the area. First, in 1971, a faunal reserve was established at the “Pavlovića Brod” location, and then, from 1995, the aforementioned decrees on the protection of the area around the Uvac River gorge followed [47]. The Uvac River gorge is also considered suitable for the reintroduction of other species of vultures that have disappeared from Serbia, such as the Egyptian vulture (*Neophron percnopterus*), the black vulture (*Aegypius monachus*), and the bearded vulture (*Gypaetus barbatus*) [49].

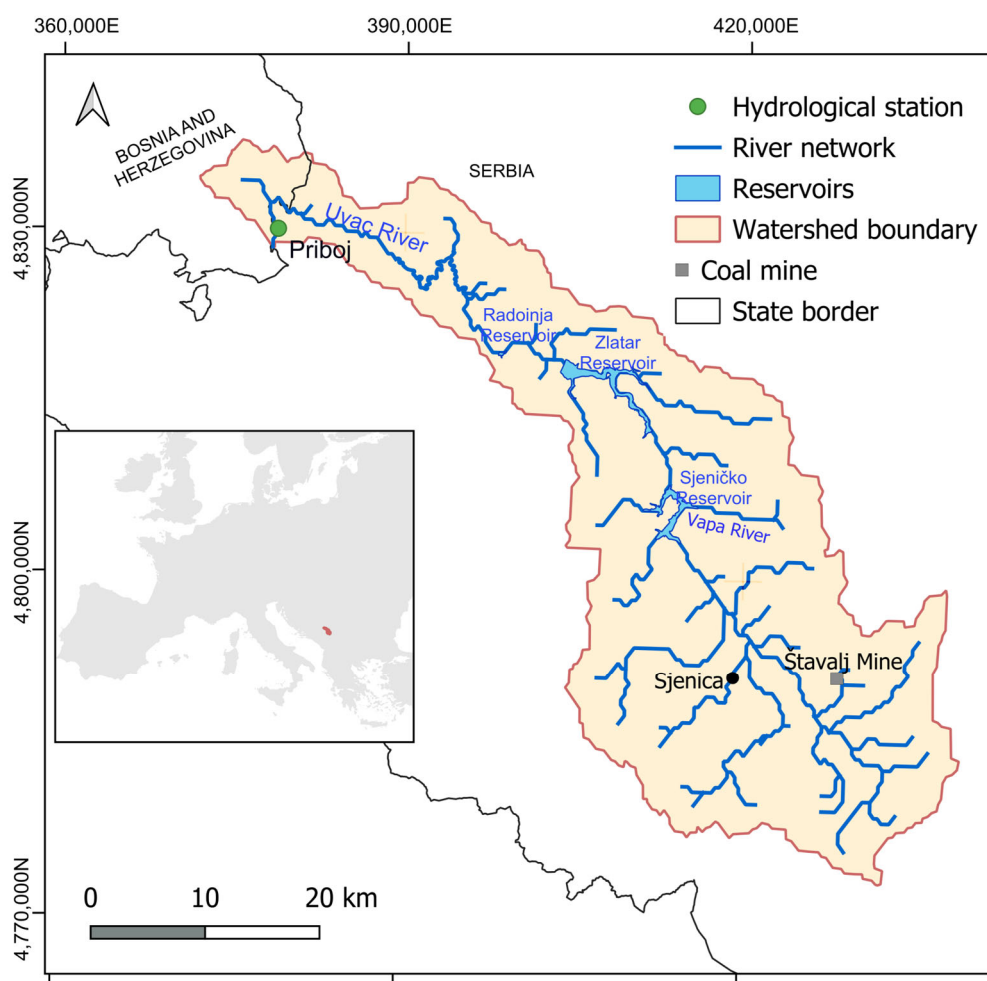


Figure 1. Location of the Uvac River basin.

Moreover, this area forms part of a tourist zone of regional importance, i.e., the Western Tourist Zone, with the potential to offer year-round tourism integrated with the surrounding region. The lakes, rivers, and distinctive Uvac meanders support a variety of tourist activities, including panoramic sightseeing, photography, wildlife observation, and the study of geomorphological features. Educational and ecological tourism, particularly ornithological tourism, such as griffon vulture watching, is especially developed. In addition, the lakes and rivers provide opportunities for water sports, sport fishing, and rafting along the Uvac meanders [50].

These natural and hydrological characteristics make the Uvac River a dynamic system sensitive to both natural variability and anthropogenic pressures, highlighting the importance of continuous water-quality monitoring and integrated assessment approaches.

2.2. Data Collection and Analyzed Parameters

Water-quality data were obtained from the official annual monitoring reports [45] published by the Serbian Environmental Protection Agency (SEPA) for the period 2021–2023. The dataset includes a comprehensive set of physicochemical, nutrient, and trace-element parameters used for the assessment of surface water quality. For the parameters included in the WPI calculation, most physicochemical and nutrient parameters were monitored 10–12 times per year, while trace elements were generally measured 9 times per year. Annual mean values were calculated using all available measurements for each parameter and year.

The analyzed physicochemical parameters included dissolved oxygen (DO), pH, biochemical oxygen demand (BOD₅), chemical oxygen demand determined using the permanganate method (COD_{Mn}), total organic carbon (TOC), suspended solids (SS), electrical conductivity (EC), chlorides (Cl[−]), and sulfates (SO₄^{2−}). Nutrient status was assessed through nitrogen species expressed as ammonium nitrogen (NH₄–N), nitrite nitrogen (NO₂–N), and nitrate nitrogen (NO₃–N), together with orthophosphates (PO₄^{3−}) and total phosphorus (TP). Trace elements were determined in the dissolved fraction and included iron (Fe), manganese (Mn), chromium (Cr), arsenic (As), and copper (Cu).

The selection of parameters was based on their availability within the national monitoring program. This combination allows for a comprehensive assessment of water quality by integrating key physicochemical conditions with indicators of anthropogenic pressure. Water-quality analyses were conducted by SEPA within the national monitoring program using standardized analytical procedures prescribed by relevant national and international standards. The verified monitoring results published in the annual SEPA reports were subsequently processed and analyzed for the purposes of this study. Analytical procedures followed standardized SRPS, ISO, EPA, APHA, and HACH methods specified in the national monitoring protocols [45].

2.3. Water Pollution Index (WPI)

To provide an integrated assessment of surface water quality at the Priboj hydrological station, the Water Pollution Index (WPI) was applied as a composite indicator relating measured concentrations to corresponding regulatory reference values. It was selected as it directly relates measured concentrations to regulatory reference values, enabling a clear and transparent assessment of deviations from excellent ecological status.

The index was calculated as the arithmetic mean of individual pollution coefficients according to the following expression:

$$WPI = \frac{1}{n} \sum_{i=1}^n \frac{C_i}{S_i} \quad (1)$$

where

C_i —mean concentration of the i -th parameter for the selected assessment period (annual or seasonal),

S_i —regulatory reference value adopted for parameter i .

n —total number of parameters included in the analysis ($n = 19$ in the present study).

The C_i/S_i ratio represents a pollution coefficient for each parameter, expressing the degree to which the measured concentration deviates from the corresponding Class I reference value. Smaller values of the C_i/S_i ratio mean smaller deviations of parameter concentrations from the Class I (excellent ecological status) reference values and a further smaller WPI value, which means better water quality. The significance of analyzing the C_i/S_i ratio for each parameter is to examine the contribution of each single parameter in the final WPI value.

In some previous studies (e.g., Brankov et al. [32]), the same concept has been expressed using the notation SFQS, which is equivalent to the parameter S_i used in this study and refers to Class I surface water quality standards in Serbia. Despite the different notation, both approaches represent identical regulatory threshold values.

For annual assessment, C_i values correspond to arithmetic yearly averages. Seasonal water-quality patterns were evaluated by comparing seasonal mean concentrations (C_i) with corresponding regulatory reference values (S_i). Seasons were defined on a three-month basis (March–May, June–August, September–November, and December–February). For seasonal assessments, the C_i value corresponds to the arithmetic mean of all measurements available within the respective three-month period.

Reference values (S_i) were adopted from Serbian national legislation. For pH, the upper limit of Class I (8.5) was used as S_i in the WPI calculation. For dissolved oxygen (DO), the Class I criterion prescribed by Serbian legislation is 8.5 mg/L. Consequently, DO values exceeding this criterion produce C_i/S_i ratios greater than 1; however, 8.5 mg/L is the lowest value of DO for Class I, while the highest value is not defined by Serbian legislation, which means that higher values indicate favorable oxygen conditions rather than deterioration of water quality. In accordance with the original WPI methodology, equal weight was assigned to all parameters. Physicochemical and nutrient thresholds corresponding to Class I surface-water quality (excellent ecological status) for Type 3 water bodies were taken from the Regulation on Limit Values of Pollutants in Surface and Groundwater [51]. The copper (Cu) reference value was adjusted according to measured water hardness using linear interpolation between regulatory thresholds defined for different hardness classes. According to the national regulation, copper thresholds are defined in relation to water hardness, as copper generally has a lower environmental impact in harder waters. The complete set of regulatory reference values used in the WPI calculation is presented in Table 1.

Table 1. Reference values (S_i) used for WPI calculation (Type 3 water bodies) [51].

Parameter	Unit	S_i (Class I)
Dissolved Oxygen (DO)	mg/L	8.5
pH	–	6.5–8.5
Biochemical Oxygen Demand (BOD ₅)	mg/L	1.5
Total Organic Carbon (TOC)	mg/L	2
Ammonium nitrogen (NH ₄ –N)	mg/L	0.05
Nitrate nitrogen (NO ₃ –N)	mg/L	1.5
Nitrite nitrogen (NO ₂ –N)	mg/L	0.01
Orthophosphates (PO ₄ ^{3–})	mg/L	0.02
Total phosphorus (TP)	mg/L	0.05
Chlorides (Cl [–])	mg/L	50
Sulfates (SO ₄ ^{2–})	mg/L	50
Suspended solids (SS)	mg/L	25
Electrical conductivity (EC)	µS/cm	1000
COD _{Mn} (permanganate index)	mg O ₂ /L	5
Iron (Fe)	mg/L	0.2
Manganese (Mn)	mg/L	0.05
Chromium (Cr)	µg/L	25
Arsenic (As)	µg/L	5
Copper (Cu) *	µg/L	86

Notes: * Copper (Cu) reference value depends on water hardness. For this study, a single hardness-adjusted reference value was derived using the mean measured hardness for 2021–2023 ($T^{\circ} = 226.55$ mg/L as CaCO₃) and linear interpolation between regulatory thresholds.

The WPI classification scheme used in this study is presented in Table 2.

The WPI provides a clear interpretation of water quality by expressing results as deviations from Class I reference values. Lower WPI values indicate better water quality, while higher values indicate greater deviation from the reference conditions. The final WPI class is determined from the average value of all calculated pollution coefficients (C_i/S_i). WPI limitation is connected to the inverse parameter reference value (in this case DO), where only the lowest reference value is defined. If the measured concentration is higher than the reference value, the WPI value is increased, although real water quality is better. To overcome this limitation, correlation analysis between single parameters and final WPI was conducted.

Table 2. Classification of surface water quality based on WPI values.

Class	Water Quality Status	WPI
I	Very pure	≤ 0.3
II	Pure	0.3–1
III	Moderately polluted	1–2
IV	Polluted	2–4
V	Impure	4–6
VI	Heavily impure	> 6

Note: Source: [52].

2.4. Correlation Analysis

In order to better understand relationships between single water-quality parameters and overall pollution levels, a correlation analysis was performed. Relationships between the WPI and selected physicochemical and nutrient indicators were then examined. The aim was to identify the main parameters influencing temporal variability in water quality and to evaluate their relationship with WPI values.

The analysis included 14 parameters, which represent key indicators of physicochemical conditions and nutrient dynamics (DO, pH, BOD₅, TOC, NH₄-N, NO₃-N, NO₂-N, PO₄³⁻, TP, Cl⁻, SO₄²⁻, SS, EC, and COD_{Mn}). These parameters were selected based on their consistent availability in the monitoring dataset and their relevance for describing organic pollution, nutrient enrichment, and general hydrochemical conditions. Trace elements were excluded due to their generally low concentrations relative to Class I reference values and their lower sampling frequency, which may reduce the reliability of the statistical analysis.

The correlation analysis was based on monthly data collected during the 2021–2023 period ($n \approx 33$ for most parameters). For each parameter, only months with available data were included in the calculations. Pearson correlation analysis was applied to assess associations between WPI values and the selected water-quality parameters. The statistical significance of the correlation coefficients was evaluated at $p < 0.05$ and $p < 0.01$ levels. Correlation coefficients were calculated using monthly observations from the combined 2021–2023 dataset. The method was selected because the study focused on identifying general linear relationships between WPI and single water-quality parameters.

3. Environmental Pressures in the Uvac River Basin

The following section provides background information on the main environmental pressures present within the Uvac River basin. Although the study is based on monitoring data from the Priboj hydrological station, understanding the broader environmental context is important for interpreting observed water-quality conditions and discussing potential factors that may contribute to their temporal variability.

Anthropogenic influence in the area of the Uvac SNR is most clearly reflected in the artificial reservoirs constructed between the 1960s and 1980s. However, their presence does not significantly threaten the natural values of the Uvac SNR, and today they represent one of its recognizable landscape features.

The main pressures affecting environmental quality in the Uvac SNR include the use of pesticides and mineral fertilizers in agriculture, unregulated landfills, traffic, tourism and urban settlements, as well as energy facilities.

3.1. Agriculture and Land Use

Agricultural activities represent one of the main sources of environmental pressure in the Uvac River basin. Due to the dominance of meadows and pastures, livestock farming is the most common form of agricultural production. Free grazing reduces the biomass

of useful plant species and leads to the spread of weeds. Pastures are mowed irregularly, which reduces biomass yield and plant diversity. In addition, livestock is often taken to early spring grazing too soon, causing damage to young shoots.

Agricultural activities in the area of the Uvac SNR, particularly the use of pesticides, mineral fertilizers, and other chemical agents, directly threaten the fauna, as well as the quality of karst aquifers. Indirectly, they also pose a threat to the underground karst relief by altering the chemical composition of percolating waters, which may lead to the erosion of cave formations [48].

Furthermore, when referring to toxic substances and similar hazardous chemicals, it is important to highlight the poor practice of the occasional poisoning of wolves, dogs, and other animals within the Uvac SNR. This has particularly negative effects on the most endangered and well-known species of the area—the griffon vulture, a scavenger that feeds on carcasses that may be poisoned or contaminated with veterinary drugs [53].

3.2. Solid Waste and Landfills

Rural settlements within the Uvac SNR are not included in an organized waste collection and disposal system, and therefore almost every village has its own uncontrolled landfill. Most landfills are located near houses, farms, or in river valleys (in many cases directly in riverbeds of the Uvac River and its tributaries), while in some cases waste is incinerated by the local population [54]. In larger settlements (Nova Varoš and Sjenica), waste management is also inadequate. Although waste collection is organized, there is no regional landfill, and disposal is carried out at unregulated sites, which leads to soil and water contamination in the area [55]. The largest number of unregulated landfills is located near Nova Varoš (9) and the Tisovica settlement (13). The sites with the greatest potential impact on water resources are located close to water bodies, particularly in the Negbina settlement along the Uvac River, near Zlatar Lake, and in the Radijevića settlement near Uvac Lake [56]. Pollutants from these sites infiltrate into the soil and subsequently reach groundwater and surface water bodies [48].

3.3. Wastewater and Settlements

The lack of sewerage infrastructure in settlements within the Uvac River basin represents a major environmental problem. Both municipalities within the SNR (Sjenica and Nova Varoš) have low coverage of sewerage networks [43]. Approximately 65% of water users in Sjenica are connected to the sewerage system, compared to 81% in Nova Varoš [55]. There is no established sewage system in rural settlements, and unsanitary septic tanks are commonly used. Barn cesspits are often constructed improperly, posing a potential source of contamination [54].

Municipal wastewater from Sjenica is one of the two most significant point sources of pollution (the other being the Štavalj coal mine). The spatial plan of the Special Purpose Area from 2010 already envisaged urgent rehabilitation measures, including the connection of the entire settlement of Sjenica to the sewerage system and the construction of a wastewater treatment plant [55].

The Vapa River, a tributary of the Uvac River, is one of the main sources of its pollution as it transports contaminants originating from the Štavalj coal mine as well as untreated municipal wastewater from the town of Sjenica. These impacts also negatively affect fish fauna by altering water quality [48]. The Vapa River flows into the Sjeničko Reservoir before reaching the downstream sections of the Uvac River. Consequently, pollutant loads originating from municipal wastewater, mining activities, and other sources within the Vapa catchment may be modified during their passage through the reservoir system. As

a result, water quality at the Priboj hydrological station reflects the combined influence of upstream pressures and processes occurring within the reservoir cascade.

3.4. Tourism and Infrastructure

Tourism and related infrastructure are becoming an increasingly important source of environmental pressure in the Uvac River basin. Although still underdeveloped, tourism in this area is expected to drive future development and may become a major pressure factor. Following the initial unplanned construction of individual buildings, numerous sites designated for weekend leisure vacations have emerged. As a result, tourism has contributed to the risk of transforming the area into an increasingly anthropogenic landscape. Unplanned construction primarily degrades soil quality, but it also negatively affects hydrographic resources due to the lack of infrastructure for wastewater collection and treatment in such settlements. Approximately 250 illegal buildings have been constructed within the SNR [47]. The most affected area is the shoreline of Zlatar Lake near the mouth of the Tisovica River [47].

In addition, the unplanned adaptation of caves for tourism purposes, particularly inadequate lighting that disturbs microclimatic conditions, may threaten cave fauna [48]. For this reason, a document entitled “Guidelines for the Use of the Ice Cave” was prepared in 2018, based on which visits are organized, visitor numbers are limited, and the entire Ušački cave system is protected [47].

The negative impact of traffic is reflected in the construction of forest roads, which leads to habitat fragmentation [48]. However, due to low population density, still underdeveloped tourism, and a relatively sparse road network, the area currently does not experience significant pressure from these activities.

3.5. Industrial and Energy Pressures

Industrial and energy-related activities also contribute to environmental pressures in the Uvac basin. Energy sources in the SRP area are hydropower, coal and wood. All of them put pressure on the environment.

Hydropower plants (“Uvac”, “Kokin Brod” and “Bistrica”) have led to the loss, degradation, and fragmentation of habitats within the Uvac SNR. Also, these are not the only energy facilities in the Uvac Special Nature Reserve that operate in this way. Among other energy-related structures, the construction of telecommunication facilities should also be mentioned [53].

The Štavalj brown coal mine is located within the municipality of Sjenica, at an altitude of approximately 1100 m, and its basin covers an area of about 30 km². A pit mining type of exploitation is used [57]. Findings regarding its environmental impact are inconsistent. According to Vučković et al. [58], analyses of total heavy metal content (Zn, Cu, Pb, and As) in soil and tailings indicate concentrations around or below the average values for Serbia (Pb and As) or several times lower (Zn and Cu). In contrast, Bajrović et al. [59] reported significant water-quality changes caused by wastewater discharge from the mine, resulting in elevated concentrations of nitrates, nitrites, and sulfates above established limits.

The processing industry, especially wood and wood product processing, drives this area’s development. Timber is exploited in a traditional way. Beech, spruce, fir, and black and white pine dominate. In terms of ownership structure, state forests dominate (about 80%). There are also private forests, but they have not been inventoried, and there is no reliable data on their production values. More than half of private forests are of coppice origin, while that percentage is significantly lower in the case of state forests. In the area of the SNR, clear-cutting and deforestation are prohibited, except for the purposes of constructing forest communications and permitted structures as well as the protection and

monitoring of natural values. However, unplanned logging is always ongoing. The negative anthropogenic impact was particularly felt during times of crisis, when the majority of the forests were cut down. Therefore, today the forest communities in the SNR are in a degraded state. The stands are thinned out, mostly young and of medium age, with trees developed from vegetative shoots. Illegal logging directly threatens the fauna of amphibians, reptiles, and birds, as it destroys their habitats. Also, one of the negative consequences of forest exploitation in the studied area is the frequent, uncontrolled disposal of wood processing waste in illegal dumps [47,48].

3.6. Management Measures

Measures are already in place to limit the negative effects of tourism on hydrographic resources. For example, due to increasing visitor numbers, the Visitor Management Plan for the Uvac Special Nature Reserve was adopted in 2017, which regulates both the number and timing of visits to Sjeničko Reservoir [47].

This document, prepared using data from the Institute for Nature Conservation of Serbia, defines limits on visitor activities in order to prevent negative impacts on natural, particularly hydrographic, values. It prescribes restricted use of the protected area, including a maximum of 10 boat departures per day from the Rastoke site and 10 from the Krstac/Markova Ravan site. Visitors are required to remain in the central part of the lake, without approaching the shoreline, except at designated access points such as the Ice Cave entrance and starting points of walking tours. The use of tourist vessels in areas under the second level of protection is regulated and controlled by the Uvac SNR management through contractual arrangements and fee systems for operators organizing boat tours [47].

4. Results and Discussion

4.1. Parameters Deviation from Class I—Uvac River (Priboj Hydrological Station)

This section presents the relationship between mean annual concentrations and Class I water-quality standards for the Uvac River at the Priboj hydrological station, based on monitoring data from 2021 to 2023 (Table 3 and Table S1 Supplementary File). As a part of WPI methodology, C_i/S_i ratios provide insight into the contribution of each single parameter to the final WPI.

Table 3. Ratios (C_i/S_i) of mean annual concentrations (C_i) to Class I water-quality standards.

C_i	DO	pH	BOD ₅	TOC	COD _{Mn}	NH ₄ ⁺ N	NO ₃ [−] N	NO ₂ [−] N	PO ₄ ^{3−}	TP	Cl [−]	SO ₄ ^{2−}	SS	EC	Fe	Mn	Cr	As	Cu
2021	11.16	8.39	2.56	4.46	4.22	0.06	0.42	0.01	0.04	0.14	6.30	8.82	4.00	378.1	0.02	0.01	1.34	0.99	3.67
2022	11.05	8.42	2.89	4.67	4.16	0.17	0.47	0.01	0.03	0.15	8.44	9.80	6.33	377.6	0.02	0.01	1.98	0.50	1.77
2023	10.74	8.37	2.87	5.11	4.71	0.15	0.53	0.02	0.04	0.11	6.38	11.67	9.33	386.7	0.02	0.01	1.98	0.50	1.10
C_i/S_i																			
2021	1.32	0.99	1.73	2.25	0.84	2.00	0.27	1.00	1.80	2.84	0.13	0.18	0.16	0.38	0.51	0.20	0.05	0.20	0.04
2022	1.30	0.99	1.93	2.34	0.83	3.40	0.31	1.00	1.70	3.00	0.17	0.20	0.25	0.38	0.10	0.20	0.08	0.10	0.02
2023	1.26	0.98	1.91	2.56	0.94	3.00	0.35	2.00	2.00	2.20	0.13	0.23	0.37	0.39	0.10	0.20	0.08	0.10	0.01

Dissolved oxygen (DO) values remained consistently high, ranging from 9.10 to 12.84 mg/L. All measured values exceeded the Class I reference threshold. However, taking into account that 8.5 mg/L presents the lowest DO reference value for Class I, higher DO concentrations reflect favorable oxygen conditions rather than increased pollution. High DO concentrations are in line with the study of Zlatar Lake and the Marića River (tributary of the Uvac River) conducted by Vasiljević et al. [36] in August and October 2021.

pH values remained within a narrow alkaline range (7.6–9.0), showing only minor seasonal variation. This stability likely reflects the river's natural buffering capacity, characteristic of watercourses draining limestone-dominated catchments. No significant deviations were observed that would indicate external chemical pressures.

Biochemical oxygen demand (BOD₅) values showed moderate seasonal variability, ranging from 1.00 to 7.80 mg/L. Lower concentrations were generally recorded during summer low-flow conditions, whereas higher values occurred in spring and autumn, reflecting increased runoff and the transport of organic matter from the catchment. This pattern is further supported by the ratio values ($C_i/S_i \approx 1.73\text{--}1.93$), which consistently exceeded the Class I reference level, indicating a moderate organic load. Despite these fluctuations, the observed values suggest largely natural contributions of organic matter, with occasional increases likely associated with episodic inputs.

Total organic carbon (TOC) showed moderate variability, ranging from approximately 2.8 to 13.8 mg/L. The corresponding TOC ratios (2.25–2.56) consistently exceeded the Class I reference level, indicating a moderate organic load. Higher values generally coincided with periods of intensified runoff, while lower concentrations were recorded during low-flow conditions, reflecting reduced transport of allochthonous organic material. These patterns suggest that TOC variability is mainly controlled by hydrological processes rather than sustained external pollution sources. Variations may also be partly associated with diffuse inputs from the catchment, as discussed in Section 3.

Ammonium nitrogen (NH₄-N) annual mean concentrations ranged from 0.10 to 0.17 mg/L, with corresponding C_i/S_i ratios (2.00–3.40), indicating exceedances of the Class I reference value. Nitrate and nitrite concentrations remained generally low and relatively stable. Nitrate (NO₃-N) values ranged approximately from 0.2 to 1.3 mg/L, with corresponding C_i/S_i ratios ($\approx 0.27\text{--}0.35$) consistently below the Class I threshold. Nitrite (NO₂-N) concentrations were low in absolute terms (0.004–0.08 mg/L), but their C_i/S_i ratios ($\approx 1.00\text{--}2.00$) occasionally exceeded unity due to the strict reference limit for this parameter. Low concentrations of these parameters were also recorded in the study conducted by Vasiljević et al. [36] in August and October 2021.

Phosphate forms of phosphorus showed moderate variability. Orthophosphate (PO₄³⁻) concentrations ranged from 0.01 to 0.083 mg/L, with corresponding C_i/S_i ratios ($\approx 1.70\text{--}2.00$), indicating deviations from the Class I reference level. Total phosphorus (TP) exhibited a wider range (0.017–0.399 mg/L), with higher C_i/S_i ratios ($\approx 2.20\text{--}3.00$) reflecting episodic increases during individual sampling periods. These patterns suggest that phosphorus dynamics were influenced by short-term inputs or hydrological variability rather than continuous external loading. Overall, phosphorus concentrations remained relatively low in absolute terms, although they periodically exceeded reference conditions.

Chloride and sulfate concentrations remained relatively low and showed limited temporal variability. Chloride values ranged from approximately 5.0 to 12.5 mg/L, while sulfate concentrations varied between approximately 4 and 64 mg/L. The corresponding C_i/S_i ratios (<0.23 for both parameters) remained well below the Class I reference limits, indicating no significant deviation from background conditions. Slight increases were observed during individual sampling periods, but no consistent seasonal pattern or long-term trend was identified. These results suggest a consistent mineral composition of the water, with dissolved ions primarily reflecting baseline hydrochemical conditions typical of natural waters [60].

Suspended solids (SS) concentrations were generally low but exhibited occasional increases, ranging approximately from 4 to 37 mg/L. Higher values were recorded during periods of intensified runoff, reflecting enhanced transport of particulate material from the catchment, while lower concentrations were typical of stable low-flow conditions. The corresponding C_i/S_i ratios ($\approx 0.16\text{--}0.37$) remained below the Class I reference level, indicating limited overall particulate load. These results suggest that variations in suspended solids were primarily driven by hydrological conditions rather than continuous external inputs.

Electrical conductivity (EC) ranged approximately from 257 to 477 $\mu\text{S}/\text{cm}$, showing moderate variability with no consistent temporal trend. The corresponding C_i/S_i ratios (≈ 0.38 – 0.39) remained well below the Class I reference level, indicating relatively uniform mineralization conditions. Variations in EC are likely associated with hydrological conditions, particularly changes in discharge, reflecting possible dilution effects during higher flow periods.

Permanganate index (COD_{Mn}) values ranged from approximately 1.85 to 13.8 mg/L , with C_i/S_i ratios (≈ 0.83 – 0.94) generally below the Class I threshold. Elevated values were recorded during individual periods, suggesting episodic increases in organic matter. Despite these episodic increases, COD_{Mn} values indicate a relatively low overall organic load.

Iron (Fe) and manganese (Mn) concentrations were generally low, although occasional increases were observed. Iron concentrations ranged from approximately 0.01 to 0.81 mg/L , with corresponding C_i/S_i ratios (≈ 0.10 – 0.51), reflecting episodic elevations during individual sampling periods. Manganese concentrations showed a narrower range (0.01–0.045 mg/L), with C_i/S_i ratios (≈ 0.20) remaining relatively stable. These variations suggest that the mobility of these elements was influenced by short-term environmental conditions rather than sustained inputs, while overall concentrations remained low in most observations.

Chromium (Cr), arsenic (As), and copper (Cu) were generally present at low concentrations, although occasional elevated values were observed. Chromium ranged approximately from 0.5 to 4.3 $\mu\text{g}/\text{L}$, with C_i/S_i ratios (≈ 0.05 – 0.08) remaining well below the Class I reference level. Arsenic concentrations were mostly stable around 0.5 $\mu\text{g}/\text{L}$ but reached up to 4.9 $\mu\text{g}/\text{L}$ during individual sampling events, corresponding to C_i/S_i ratios ≈ 0.10 – 0.20 . Copper showed the highest variability, ranging from about 1.0 to 15.9 $\mu\text{g}/\text{L}$, with C_i/S_i ratios (≈ 0.01 – 0.04) indicating low overall levels despite occasional peaks. These results suggest that trace metals were generally present in low concentrations, with short-term variations likely related to episodic inputs rather than sustained contamination.

Results indicate that the Uvac River maintained generally stable physicochemical conditions, with only minor to moderate deviations from Class I standards. Most parameters showed limited temporal variability, with fluctuations largely associated with hydrological conditions, particularly changes in discharge and runoff. Organic matter indicators (BOD_5 , TOC, COD_{Mn}) and suspended solids exhibited moderate variability with occasional peaks, while nutrient concentrations reflected low nitrogen levels and more variable phosphorus dynamics, likely related to short-term inputs. Dissolved ions remained relatively uniform and within typical background ranges, and trace elements were generally present at low concentrations despite sporadic increases. The observed patterns suggest that water quality is mainly influenced by natural processes, although localized anthropogenic pressures may also contribute to the observed variability.

Total coliform (TC) concentrations varied widely, ranging from approximately 4100 to 82,000 organisms per 100 mL ($n/100\text{ mL}$) [45]. However, the number of measurements per year was very limited, which makes it difficult to assess seasonal patterns and overall variability. Due to this low sampling frequency, total coliforms were not included in the WPI calculation. Although this parameter is not included in the WPI calculation, occasionally high values of TC present monitoring concern, indicating potential microbiological contamination during individual sampling events. More frequent microbiological monitoring would be necessary to include TC in WPI and to better understand the temporal dynamics of total coliforms and evaluate the potential impacts of tourism activities and wastewater inputs on water quality.

Despite the upstream pollution sources from coal mines, the municipal sewage of Sjenica, landfills and agriculture, which introduce sulfate, heavy metals and organic pol-

lution, the downstream Priboj station records alkaline water, negligible sulfate and heavy metal concentrations and organic loads below Class I thresholds. This could be explained by the existence of three reservoirs, the Sjeničko, Zlatarsko, and Radoinjsko reservoirs, between upstream pollution and the downstream Priboj station. These reservoirs act as biogeochemical buffers mitigating upstream pollution. The slower flow and increased residence time in the reservoirs could facilitate the sedimentation of pollutants, neutralization of acid mine drainage, and biological assimilation of nutrients. Therefore, the water quality measured at Priboj station primarily represents the post-retention outflow rather than the ecological status of the entire Uvac River basin.

4.2. Seasonal Analysis

As a part of seasonal WPI, C_i/S_i was applied based on the mean seasonal C_i concentrations and the S_i reference values of each parameter. Seasonal analysis at the Priboj hydrological station (Table 4) indicates that physicochemical parameters exhibit clear but moderate seasonal variability. Spring data indicate a stable oxygen regime throughout all three years. Dissolved oxygen remained consistently above reference conditions ($C_i/S_i \approx 1.17$ – 1.28), indicating no evidence of early-season depletion. pH values were relatively uniform and close to the reference range ($C_i/S_i \approx 0.95$ – 1.02).

Table 4. Seasonal ratio values (C_i/S_i) relative to Class I standards at the Priboj hydrological station (2021–2023).

	DO	pH	BOD ₅	TOC	COD _{Mn}	NH ₄ ⁺ N	NO ₃ [−] N	NO ₂ [−] N	PO ₄ ^{3−}	TP	Cl [−]	SO ₄ ^{2−}	SS	EC	Fe	Mn	Cr	As	Cu
Spring																			
2021	1.28	1.02	1.80	2.62	0.90	1.26	0.29	0.70	2.30	3.92	0.13	0.15	0.16	0.37	0.10	0.22	0.03	0.10	0.02
2022	1.17	1.01	2.29	1.92	0.75	1.60	0.27	1.00	1.50	4.40	0.19	0.21	0.33	0.39	0.05	0.20	0.07	0.10	0.03
2023	1.28	0.95	2.33	3.07	1.13	2.74	0.33	2.20	1.75	2.00	0.11	0.15	0.16	0.42	0.14	0.20	0.07	0.10	0.01
Summer																			
2021	1.14	0.96	1.45	2.10	0.71	0.54	0.29	0.70	1.25	1.82	0.14	0.22	0.16	0.41	0.05	0.20	0.04	0.39	0.02
2022	1.36	1.01	1.35	1.84	0.65	4.20	0.20	1.00	2.00	2.20	0.16	0.09	0.30	0.42	0.05	0.20	0.04	0.10	0.02
2023	1.16	1.02	1.13	1.72	0.61	2.54	0.40	0.90	1.55	1.74	0.12	0.14	0.17	0.41	0.05	0.20	0.07	0.10	0.01
Autumn																			
2021	1.44	1.01	1.42	1.95	0.69	1.66	0.29	1.40	2.00	1.36	0.13	0.19	0.16	0.38	1.35	0.20	0.10	0.10	0.08
2022	1.28	0.96	2.89	4.08	1.32	6.40	0.33	1.10	1.85	4.00	0.15	0.18	0.16	0.37	0.31	0.56	0.13	0.10	0.01
2023	1.21	1.02	1.55	1.94	0.71	3.40	0.31	3.70	1.70	2.58	0.16	0.14	0.56	0.40	0.17	0.20	0.10	0.10	0.01
Winter																			
2021	1.42	0.94	2.40	0.00	1.19	0.90	0.23	1.10	1.50	5.00	0.10	0.13	0.16	0.34					
2022	1.39	0.94	1.53	2.20	0.84	2.00	0.87	2.40	2.20	1.82	0.11	0.30	0.20	0.28					
2023	1.39	0.99	2.62	3.50	1.32	3.00	0.35	1.00	2.50	2.80	0.12	0.51	0.60	0.31	0.05	0.20	0.10	0.10	0.01

Organic matter indicators show moderate interannual variability. BOD₅ ($C_i/S_i \approx 1.80$ – 2.33) and TOC ($C_i/S_i \approx 1.92$ – 3.07) indicate a noticeable increase, with the highest ratios observed in 2023, likely associated with seasonal hydrological conditions typical of the spring period. COD_{Mn} remained within moderate levels ($C_i/S_i \approx 0.75$ – 1.13).

Nutrient concentrations do not show a consistent seasonal pattern. Ammonium exhibits an increasing trend ($C_i/S_i \approx 1.26$ – 2.74), while nitrate remains low and relatively uniform ($C_i/S_i \approx 0.27$ – 0.33). Nitrite concentrations are generally low, although a higher ratio ($C_i/S_i \approx 2.20$) was observed in 2023. Phosphorus compounds show elevated ratios in earlier years (PO₄^{3−}: $C_i/S_i \approx 1.50$ – 2.30 ; TP: $C_i/S_i \approx 2.00$ – 4.40), with somewhat lower values observed in 2023.

Dissolved ions remained stable and well below reference limits (Cl[−]: $C_i/S_i \approx 0.11$ – 0.19 ; SO₄^{2−}: $C_i/S_i \approx 0.15$ – 0.21), while suspended solids were low to moderate ($C_i/S_i \approx 0.16$ – 0.33). Metal concentrations showed no pronounced variability and remained far below reference thresholds.

Summer data for the Priboj hydrological station indicate stable oxygen conditions, with dissolved oxygen consistently above reference levels ($C_i/S_i \approx 1.14$ – 1.36), while pH remained relatively uniform and close to reference conditions ($C_i/S_i \approx 0.96$ – 1.02).

Organic matter indicators show moderate interannual variability, with BOD₅ ($C_i/S_i \approx 1.13\text{--}1.45$) and TOC ($C_i/S_i \approx 1.72\text{--}2.10$) indicating moderate organic loading, while COD_{Mn} remained low ($C_i/S_i \approx 0.61\text{--}0.71$).

Nutrient concentrations show more pronounced variability, particularly for ammonium ($C_i/S_i \approx 0.54\text{--}4.20$). In contrast, nitrate and nitrite remained low and stable (NO₃-N: $C_i/S_i \approx 0.20\text{--}0.40$; NO₂-N: $C_i/S_i \approx 0.70\text{--}1.00$). Phosphorus forms remained at moderate levels (PO₄³⁻: $C_i/S_i \approx 1.25\text{--}2.00$; TP: $C_i/S_i \approx 1.74\text{--}2.20$).

Dissolved ions showed limited summer variability and remained well below reference limits (Cl⁻: $C_i/S_i \approx 0.12\text{--}0.16$; SO₄²⁻: $C_i/S_i \approx 0.09\text{--}0.22$), while suspended solids were low ($C_i/S_i \approx 0.16\text{--}0.30$). Metal concentrations remained uniform and low, without pronounced variability during the summer period.

Autumn data for the Priboj hydrological station indicate stable oxygen conditions throughout all three years, with dissolved oxygen consistently above reference levels ($C_i/S_i \approx 1.21\text{--}1.44$), while pH remained relatively uniform ($C_i/S_i \approx 0.96\text{--}1.02$).

Organic matter indicators show more pronounced interannual variability, with BOD₅ ($C_i/S_i \approx 1.42\text{--}2.89$) and TOC ($C_i/S_i \approx 1.94\text{--}4.08$) indicating elevated levels of organic matter, while COD_{Mn} ranged from low to slightly elevated values ($C_i/S_i \approx 0.69\text{--}1.32$).

Nutrient concentrations show clear interannual variability. Ammonium exhibited strong fluctuations ($C_i/S_i \approx 1.66\text{--}6.40$), while TOC also showed pronounced interannual variability, whereas nitrate remained relatively uniform at moderate levels ($C_i/S_i \approx 0.29\text{--}0.33$). Nitrite showed greater variability ($C_i/S_i \approx 1.10\text{--}3.70$). Phosphorus compounds were generally elevated, with PO₄³⁻ ($C_i/S_i \approx 1.70\text{--}2.00$) and TP ($C_i/S_i \approx 1.36\text{--}4.10$). In addition to seasonal hydrological processes, diffuse inputs from agricultural land and insufficiently treated wastewater within the catchment may also contribute to the observed increases in nutrient and ammonium concentrations. Occasional high-flow events may further enhance the transport of phosphorus and other nutrients from surrounding agricultural areas into the river system.

Dissolved ions remained stable and below reference thresholds (Cl⁻: $C_i/S_i \approx 0.13\text{--}0.16$; SO₄²⁻: $C_i/S_i \approx 0.14\text{--}0.19$), while suspended solids showed increased variability ($C_i/S_i \approx 0.16\text{--}0.56$). Metal concentrations remained generally low, with some variability observed for iron.

Winter data for the Priboj hydrological station indicate stable oxygen conditions, with dissolved oxygen consistently above reference levels ($C_i/S_i \approx 1.39\text{--}1.42$), while pH remained within a narrow range ($C_i/S_i \approx 0.94\text{--}0.99$).

Organic matter indicators show pronounced interannual variability, with BOD₅ ($C_i/S_i \approx 1.53\text{--}2.62$). TOC data were available only for 2022 and 2023 ($C_i/S_i \approx 2.20\text{--}3.50$), as no TOC measurements were available for winter 2021, which limits direct comparison among all three years. The observed differences in BOD₅ and TOC among individual years likely reflect interannual variability in hydrological conditions and organic matter transport during the winter period. COD_{Mn} ranged from moderate to slightly elevated values ($C_i/S_i \approx 0.84\text{--}1.32$).

Nutrient concentrations show pronounced variability during the winter period. Ammonium showed a marked increase trend ($C_i/S_i \approx 0.90\text{--}3.00$), while nitrate showed wider variability ($C_i/S_i \approx 0.23\text{--}0.87$). Nitrite ranged from low to moderately elevated values ($C_i/S_i \approx 1.00\text{--}2.40$). Phosphorus compounds were elevated, with PO₄³⁻ ($C_i/S_i \approx 1.50\text{--}2.50$) and TP showing the highest variability ($C_i/S_i \approx 1.82\text{--}5.00$). The elevated winter nutrient levels may also reflect diffuse agricultural sources and wastewater inputs within the basin, although their relative contribution cannot be determined from the available monitoring data.

Dissolved ions remained below reference thresholds (Cl^- : $C_i/S_i \approx 0.10\text{--}0.12$; SO_4^{2-} : $C_i/S_i \approx 0.13\text{--}0.51$), while suspended solids showed increased variability ($C_i/S_i \approx 0.16\text{--}0.60$). Although sulfate concentrations remained below the Class I threshold, the highest winter values may partly reflect inputs from the wider basin, including areas influenced by mining activities described in Section 3. Metal data were not available for 2021 and 2022, which represents a limitation for more detailed analysis, while in 2023 concentrations remained low and below reference levels.

Seasonal analysis at the Priboj hydrological station suggests that physicochemical parameters exhibit clear but moderate seasonal variability. Dissolved oxygen remained stable throughout the year, without pronounced depletion, while pH showed only minor fluctuations. Organic matter indicators displayed moderate seasonal differences, with generally lower values in spring and summer and higher values in autumn and winter, particularly in 2022 and 2023.

Nutrients showed the most pronounced variability. Ammonium concentrations were generally lower during warmer periods and increased in autumn and winter, while nitrate tended to reach higher levels during winter. Nitrite remained generally low, with occasional increases. Phosphorus forms exhibited seasonal maxima in autumn and winter, suggesting possible episodic inputs or increased mobilization under varying hydrological conditions. These seasonal increases may also be influenced by diffuse agricultural pressures and wastewater inputs present within the basin.

Dissolved ions generally remained within moderate ranges across all seasons, with slightly elevated sulfate concentrations during winter. Suspended solids showed the greatest seasonal variability, with lower values in spring and higher concentrations during winter, which may be associated with short-term hydrological variability. Similar effects of runoff variability and hydrological conditions have also been reported in other Serbian river basins [61]. In karst environments, intense precipitation events may activate rapid conduit-flow pathways and enhance the transport of terrestrial sediments into the river network with limited filtration. Such processes can contribute to short-term increases in suspended solids and have been documented in previous studies of karst hydrological systems [62]. Data on trace metals were limited during winter, while in other seasons concentrations were consistently low and showed no pronounced seasonal variation.

These seasonal variations are reflected in the corresponding fluctuations of the Water Pollution Index (WPI), which integrates the combined influence of these parameters.

4.3. Water Pollution Index (WPI) Analysis

Annual WPI values obtained for the Priboj hydrological station indicate a stable and relatively low level of water pollution during the 2021–2023 monitoring period. The index ranged from 0.89 in 2021 to 0.96 in 2022 and 0.99 in 2023, with all values classified as Class II (pure water) according to the adopted categorization.

Although a slight increase is visible across the three years, the change is small and remains well below the upper limit of Class II ($\text{WPI} = 1$). This variation likely reflects natural hydrological and biogeochemical variability rather than increased anthropogenic influence.

Seasonal WPI values at the Priboj hydrological station indicate noticeable intra-annual differences in water quality. These variations reflect the combined influence of hydrological conditions, seasonal runoff patterns, and biogeochemical processes within the Uvac River Basin. The index shows that water quality generally oscillates between Class II (pure) and Class III (moderately polluted), with more pronounced deviations occurring during autumn and winter (Figure 2). Similar results were obtained in the study by Kračun-Kolarević et al. [37] during August and October 2021, where they recorded Class I and

Class II quality at most of the 14 sampling sites, with two exceptions at the Vapa Čedovo and Uvac Čedovo sites, where the Class III was present.

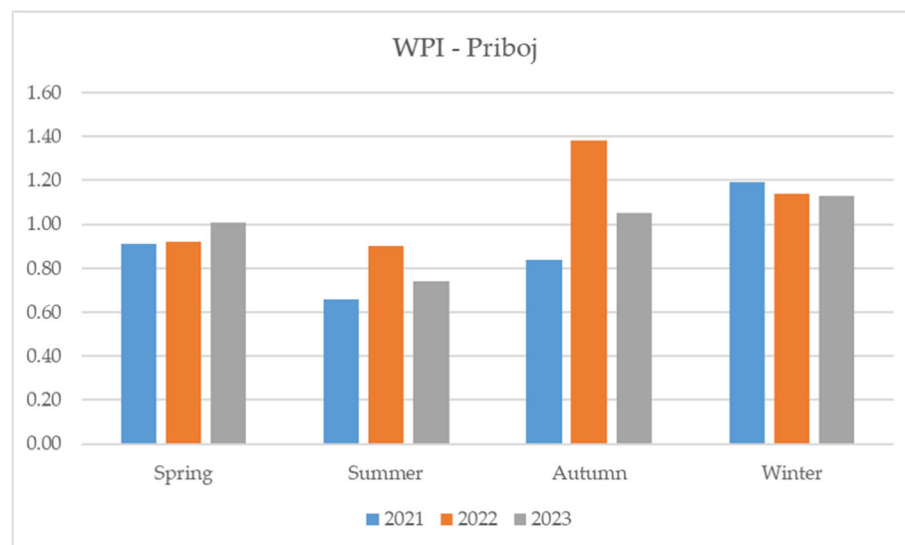


Figure 2. Seasonal Water Pollution Index (WPI) trends at the Priboj hydrological station (2021–2023). Each bar represents a WPI value calculated from the seasonal mean concentrations of the monitored parameters.

Spring WPI values ranged from 0.91 to 1.01, placing 2021 and 2022 in Class II, while 2023 slightly exceeded the threshold and entered Class III. This seasonal pattern aligns with the detailed hydrochemical results: early-season runoff may introduce elevated loads of organic matter and nutrients, particularly ammonium, nitrites, and phosphorus forms. Although oxygen conditions remain stable and pH shows minimal variation, the increased ratios of BOD₅, TOC, and certain nutrient parameters in 2023 likely contribute to the small increase in the WPI above 1. The spring classification therefore likely reflects the influence of catchment flushing processes typical for snowmelt-driven mountain systems.

Summer WPI values (0.66–0.90) consistently fall within Class II, indicating the most favorable seasonal conditions. This corresponds well with the hydrochemical profile: dissolved oxygen remains high, pH is relatively uniform, and organic load is generally lower than in other seasons. Nutrient concentrations, especially ammonium and phosphorus, tend to decrease, likely due to reduced runoff, enhanced biological uptake, and increased sedimentation during periods of low flow and higher temperatures. The summer classification thus likely reflects a well-oxygenated system with limited anthropogenic and catchment-driven influence.

Autumn shows the strongest seasonal variability, with WPI values ranging from 0.84 (Class II) to 1.38 and 1.05 (Class III). The shift toward Class III in 2022 and 2023 is consistent with the observed increases in BOD₅, TOC, COD_{Mn}, NH₄-N, NO₂-N, and TP. These changes are likely associated with intensified decomposition of organic material, increased soil leaching during early autumn rainfall, and reduced biological assimilation as temperatures decline. Although oxygen conditions remain favorable, the elevated ratios of organic and nutrient parameters likely contribute to the increase in WPI into the moderately polluted category. Autumn therefore represents a transitional period in which catchment processes likely exert a stronger influence on water quality.

Winter WPI values (1.19 in 2021, 1.14 in 2022 and 1.13 in 2023) consistently fall within Class III, making winter the season with the most persistent moderate pollution signal. This classification is supported by the hydrochemical data: organic load (BOD₅, TOC, COD_{Mn}) is higher relative to spring and summer, while nutrient concentrations—

particularly ammonium, nitrates, and total phosphorus—show their highest seasonal values. Reduced biological activity, limited assimilation, and episodic winter runoff are likely associated with these patterns. The observed differences in BOD₅ and TOC among individual years likely reflect interannual variability in hydrological conditions and organic matter transport. Despite stable dissolved oxygen and relatively low mineral ion concentrations, the elevated nutrient and organic matter ratios are sufficient to maintain WPI values slightly above the Class II threshold.

These results highlight the sensitivity of the WPI to seasonal changes in organic matter and nutrient dynamics, particularly during transitional hydrological periods. These seasonal patterns are largely controlled by hydrological conditions and catchment processes, which is consistent with recent studies highlighting the dominant influence of short-term hydroclimatic variability on water-related indices [63,64]. Increased runoff during spring and autumn enhances the transport of organic matter and nutrients from the surrounding terrain into the river. During winter, reduced biological activity limits nutrient uptake and may contribute to higher concentrations. In contrast, summer low-flow conditions promote sedimentation and biological assimilation, leading to lower WPI values. Karst conditions in the catchment also influence water quality by controlling flow pathways and reducing short-term changes in solute concentrations [65].

4.4. Relationships Between WPI and Water-Quality Parameters

To further explore the relationships between WPI and single water-quality parameters, a correlation analysis was performed using monthly observations from the combined 2021–2023 dataset. The strongest correlations were recorded between WPI and TOC, BOD₅, COD_{Mn}, NH₄-N and SS ($p < 0.001$); PO₄³⁻, NO₂-N, SO₄²⁻ and TP were statistically significant ($p < 0.01$), whereas the remaining parameters showed weak and statistically non-significant relationships with WPI (Table S2 Supplementary File).

The analysis indicated clear relationships between WPI values and several key water-quality parameters (Figure 3). The strongest positive correlations were identified for total organic carbon (TOC, $r = 0.76$), biochemical oxygen demand (BOD₅, $r = 0.76$), and COD_{Mn} ($r = 0.73$). Since WPI is derived from the analyzed parameters, the observed correlations partly reflect the structure of the index. These results highlight the important role of organic matter in influencing variations in overall water quality, suggesting that periods of elevated WPI values are mainly associated with increased organic matter inputs.

DO	pH	BOD ₅	TOC	NH ₄ -N	NO ₃ -N	NO ₂ -N	PO ₄ ³⁻	TP	Cl ⁻	SO ₄ ²⁻	SS	EC	CODMn
0.15	-0.01	0.76	0.76	0.64	0.16	0.47	0.51	0.46	0.10	0.47	0.62	-0.30	0.73

Figure 3. Correlation coefficients between WPI and selected water-quality parameters based on monthly observations collected during 2021–2023. Red colors indicate positive correlations, white indicates near-zero values, and blue indicates negative correlations.

In addition to organic indicators, several parameters related to nutrient enrichment and particulate transport showed moderate positive correlations with WPI. Ammonium (NH₄-N, $r = 0.64$) and suspended solids ($r = 0.62$) exhibited relatively strong relationships, while orthophosphates (PO₄³⁻, $r = 0.51$), nitrite (NO₂-N, $r = 0.47$), sulfates ($r = 0.47$), and total phosphorus ($r = 0.46$) were also associated with WPI variability. These findings suggest that nutrient inputs and the mobilization of suspended material represent important secondary factors influencing water-quality conditions, likely reflecting a combination of diffuse inputs and hydrological processes.

By contrast, nitrate (NO₃-N) and chlorides (Cl⁻) showed only weak correlations with WPI, indicating a limited contribution to short-term variability in the index. Electrical con-

ductivity (EC) exhibited a moderate negative correlation ($r = -0.30$), which may reflect dilution effects or changes in ionic composition under different hydrological conditions. Dissolved oxygen and pH displayed weak or negligible relationships with WPI, suggesting that these parameters are more strongly controlled by natural physicochemical processes than by pollution dynamics captured by the index.

The results indicate that WPI variability is mainly associated with organic matter dynamics, as reflected by strong correlations with TOC, BOD₅, and COD_{Mn}. Moderate relationships with ammonium, nitrite, orthophosphates, and suspended solids suggest the additional influence of nutrient inputs and runoff processes. Other parameters showed weak or negligible correlations, indicating a lesser role in short-term water-quality variability.

A limitation of the present study is the absence of biological indicators, including algal-related parameters, which could provide additional insight into ecological status and eutrophication processes. Future studies should integrate physicochemical, biological, and microbiological indicators to achieve a more comprehensive assessment of water quality in the Uvac River.

5. Conclusions

The results indicate that the Uvac River maintains generally good water quality during the 2021–2023 period, with annual WPI values consistently within Class II. This indicates generally stable conditions, without clear evidence of significant water-quality degradation at the Priboj hydrological station.

The C_i/S_i ratio indicated generally stable physicochemical conditions, with only minor to moderate deviations from Class I standards. By analyzing the C_i/S_i ratio for each parameter, it could be concluded that organic matter indicators (BOD₅, TOC, COD_{Mn}) and suspended solids exhibited moderate variability with occasional peaks; nutrient concentrations reflected low nitrogen levels and more variable phosphorus dynamics, likely related to short-term inputs. Seasonal analysis reveals moderate intra-annual variability, with water quality occasionally shifting to Class III during autumn and winter. These variations are associated with increased runoff, enhanced transport of organic matter and nutrients, and reduced biological assimilation during colder periods. In contrast, summer conditions are characterized by lower WPI values, reflecting more uniform hydrological conditions and reduced external inputs.

The correlation analysis shows that water quality is primarily associated with organic matter dynamics, as indicated by strong relationships between WPI and parameters such as TOC, BOD₅, and COD_{Mn}. Moderate correlations with ammonium, suspended solids, and phosphorus compounds further suggest that nutrient inputs and hydrological conditions contribute to temporal variations in water quality.

The observed patterns indicate that water-quality variability is largely influenced by natural hydrological and biogeochemical processes, while localized anthropogenic pressures may also contribute to the observed variability. These findings are consistent with the identified environmental pressures in the Uvac River basin, where diffuse anthropogenic influences such as agriculture, wastewater discharge, and tourism remain present but relatively limited in their overall impact on water quality. The karstic characteristics of the catchment further influence water quality by regulating flow pathways and moderating short-term changes in solute concentrations.

This study enhances knowledge on the state of hydrological resources, which are essential for the sustainable development of protected areas. Although moderate anthropogenic pressures are present, particularly from waste disposal, insufficient wastewater treatment, and tourism, they have not yet significantly compromised water qual-

ity in the Uvac River at the Priboj hydrological station, which reflects downstream post-reservoir conditions.

Although the observation period was relatively short, the results provide a useful basis for future monitoring and management of water resources in protected areas. Continued monitoring is particularly important in view of increasing tourism development and other anthropogenic pressures within the basin.

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