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Water Quality Assessment of the Jerma River: Application of the Water Pollution Index (WPI) Within a Torrential Catchment

Dragana Milijašević Joksimović [1,*], Ana M. Petrović [1], Valentina Nikolova [2], Jan Babej [3] and Ivan Novković [4]

[1] Geographical Institute "Jovan Cvijić" of the Serbian Academy of Sciences and Arts, 11000 Belgrade, Serbia
[2] University of Mining and Geology, 1000 Sofia, Bulgaria
[3] Global Change Research Institute, The Czech Academy of Sciences, 60200 Brno, Czech Republic
[4] Faculty of Geography, University of Belgrade, 11000 Belgrade, Serbia
* Correspondence: d.milijasevic@gi.sanu.ac.rs

Abstract

This study evaluates long-term (2014–2023) and seasonal water quality in the Jerma River, a transboundary watershed between Serbia and Bulgaria, using annual mean physicochemical and microbiological parameters at two monitoring sites as well as Water Pollution Index (WPI) classifications. Seasonal datasets (spring, summer, autumn and winter) were applied to assess intra-annual variability. The water quality reflects the influence of geomorphology, hydrological seasonality, and anthropogenic pressures. The river reflects the influence of geomorphology, hydrological seasonality, and anthropogenic pressures typical of mountain catchments. Upstream conditions were favorable, characterized by stable oxygen regimes, low suspended solids, and low nutrient levels, with occasional phosphorus enrichment. Downstream sections showed stronger deviations, including elevated nutrients, departures from reference conditions, and variability in microbiological indicators. Seasonal analyses indicated stable oxygen conditions at both sites, while nutrient and microbial parameters varied during specific periods. Dissolved metals remained within Class I thresholds throughout the study. WPI values confirmed spatial and seasonal differences. Upstream water quality mainly corresponded to Class II, with occasional shifts toward Class III, whereas downstream values fluctuated between Classes II and IV, with short-term deterioration during seasons. Higher variability occurred in spring and summer, while winter conditions were more stable. Overall, the results indicate better upstream status and increased nutrient and microbial pressures downstream, highlighting the need for continued monitoring and management.

Keywords: Jerma River; water quality; Water Pollution Index; nutrient enrichment; seasonal variation; transboundary river

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Academic Editor: Rosanna De Rosa

Received: 18 February 2026
Revised: 19 March 2026
Accepted: 30 March 2026
Published: 2 April 2026

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1. Introduction

Rivers are complex and dynamic systems whose ecological integrity depends on the interplay between natural hydromorphological processes and anthropogenic influences. Seasonal variability in flow regimes, sediment transport, and nutrient cycling can play an important role in shaping water quality, and episodic events such as floods or droughts can additionally influence short-term ecological dynamics [1–5]. In this context, continuous monitoring and integrated assessment approaches are essential for understanding pollution dynamics and informing sustainable water resource management [6,7]. A recent study

applied water-quality indices in combination with statistical analyses to assess surface-water contamination and environmental risks in river systems [8].

The Jerma River, a transboundary watercourse flowing through southeastern Serbia and western Bulgaria, is characterized by seasonal variations in flow and a hydrological regime strongly influenced by the mountainous landscape conditions in its catchment. The upper and middle sections of the basin are shaped by steep relief and short runoff concentration times, which result in relatively quick hydrological responses to precipitation events [9]. These features, combined with localized anthropogenic influences, make the basin particularly sensitive to environmental changes [10]. The geomorphological and habitat characteristics of the Jerma have also been examined through the application of the RHS (River Habitat Survey) method, which identified the river's upper reaches as ecologically sensitive segments with largely natural channel structure [11]. The importance of geomorphological structure for hydrological functioning and ecological processes has also been confirmed in recent international studies [12]. These baseline findings highlight the importance of considering habitat and geomorphological context when interpreting contemporary water-quality dynamics.

Given the hydrological and geomorphological sensitivity of the Jerma River, water-quality indices have become essential tools for integrating diverse physicochemical and microbiological information into a single, interpretable value. These indices provide a framework for synthesizing multiple indicators into one metric, thereby facilitating classification into water-quality classes and enabling comparative assessments across sites and time periods [13,14]. Internationally, the Water Pollution Index (WPI) and related methodologies have been widely employed to assess river health, identify pollution hotspots, and support decision-making in water management. Applications have been documented in numerous case studies worldwide, including the Grenjeng River in Indonesia [15], the Chumbao River in Peru [16], and urban basins in Mexico [17]. Similar approaches have also been used in recent remote-sensing-supported assessments of river basins in Central Asia [18].

Water quality assessment in Serbia has traditionally been based on the interpretation of individual physicochemical and microbiological parameters in relation to national classification standards, although several studies have already demonstrated the usefulness of composite index approaches in this context [19–21]. In Serbia, the WPI has proven to be a suitable approach for summarizing monitoring data and supporting water-resource management at the catchment scale. The index has been applied not only in river systems, such as the Sava [22], Kolubara [23], Tamiš [24], and South Morava rivers [25], but also in standing-water systems, including assessments of water quality in the Vlasina protected area [26] and the Garaši Reservoir [27].

Mountain rivers with torrential flow regimes typically respond rapidly to precipitation events, exhibit pronounced seasonal variability, and are often sensitive to local anthropogenic pressures. These hydrological and environmental characteristics can strongly influence the dynamics of nutrients, suspended matter, and microbiological indicators. However, long-term and integrative assessments of water quality in such dynamic river systems remain relatively limited in the scientific literature. In this context, the Jerma River provides a valuable case study for examining how index-based approaches can be applied to mountain catchments and for improving the understanding of how seasonal hydrological variability shapes water-quality patterns.

However, despite these applications, the Water Pollution Index has not previously been applied to the Jerma River basin, and long-term integrative assessments of water quality in this transboundary mountain river system remain scarce in this part of Europe.

Following a previous CWQI-based assessment (Canadian Water Quality Index) of the Jerma River by Gartsiyanova, Gencev, and Kitev [28], the present study applies the Water Pollution Index (WPI) as an integrative approach that incorporates a broad set of physicochemical and microbiological parameters. This study aims to investigate the spatial and seasonal variability of water quality in the Jerma River during the period 2014–2023, using the Water Pollution Index, based on physicochemical and microbiological parameters. Annual and seasonal WPI values are calculated at upstream and downstream monitoring sites to evaluate pollution dynamics, with particular attention to microbiological indicators and to the relationships between river discharge (Q) and individual water-quality parameters.

Given that the Jerma River traverses protected areas of exceptional natural value in both Serbia and Bulgaria, systematic monitoring of chemical and ecological parameters represents a fundamental basis for safeguarding biodiversity and enhancing coordinated transboundary management.

2. Materials and Methods

2.1. Study Area

The Jerma River originates from the confluence of the Vučja and Grubinska rivers east of Vlasina Lake in southeastern Serbia. After crossing the state border twice, it flows into the Nišava River approximately 1 km downstream from the village of Gradište. From the source of the Vučja River to the settlement of Strazimirovci, the river flows northeast through Serbia for about 17 km. It then continues for around 27 km across Bulgarian territory, flowing eastward before turning north and re-entering Serbia for an additional 28 km. The total catchment area is approximately 796 km^2, of which slightly more than half (about 400 km^2) lies within Bulgaria [29].

Located at the structural boundary between the Carpatho–Balkan Mountains and the Serbian–Macedonian Massif, the Jerma Basin exhibits pronounced geological and geomorphological diversity. According to Petrović [30], about 70% of the basin consists of impermeable ancient metamorphic complexes, Paleozoic and Mesozoic clastics, and intrusive igneous formations, whereas the lower reaches are dominated by Tertiary and Quaternary deposits. The main morphographic units within the watershed area are Vlaška, Greben, Ezdimirska Planina, and Straža mountains and parts of Krajište and Znepole.

The Jerma River has a mean annual discharge of about 5.4 m^3/s (1961–1990) at the Sukovo hydrological station and is characterized by a pronounced spring high-water period. Maximum monthly flows occur in March and April (10.8 and 10.4 m^3/s), while the lowest values are recorded in August and September (2.1 and 1.9 m^3/s). Monthly runoff coefficients (Q/Q_{av}, where Q_{av} represents the mean discharge) indicate a clear nival–pluvial regime: discharges exceed the annual mean from February to June and drop to 0.4–0.5 of Q_{av} during late summer. These characteristics reflect the basin's lithology, the precipitation regime of the Krajište region, and the absence of major karst infiltration pathways [31]. Additional local-scale analyses [10] point to flow irregularities and a predisposition to rapid flood events, confirming the torrential character of the Jerma [9].

For the study period (2014–2023), mean annual discharge at the Trnski Odorovci gauging station was 3.94 m^3/s, with a pronounced spring maximum (March–April) and a late-summer minimum (August–September). These monthly mean discharges were calculated from daily values reported by the Republic Hydrometeorological Service of Serbia [32]. Mean monthly discharge values are presented to illustrate the hydrological regime during the period of water-quality assessment.

Given these hydrological characteristics, a systematic analysis of water quality was carried out at two hydrological stations along the course of the river, located in the Serbian part of the watershed (Figure 1):

- Strazimirovci hydrological station, located in the immediate vicinity of the Serbian–Bulgarian border (UTM 34T: 618,425 m E/4,739,067 m N; ~760 m a.s.l.; catchment area: 95 km^2), and
- Trnski Odorovci hydrological station, situated downstream after the river re-enters Serbia (UTM 34T: 632,696 m E/4,754,170 m N; ~550 m a.s.l.; catchment area: 557 km^2).

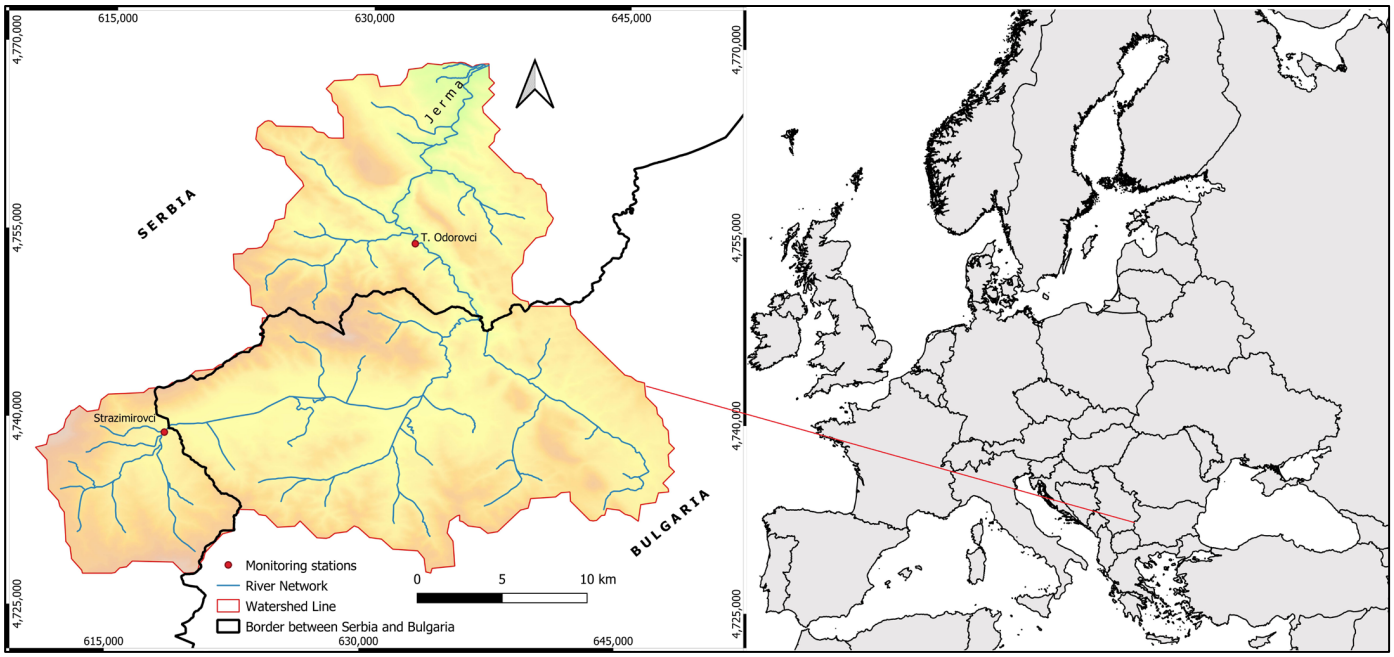


Figure 1. Geographical location of the Jerma River watershed and the monitoring stations used in the analyses.

The selection of these stations enables an upstream–downstream comparison within the Serbian section of the basin and provides a basis for assessing the influence of transboundary inflow on the water quality of the Jerma River.

Protected natural areas along the Jerma include two territories of exceptional ecological and geomorphological importance, one in Serbia and the other in Bulgaria. In Serbia, the upper and middle course of the river is part of the "Jerma" Special Nature Reserve, a Category I protected area established by the 2014 Regulation [33]. Covering nearly 7000 ha of canyons, gorges, limestone cliffs, caves, and forest habitats, it represents one of the key biodiversity refugia in southeastern Serbia. The western and southwestern parts of the study area are encompassed by the Vlasina Landscape of Outstanding Features.

Across the border in Bulgaria, the river passes through the Trnsko ždrelo (Erma Gorge), protected as a natural monument since 1961 due to its prominent canyon morphology and well-preserved habitats. This area is also part of the Natura 2000 ecological network (site BG0000313 "Ruy"), making it an internationally recognized priority site for geodiversity and biodiversity conservation [34].

Together, these protected areas contribute to preserving the integrity of the Jerma River ecosystem. They encompass segments where biological, geomorphological, and hydrological features are most pronounced, which is highly relevant for water-quality monitoring and management in this transboundary basin. Their presence further underscores the need for coordinated conservation measures, as degradation in one section of the river may adversely affect protected values downstream.

2.2. Data Sources and Analytical Methods

This study is based on water-quality data collected at two hydrological stations within the Serbian section of the Jerma River (Strazimirovci and Trnski Odorovci), representing upstream and downstream segments of the national monitoring network. These stations enable the assessment of spatial differences in water quality and the influence of transboundary inflow. It is important to note that older data (2014–2020) are available only for Trnski Odorovci, whereas monitoring at Strazimirovci has been systematically performed since 2021, resulting in two partially overlapping analytical periods.

Data were obtained from the yearbooks of the Serbian Environmental Protection Agency [35]. The evaluation encompassed a set of core physicochemical and microbiological parameters, including dissolved oxygen (DO), oxygen saturation (OS), pH, biochemical oxygen demand (BOD_5), chemical oxygen demand (CODMn), suspended solids (SS), nitrites (NO_2^-), ammonium (NH_4^+), total phosphorus (TP), orthophosphates (PO_4^{3-}), sulphates (SO_4^{2-}), selected dissolved metals (Fe, Mn, Hg, Cu, Pb, Cd), and total coliforms (TC). Although nitrate concentrations are available in the national dataset, the present study prioritizes nitrogen species more directly associated with short-term organic and municipal pollution pressure (NH_4^+ and NO_2^-), and therefore nitrate was not included in the WPI calculation.

Water-quality analyses were conducted by SEPA, operating under the Ministry of Environmental Protection of the Republic of Serbia. Sampling and laboratory procedures followed standardized national and international protocols. For both hydrological stations, water sampling and quality determination were performed approximately 10–12 times per year, except for total coliforms, which were analyzed 1–5 times annually. Microbiological parameters such as total coliforms may show higher short-term variability and are monitored less frequently within the national monitoring program. Therefore, their contribution to the WPI values should be interpreted with caution. Annual mean values were calculated as arithmetic averages of all available measurements within each year. The annual sampling frequency for physicochemical parameters and total coliforms at both monitoring stations is summarized in Table 1.

Table 1. Total number of samples for each parameter at the monitoring stations.

Parameter	Trnski Odorovci (2014–2023) n	Strazimirovci (2021–2023) n
Suspended solids (SS)	116	35
Dissolved oxygen (DO)	117	35
Oxygen saturation (OS)	117	35
pH	117	35
Ammonium (NH_4^+)	117	35
Nitrites (NO_2^-)	117	35
Orthophosphates (PO_4^{3-})	117	35
Total phosphorus (TP)	114	34
Sulphates (SO_4^{2-})	117	35
CODMn	117	35
BOD_5	117	35
Total coliforms	26	9
Dissolved metals (Fe, Mn, Cu, Pb, Cd, Hg)	85	27

The applied methods included: dissolved oxygen (DO)—SRPS ISO 5813:1994 [36]; oxygen saturation (OS)—SRPS H.Z1.160:1987 [37]; pH—SRPS H.Z1.111:1987 [38]; suspended solids (SS)—SRPS H.Z1.160:1987 [37]; biochemical oxygen demand (BOD_5)—JUS ISO 5815 [39]; and chemical oxygen demand (CODMn)—Kubel–Tiemann method (oxidation with potassium permanganate). Additional methods included: nitrites (NO_2^-)—HACH method 8507/EPA 353.2 [40]; ammonium (NH_4^+)—HACH method 8155 [41]; orthophosphates (PO_4^{3-})—HACH method 8048/EPA 365.1 [42]; total phosphorus (TP)—APHA AWWA WEF 4500 (A, B, E) [43]; sulphates (SO_4^{2-})—HACH method 8051 [44]; dissolved

metals (Fe, Mn, Cu, Cd)—EPA 6020A:2014 [45]; lead (Pb)—EPA 6020A:2007 [45]; mercury (Hg)—EPA method 245.7 [46]; and total coliforms (TC)—SRPS EN ISO 9308–1:2010 [47].

In this study, SEPA's verified analytical results were statistically processed and interpreted to evaluate annual and seasonal variations in water quality and to calculate the Water Pollution Index. All data processing and index calculations were performed independently by the authors.

2.3. Water Pollution Index (WPI)

The Water Pollution Index (WPI) was applied to quantify overall surface water quality. Unlike the Canadian Water Quality Index (CWQI), which evaluates water quality primarily through the frequency and magnitude of guideline exceedances, the WPI approach is based on the ratio between measured concentrations and reference threshold values, allowing the integration of individual parameters into a composite pollution index.

This index integrates multiple physicochemical and microbiological parameters and is calculated as the arithmetic mean of the ratios between the observed concentrations and the corresponding Class I standard limits, as follows:

$$\mathrm{WPI} = \frac{1}{n}\sum_{i=1}^{n}\frac{Ci}{Si} \quad (1)$$

where

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

S_i—Class I standard limit value according to national regulations;

n—total number of parameters included in the analysis.

In the case of parameters with a defined Class I range (e.g., pH), the upper limit was adopted as the reference value (S_i) for WPI computation.

In this study, the notation S_i denotes the standard limit value for parameter i. In previous regional studies [24,48], the same concept has been expressed using the symbol SFQS, which refers to the standard values for the first class of surface water quality in Serbia. Although the notation differs, the meaning confirms identical regulatory threshold values.

Class I standards represent water suitable for drinking (after treatment), recreation, irrigation, and various industrial uses. In the Serbian water-quality classification system, Class I represents the highest water-quality category (excellent ecological status), while higher class numbers (II–V) indicate progressively lower quality levels. The WPI methodology is flexible and allows the inclusion of different parameters depending on data availability, making it suitable for diverse monitoring programs.

Standard limit values were taken from Serbian national legislation, primarily from the Regulation on Limit Values of Pollutants in Surface and Groundwater [48], including the category defining excellent ecological status (Class I) for small and medium watercourses above 500 m a.s.l. with coarse-bed substrates. The reference values used in this study are presented in Table 2.

Table 2. Reference thresholds for class I water quality parameters.

Parameter	Unit	Class I
Dissolved Oxygen (DO)	mg/L	8.5
Oxygen Saturation (OS)	%	90
pH	-	6.5–8.5
Chemical Oxygen Demand (CODMn)	mg/L	10
Biochemical Oxygen Demand (BOD_5)	mg/L	1.8
Suspended solids (SS)	mg/L	25
Nitrites (NO_2^-)	mg/L	0.01

Table 2. *Cont.*

Parameter	Unit	Class I
Ammonium (NH_4^+)	mg/L	0.1
Orthophosphates (PO_4^{3-})	mg/L	0.02
Sulphates (SO_4^{2-})	mg/L	50
Total phosphorus (TP)	mg/L	0.05
Manganese (Mn)	mg/L	0.05
Iron (Fe)	mg/L	0.2
Mercury (Hg)	µg/L	1
Copper (Cu)	µg/L	100
Lead (Pb)	µg/L	50
Cadmium (Cd)	µg/L	5
Total Coliforms (TC)	N/100 mL	500

Source: [49–51].

The classification of surface water based on WPI values follows the scheme commonly applied in regional studies [52] and is presented in Table 3.

Table 3. Water quality classification according to pollution index.

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

Source: [52].

2.4. Statistical Evaluation of Discharge–Water Quality Relationships

Additional statistical analyses were conducted to examine interactions between individual water-quality parameters and river discharge and to improve understanding of the processes controlling WPI variability.

The statistical analysis included several methods to assess the relationships between discharge and the analyzed water-quality parameters, taking into account the distribution characteristics of the time series. Data normality was tested using standard tests (Shapiro–Wilk test and D'Agostino's K^2 test). The results indicated non-normal distributions for all variables except SO_4^{2-}. Therefore, non-parametric methods were applied, as they are less sensitive to outliers and non-linear patterns.

For correlation analysis, river discharge values measured at the Trnski Odorovci station at the time of water sampling were used, rather than monthly mean discharges. The dataset used for the statistical analyses consisted of monthly observations from the 2014–2023 period, with a sample size of 117 observations for most variables, although a small number of measurements were missing for several parameters. The same dataset was used for the exploratory factor analysis. The total number of measurements available for each parameter during the monitoring period varied depending on the sampling program and is summarized in Table 1.

Spearman's rank correlation was used to evaluate the relationships between discharge and individual water-quality parameters. This method allows the identification of monotonic relationships without assuming normality, making it particularly suitable for hydrological analyses where seasonal effects and episodic concentration peaks are common. The results are presented using a correlation heatmap, which provides a clear visual overview of correlation patterns among multiple variables.

Because the dataset is based on discrete monitoring observations rather than continuous high-frequency measurements, the hydrological interpretation focuses on relationships

between discharge measured at the time of sampling and individual water-quality parameters. Flow-normalized concentrations were therefore not considered in this study.

Spearman's rank correlation was additionally applied using different time lags to examine the response time between discharge and water-quality parameters. The analysis showed that most parameters exhibit the strongest relationships at lag = 0, indicating a simultaneous response of water quality to changes in discharge.

Finally, factor analysis (FA) was performed to identify latent structures in the dataset and shared patterns of variability among the parameters. Unlike bivariate correlation analysis, factor analysis does not assess direct dependence on discharge but instead helps to identify dominant processes that simultaneously influence multiple water-quality indicators. The extracted factors explained approximately 66% of the total variance. Factor 1 accounted for 25.19% of the variance, followed by Factor 2 (15.75%), Factor 3 (8.88%), Factor 4 (9.74%), and Factor 5 (6.44%).

3. Results and Discussion

3.1. Parameter Deviation from Class I—Jerma River (Trnski Odorovci Station)

This section presents the ratio of mean annual concentrations to Class I water-quality standards for the Jerma River at the Trnski Odorovci hydrological station, based on monitoring data collected between 2014 and 2023 (Table 4).

Table 4. Annual concentration ratios based on class I water-quality criteria.

Strazimirovci																		
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2021	1.09	0.91	0.82	0.43	0.74	0.26	0.50	0.26	0.65	0.09	1.72	0.24	0.18	0.06	0.02	0.01	0.003	2.83
2022	1.23	1.05	0.91	0.24	0.62	0.25	0.70	0.22	0.80	0.10	1.62	0.22	0.12	0.07	0.03	0.02	0.006	5.35
2023	1.24	0.99	0.91	0.23	0.74	0.28	0.50	0.34	0.70	0.10	1.72	0.22	0.19	0.07	0.02	0.01	0.005	17.07
Trnski Odorovci																		
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2014	1.28	1.20	0.98	0.49	0.89	0.22	1.70	0.41	1.05	0.30	2.04	0.20	-	-	-	-	-	22.00
2015	1.32	1.11	0.96	1.17	0.89	0.26	1.50	0.34	1.20	0.36	1.82	0.20	-	-	-	-	-	-
2016	1.31	1.18	0.98	0.37	1.06	0.32	1.80	0.33	0.90	0.50	0.76	0.20	0.07	0.10	0.01	0.01	0.005	7.50
2017	1.34	1.18	0.99	1.22	1.17	0.36	2.50	0.64	1.30	0.49	1.08	0.20	0.08	0.07	0.01	0.01	0.004	28.30
2018	1.35	1.18	0.98	0.63	1.06	0.34	1.90	0.54	1.15	0.44	1.02	0.26	0.11	0.07	0.02	0.01	0.005	13.27
2019	1.24	1.14	0.98	0.19	1.00	0.33	2.30	0.81	1.55	0.44	1.04	0.22	0.07	0.07	0.01	0.01	0.006	3.20
2020	1.28	1.16	0.98	0.25	1.17	0.37	2.20	0.83	2.40	0.49	2.36	0.20	0.11	0.07	0.02	0.02	0.006	13.40
2021	1.22	1.12	0.98	0.34	1.00	0.36	1.90	0.83	2.55	0.45	2.26	0.20	0.09	0.07	0.04	0.01	0.004	8.23
2022	1.34	1.21	0.98	0.22	0.94	0.32	1.90	0.79	2.25	0.44	2.20	0.20	0.08	0.07	0.05	0.01	0.004	2.55
2023	1.20	1.11	0.98	0.29	1.11	0.39	2.00	0.61	2.55	0.42	3.00	0.20	0.09	0.07	0.05	0.01	0.007	11.83

Note: "-" indicates parameters that were not measured or for which data were unavailable in the given year.

Dissolved oxygen (DO) ratios ranged from 1.20 to 1.35, while oxygen saturation (OS) varied between 1.11 and 1.21. Both parameters consistently exceeded Class I standards, indicating supersaturated conditions throughout the study period. Oversaturation of oxygen in aquatic ecosystems is often associated with enhanced photosynthetic activity [53]; however, it may also reflect natural aeration processes typical of turbulent mountain streams. Such conditions are consistent with the hydromorphological characteristics of the Jerma River, where steep channel gradients and turbulent flow promote rapid oxygen exchange with the atmosphere.

Throughout the monitoring period, pH values remained stable and close to the Class I reference range, with ratio values between 0.96 and 0.99. Stable pH levels indicate a carbonate-influenced system that naturally maintains chemical buffering capacity, typical of basins developed on carbonate lithology and supportive of ecological stability [54].

Suspended solids (SS) showed moderate variability, with occasional exceedances of Class I limits in years with elevated discharge. While most years remained below the Class I limit, slight exceedances occurred in 2015 (1.17) and 2017 (1.22). These events may be linked to seasonal runoff, upstream erosion or hydrological disturbances during periods of elevated discharge, consistent with the positive SS–discharge relationship observed in the statistical analysis. These patterns are also consistent with the torrential hydrological regime of the Jerma River, where rapid runoff events can enhance sediment mobilization and nutrient transport within the catchment.

Spearman correlation analysis indicated that suspended solids showed the strongest positive association with discharge, reflecting enhanced sediment mobilization during high-flow events, whereas several nutrient parameters displayed weaker or negative relationships, suggesting a stronger influence of local anthropogenic inputs and in-stream transformation processes.

Biochemical oxygen demand (BOD_5) ratios ranged from 0.89 to 1.17, with exceedances observed in 2016, 2017, 2018, 2020 and 2023. These values indicate increased loads of biodegradable organic matter and enhanced microbial activity. The observed pattern suggests a dominant influence of anthropogenic inputs rather than direct hydrological control [55].

Chemical oxygen demand (CODMn) remained consistently below the Class I threshold throughout the monitoring period. This indicates low concentrations of oxidizable substances and suggests that chemical pollution from industrial or urban sources was not a major pressure during the investigated period.

At the Trnski Odorovci station, elevated nitrite levels were consistently observed, with repeated exceedances of Class I standards indicating persistent nutrient pressure. Elevated nitrite concentrations are commonly associated with agricultural runoff, insufficient wastewater treatment, and in-stream microbial processes [56].

Ammonium (NH_4^+) ratios remained within the Class I range throughout the monitoring period (0.33–0.83), indicating generally good status with respect to reduced inorganic nitrogen. The statistical analysis similarly identified a negative relationship between ammonium and discharge, suggesting that NH_4^+ accumulation is favored under low-flow conditions, when dilution is limited and biochemical transformation processes slow down.

Dissolved metals showed highly stable behavior. Monitoring began in 2016, and throughout the available period, iron (Fe) ratios ranged from 0.07 to 0.11, while manganese (Mn) values remained constant at 0.20. Copper (Cu) concentrations were very low (0.01–0.05), and lead (Pb) and cadmium (Cd) remained consistently below Class I thresholds. Mercury (Hg) also remained low (0.06–0.07). The statistical analysis confirmed no meaningful trends or correlations with discharge, indicating predominantly geogenic sources and minimal anthropogenic impact.

Similar patterns of stable, mainly geogenic metal concentrations have also been reported for inland water bodies of the Volga–Akhtuba floodplain, where metal distribution is largely controlled by hydrodynamic conditions and sediment–water interactions [57].

Orthophosphate (PO_4^{3-}) ratios ranged from 0.90 to 2.55, with the highest values observed after 2020. Statistical analysis did not show a significant correlation with discharge, suggesting that orthophosphate dynamics are mainly influenced by local point sources and episodic inputs. Elevated orthophosphate concentrations increase eutrophication risk and may negatively affect aquatic habitats [58].

Sulphate (SO_4^{2-}) levels remained stable and within Class I criteria, with ratios between 0.30 and 0.50, consistent with the statistical finding of no significant correlation with discharge.

Total phosphorus (TP) reveals a more pronounced long-term pattern. The ratios show a clear increasing tendency during the monitoring period, particularly after 2019. This pattern may be associated with nutrient enrichment related to diffuse catchment sources and wastewater inputs. Similar relationships between land-use change, anthropogenic pressures, and elevated nutrient levels, as well as eutrophication risk, have been reported for Iberian water bodies [59].

Microbiological indicators showed the highest variability. Total coliform (TC) ratios ranged from 2.55 in 2022 to 28.30 in 2017. No statistically significant correlation with discharge was observed, indicating that microbiological contamination is primarily driven by local sanitary conditions and episodic inputs. The very high value recorded in 2017 suggests a short-term episode of fecal contamination and may indicate increased sanitary pressure within the catchment. It is important to note that the presented data are based on a limited sampling frequency (typically one to five measurements per year). Therefore, the results represent indicative trends rather than continuous monitoring, and short-term pollution events may not be fully captured.

The Trnski Odorovci station shows persistent and more pronounced exceedances of Class I criteria throughout the 2014–2023 period. Elevated ratios are observed primarily for NO_2^-, PO_4^{3-} and total phosphorus, while NH_4^+ generally remained within Class I limits. Organic matter indicators (BOD_5) also periodically exceed Class I limits, while total coliforms exhibit very high ratios in multiple years, indicating recurring episodes of microbiological contamination. Although heavy metals generally remain below critical thresholds, the cumulative pattern of nutrient, organic, and microbial pressures suggests the presence of anthropogenic influences within the basin.

Downstream of the town of Tran, the Bulgarian section of the Jerma River generally maintains a "good" ecological status (Class II water quality); however, several parameters indicate episodic anthropogenic influence. Elevated levels of nitrogen, phosphorus, orthophosphates and BOD_5, along with occasional exceedances of ammonium, nitrate, nitrite and trace metals such as copper and zinc measured in 2021, resulted in a "polluted" classification [28]. The higher deviations observed at Trnski Odorovci, particularly for NO_2^-, NH_4^+, total P, and microbiological parameters, suggest that transboundary pressures interact with additional local sources, emphasizing the need for coordinated catchment-wide management.

The presence of two protected areas along the Jerma River further underscores the need to maintain high hydrological and chemical standards. Because these ecosystems depend on stable water conditions to preserve endemic and relict species, reducing diffuse agricultural inputs, improving wastewater treatment and strengthening sanitary control are essential for safeguarding ecological integrity.

Taken together, the observed patterns suggest that water-quality variability at the downstream station is influenced by a combination of hydrological dynamics and catchment-scale pressures. Generally stable oxygen conditions reflect strong natural aeration typical of mountain streams, whereas nutrients and suspended solids respond more directly to hydrological fluctuations and local inputs within the catchment. Factor analysis further supported these observations by indicating two main variability patterns within the dataset. The extracted factors accounted for approximately 66% of the total variance. Factor 1 explained 25.19% of the variance and was primarily associated with nutrient-related variables (NO_2^-, PO_4^{3-} and TP), indicating the influence of anthropogenic pressures, while oxygen-related parameters (DO and OS) formed a separate group reflecting natural aeration processes. The cumulative increase in nutrient-related ratios toward the downstream section suggests that water quality integrates both upstream influences and additional local pressures along the river course.

These results also illustrate the usefulness of index-based approaches for integrating heterogeneous monitoring data in rivers characterized by strong hydrological variability. Such approaches may be particularly valuable in mountain catchments where monitoring programs often rely on discrete observations rather than continuous measurements.

3.2. Parameter Deviation from Class I—Jerma River (Strazimirovci Station)

This subsection presents deviations of key physicochemical and microbiological parameters from Class I water-quality standards for the Strazimirovci station, based on monitoring data collected between 2021 and 2023 (Table 4).

Because monitoring at the Strazimirovci station has been conducted only since 2021, direct comparisons between the two stations primarily refer to the common monitoring period 2021–2023, while earlier data from Trnski Odorovci (2014–2020) are used to illustrate longer-term trends in water quality.

Dissolved oxygen (DO) at the Strazimirovci station showed stable and elevated values during the 2021–2023 period, with ratios consistently exceeding Class I standards (Table 4). These results indicate strong oxygen availability, characteristic of well-aerated systems with low levels of biodegradable organic pollution. The persistent supersaturation of DO throughout the monitoring period confirms favorable conditions for aerobic biological processes and suggests the absence of significant anthropogenic pressures that would lead to oxygen depletion.

Oxygen saturation (OS) values at the Strazimirovci station also showed stable interannual behavior, with ratios ranging from 0.91 in 2021 to 1.05 in 2022, followed by a near-optimal value of 0.99 in 2023. The slightly lower value in 2021 indicates a marginal deviation from the Class I threshold, whereas the increase above unity in 2022 suggests favorable aeration conditions.

During the 2021–2023 period, pH values at Strazimirovci remained highly stable, with ratios ranging from 0.82 (2021) to 0.91 (2022–2023).

Suspended solids (SS) showed slight variability, with ratios decreasing from 0.43 (2021) to 0.23 (2023). All values remained well below the Class I limit, indicating low particle concentrations in the water. The consistently low SS ratios indicate limited sediment mobilization under typical flow conditions in the upper part of the catchment.

Biochemical oxygen demand (BOD_5) exhibited minor oscillations, with ratios ranging from 0.62 (2022) to 0.74 (2021 and 2023). All values remained within Class I limits, indicating moderate concentrations of biodegradable organic matter. These results suggest that occasional pressures, such as agricultural runoff or localized wastewater inputs, were not sufficiently intense to disrupt the oxygen balance of the aquatic ecosystem.

Chemical oxygen demand (CODMn) remained very stable and low throughout the study period, with ratios ranging from 0.25 in 2022 to 0.28 in 2023. These values suggest that chemical pollution, particularly from industrial or urban sources, did not represent a dominant pressure in this section of the catchment. The low CODMn levels further indicate generally preserved chemical conditions.

Nitrite (NO_2^-) concentrations at Strazimirovci were consistently low, with ratios ranging from 0.50 to 0.70 during 2021–2023 (Table 4). These values are considerably lower than at the Trnski Odorovci station, where nitrite levels repeatedly exceeded Class I limits.

Ammonium (NH_4^+) also remained below the Class I threshold, with ratios between 0.22 (2022) and 0.34 (2023). In contrast to Trnski Odorovci, where long-term nitrite and ammonium exceedances were recorded, nitrogen conditions at Strazimirovci are generally better.

Orthophosphates (PO_4^{3-}) showed moderately elevated values, with ratios ranging from 0.65 in 2021 to 0.80 in 2022, followed by a slight decrease to 0.70 in 2023. All values

remained below the Class I limit. These levels may reflect diffuse phosphorus inputs from detergents or agricultural fertilizers. Compared to Trnski Odorovci, orthophosphate levels at Strazimirovci were lower, indicating a reduced eutrophication pressure.

Total phosphorus (TP) showed stable but moderately elevated levels, with ratios ranging from 1.62 in 2022 to 1.72 in 2021 and 2023. These results indicate that Class I limits were exceeded in all monitored years. However, the values remained distinctly lower than those observed at Trnski Odorovci. This difference may indicate a lower cumulative phosphorus load at Strazimirovci, potentially related to differences in land use, population density, or the effectiveness of local wastewater infrastructure.

Dissolved metals at Strazimirovci showed a stable and favorable chemical profile, with all concentrations remaining well within Class I limits. Iron and manganese exhibited low and stable ratios. Copper, lead, cadmium and mercury occurred at very low levels, indicating minimal anthropogenic influence and the absence of industrial contamination. Overall, dissolved metals indicate low ecological pressure and generally preserved chemical quality in this section of the Jerma River.

Total coliform (TC) concentrations showed strong variability, with values increasing from 2.83 in 2021 to 5.35 in 2022 and peaking at 17.07 in 2023 (Table 4). The high value in 2023 indicates a short-term episode of elevated microbial contamination, likely related to wastewater inputs or livestock runoff. It should be noted that TC data are based on limited sampling frequency (typically one to five measurements per year) and therefore reflect indicative trends rather than continuous monitoring.

Data from the Strazimirovci station indicate that the majority of physicochemical parameters during 2021–2023 exhibit ratios below or close to unity, indicating generally good water quality. Organic pollution indicators (BOD_5 and CODMn), suspended solids, nutrients (NO_2^-, NH_4^+, PO_4^{3-}), sulfates, and heavy metals mostly remain well within Class I limits. However, TP consistently exceeds Class I criteria (ratios ~1.6–1.7), suggesting moderate nutrient enrichment. In addition, TC shows markedly elevated ratios, particularly in 2022 and 2023, pointing to episodic microbiological contamination, likely linked to untreated wastewater inputs or diffuse sources.

A synthesis of the 2021–2023 data indicates distinct contrasts between the two monitoring sites. Strazimirovci reflects lower anthropogenic pressure, with stable oxygen conditions, low nutrient levels and limited microbiological fluctuations. In contrast, Trnski Odorovci is characterized by recurrent nutrient and coliform exceedances, indicating stronger cumulative impacts from downstream land use, wastewater inputs, and local hydromorphological alterations. These contrasts point to the need for targeted management measures in the lower section of the Jerma basin, particularly regarding nutrient reduction and sanitary control.

3.3. Seasonal Analysis

Seasonal water quality dynamics were assessed in relation to Class I standards, highlighting temporal variations shaped by both natural hydrological regimes and anthropogenic inputs. Spring was evaluated using mean values of parameters measured in March, April, and May; summer as the average of June, July, and August; autumn as the mean of September, October, and November; and winter as the mean of December, January, and February. Seasonal patterns are presented descriptively to illustrate general temporal variability in the monitoring data. Formal statistical testing of seasonal differences was not performed in this study. The seasonal analysis aims to illustrate general temporal patterns in water quality rather than to provide a detailed comparison of seasonal WPI values between individual years. Across seasons, most physicochemical parameters generally remain below Class I reference values (ratio < 1), while exceedances are mainly

associated with nutrients (particularly total phosphorus) and microbiological indicators. This approach allows the identification of parameters that occasionally exceed reference limits and supports a general evaluation of seasonal water-quality conditions in the river.

Seasonal dynamics of water quality in the Jerma River have not previously been analyzed using an index-based integrative approach, although similar approaches have been applied in studies of other river systems [24].

Spring conditions at both stations generally show favorable oxygen regimes, with DO ratios ranging between 1.14 and 1.34 at Strazimirovci and 1.18–1.40 at Trnski Odorovci, consistently exceeding Class I reference values (Table 5). Suspended solids show greater variability, ranging from 0.25 to 0.43 at Strazimirovci and reaching up to 3.06 at Trnski Odorovci during periods of increased runoff, while upstream values remain lower and more stable.

Table 5. Seasonal concentration ratios based on class I water-quality criteria (spring).

Strazimirovci																	
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2021	1.14	1.06	0.89	0.41	0.83	0.27	0.60	0.37	0.65	0.09	3.86	0.20	0.22	0.07	0.02	0.01	0.004	29.15
2022	1.34	1.07	0.92	0.25	0.62	0.25	1.00	0.20	1.00	0.09	2.28	0.20	0.10	0.07	0.02	0.01	0.004	-
2023	1.33	1.04	0.92	0.43	0.79	0.29	0.70	0.20	0.55	0.08	1.58	0.20	0.20	0.07	0.02	0.01	0.007	11.00
Trnski Odorovci																		
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2014	1.29	1.25	1.00	0.61	0.78	0.19	0.90	0.50	0.95	0.26	-	-	-	-	-	-	-	-
2015	1.34	1.07	0.95	3.06	0.94	0.40	2.10	0.23	2.55	0.30	1.10	-	-	-	-	-	-	-
2016	1.24	1.20	0.96	0.21	0.94	0.30	1.60	0.27	0.60	0.55	0.80	0.20	0.06	0.10	0.01	0.01	0.004	-
2017	1.32	1.17	0.98	1.49	1.61	0.46	2.70	0.73	1.40	0.40	1.70	0.20	0.12	0.07	0.01	0.01	0.004	2.00
2018	1.40	1.27	0.98	0.92	1.17	0.37	2.00	0.53	1.20	0.38	1.20	0.20	0.20	0.07	0.01	0.01	0.006	6.30
2019	1.22	1.25	0.97	0.27	0.94	0.29	1.50	0.93	1.75	0.33	1.00	0.20	0.05	0.07	0.01	0.01	0.004	1.00
2020	1.18	1.06	0.98	0.33	1.39	0.41	2.10	0.70	2.40	0.37	2.7	0.36	0.06	0.07	0.02	0.03	0.006	30.90
2021	1.27	1.11	0.94	0.68	1.00	0.37	1.70	0.67	2.45	0.42	1.72	0.20	0.07	0.07	0.03	0.01	0.004	3.10
2022	1.33	1.21	0.98	0.19	1.00	0.32	2.00	0.70	2.50	0.40	2.00	0.20	0.10	0.07	0.05	0.01	0.004	1.00
2023	1.25	1.12	0.96	0.43	1.22	0.41	1.80	0.53	2.40	0.35	2.60	0.20	0.11	0.07	0.05	0.01	0.012	16.90

Note: "-" indicates parameters that were not measured or for which data were unavailable in the given year.

Indicators of nutrient status show clear differences between the stations. At Trnski Odorovci, nitrite ratios range between 0.9 and 2.7, ammonium between 0.23 and 0.93, and orthophosphate between 0.6 and 2.55, occasionally exceeding Class I limits. In contrast, Strazimirovci maintains lower and more stable concentrations. Although some spring measurements show increased nutrient ratios, the available data do not indicate a consistent seasonal pattern. Variability differs between years and between stations, suggesting that these fluctuations are influenced by short-term hydrological or local catchment conditions.

Microbiological indicators appear to show higher variability during spring, including occasional high coliform values associated with intensive runoff or localized sanitary inputs.

Summer conditions are characterized by low discharge, higher temperatures and intensified biological activity. Oxygen-related parameters remain favorable, with DO and OS ratios above Class I limits and pH showing little seasonal change. Suspended solids stay generally low to moderate, while BOD_5 and CODMn show slight increases due to stronger microbial decomposition under warm, low-flow conditions.

Summer months tend to show higher nutrient values in the available observations, particularly at the Trnski Odorovci station. Nitrite ratios range between 1.10 and 3.50, frequently exceeding Class I thresholds, while orthophosphate ratios range between 0.50 and 3.25. Total phosphorus often reaches its highest seasonal values, ranging from 0.40 to 4.36. These patterns may reflect enhanced eutrophication pressure during the low-flow period. Upstream at Strazimirovci, nutrient levels are more stable, with lower nitrite and ammonium concentrations and only moderate phosphorus enrichment (Table 6).

Table 6. Seasonal concentration ratios based on class I water-quality criteria (summer).

Strazimirovci																	
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2021	1.07	1.06	0.92	0.27	0.81	0.29	0.60	0.27	0.80	0.11	2.42	0.52	0.27	0.07	0.02	0.01	0.004	16.00
2022	1.00	1.04	0.92	0.40	0.77	0.28	0.70	0.27	0.65	0.12	1.74	0.20	0.05	0.07	0.04	0.03	0.005	
2023	1.02	1.05	0.92	0.17	0.79	0.29	0.80	0.23	0.65	0.09	1.48	0.24	0.14	0.07	0.02	0.01	0.005	15.05
Trnski Odorovci																		
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2014	1.18	1.14	0.96	0.35	0.78	0.21	1.50	0.30	1.70	0.27	3.16	-	-	-	-	-	-	22.00
2015	1.18	1.16	0.98	0.31	0.87	0.22	1.10	0.20	0.50	0.42	0.64	-	-	-	-	-	-	-
2016	1.19	1.20	0.99	0.19	1.22	0.35	2.10	0.43	0.80	0.57	0.44	0.20	0.05	0.10	0.01	0.001	0.004	7.50
2017	1.15	1.20	0.99	0.41	1.07	0.35	3.50	0.67	1.45	0.53	0.82	0.20	0.05	0.07	0.01	0.011	0.004	110.00
2018	1.08	1.11	0.98	1.11	1.07	0.38	2.00	0.60	1.15	0.47	1.46	0.20	0.06	0.07	0.01	0.010	0.004	29.40
2019	1.12	1.19	0.99	0.16	1.05	0.34	2.50	0.67	0.90	0.44	0.40	0.20	0.07	0.07	0.01	0.010	0.011	1.00
2020	1.18	1.24	0.99	0.16	1.05	0.35	2.30	0.80	2.75	0.48	2.60	0.30	0.11	0.07	0.01	0.010	0.005	5.20
2021	1.06	1.13	0.98	0.21	1.00	0.37	1.90	0.93	2.55	0.47	1.70	0.20	0.10	0.07	0.01	0.013	0.005	9.50
2022	1.13	1.20	0.98	0.36	1.00	0.36	2.10	0.93	3.25	0.45	4.34	0.20	0.05	0.07	0.03	0.022	0.004	3.00
2023	1.05	1.09	0.96	0.40	1.39	0.46	2.00	0.51	2.30	0.45	4.36	0.20	0.07	0.07	0.03	0.010	0.004	9.30

Note: "-" indicates parameters that were not measured or for which data were unavailable in the given year.

Microbiological indicators also intensify during summer, especially downstream, where TC ratios range from 1.00 to 110.00, reflecting increased sensitivity to local sanitary conditions and episodic contamination during this period.

Autumn represents a transitional period marked by cooling temperatures, reduced biological activity and more stable discharge. Oxygen conditions generally improve compared to summer, with DO ratios ranging between 1.07 and 1.28 at Strazimirovci and 1.15–1.45 at Trnski Odorovci, consistently exceeding Class I reference values while pH remains stable at both stations. Suspended solids remain low, typically around 0.16–0.31, reflecting limited sediment transport as flows become more uniform.

Nutrient concentrations remain variable, with clear differences between the stations. At Trnski Odorovci, nitrite ratios range between 1.30 and 2.80, frequently exceeding Class I thresholds, while orthophosphate ranges between 0.65 and 2.65. Total phosphorus may reach high autumn values, ranging from 0.50 to 4.30, indicating that eutrophication pressure persists even as hydrological conditions become more stable (Table 7). Upstream at Strazimirovci, nutrient levels are lower and more stable, with orthophosphate usually within Class I limits and total phosphorus only moderately elevated.

Table 7. Seasonal concentration ratios based on class I water-quality criteria (autumn).

Strazimirovci																	
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2021	1.28	1.03	0.91	0.16	0.85	0.28	0.60	0.23	0.80	0.09	0.78	0.20	0.10	0.07	0.04	0.01	0.004	8.50
2022	1.07	1.03	0.91	0.16	0.67	0.20	0.90	0.20	0.85	0.10	1.28	0.28	0.25	0.07	0.04	0.01	0.008	5.35
2023	1.11	1.03	0.91	0.16	0.81	0.27	0.80	0.60	0.90	0.12	1.62	0.20	0.22	0.07	0.03	0.01	0.004	27.20
Trnski Odorovci																		
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2014	1.31	1.21	0.98	0.70	1.11	0.25	2.80	0.36	0.65	0.35	1.96	-	-	-	-	-	-	-
2015	1.20	1.10	0.96	0.16	0.72	0.21	1.30	0.40	0.85	0.37	0.66	-	-	-	-	-	-	-
2016	1.45	1.17	0.98	0.17	0.89	0.28	1.80	0.33	0.75	0.56	0.50	0.20	0.07	0.10	0.01	0.01	0.004	-
2017	1.26	1.16	1.00	0.16	1.06	0.33	1.90	0.73	1.20	0.60	0.56	0.20	0.05	0.07	0.01	0.01	0.004	0.60
2018	1.27	1.15	0.98	0.16	1.06	0.30	1.80	0.43	1.25	0.49	0.64	0.20	0.06	0.07	0.01	0.01	0.004	4.10
2019	1.21	1.16	0.98	0.16	1.00	0.33	2.80	0.87	1.05	0.50	0.56	0.20	0.10	0.07	0.01	0.01	0.004	4.90
2020	1.28	1.17	0.99	0.31	1.00	0.36	2.00	0.93	2.65	0.62	3.12	0.20	0.15	0.07	0.02	0.01	0.004	4.10
2021	1.24	1.14	0.98	0.16	1.00	0.34	2.00	0.87	2.55	0.50	4.30	0.20	0.05	0.07	0.04	0.01	0.004	12.10
2022	1.21	1.18	0.98	0.16	0.78	0.31	1.80	0.80	1.85	0.47	1.50	0.20	0.09	0.07	0.06	0.01	0.004	
2023	1.15	1.13	0.98	0.16	0.94	0.35	2.20	0.67	2.65	0.48	2.08	0.20	0.10	0.07	0.07	0.01	0.004	

Note: "-" indicates parameters that were not measured or for which data were unavailable in the given year.

Microbiological indicators sometimes show autumn increases, with TC ratios ranging from 0.60 to 27.20 at the monitoring stations. Metal concentrations remain within Class I thresholds throughout the season. In general, autumn is characterized by improved oxygen conditions but continued variability in nutrient and microbial indicators, especially at the downstream station.

Winter conditions show the greatest physicochemical stability (Table 8), driven by low temperatures and minimal biological activity. DO ratios range between 1.29 and 1.58 at Strazimirovci and 1.33–1.64 at Trnski Odorovci, consistently exceeding Class I reference values. pH exhibits only slight variation, while suspended solids generally remain low, typically between 0.16 and 1.32, indicating limited erosion and sediment transport.

Table 8. Seasonal concentration ratios based on class I water-quality criteria (winter).

Strazimirovci																	
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2021	1.29	1.09	0.88	1.32	0.89	0.29	0.50	0.25	0.60	0.08	2.30	0.20	0.20	0.07	0.06	0.01	0.004	
2022	1.58	1.05	0.92	0.16	0.64	0.25	0.70	0.20	0.80	0.10	1.18	0.20	0.07	0.07	0.01	0.01	0.004	
2023	1.48	0.84	0.91	0.16	0.67	0.26	0.70	0.33	0.65	0.11	2.18						0.004	
Trnski Odorovci																		
Year	DO	OS	pH	SS	BOD_5	COD_{Mn}	NO_2^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	TP	Mn	Fe	Hg	Cu	Pb	Cd	TC
2014	1.34	1.21	0.95	0.20	0.81	0.23	1.30	0.50	0.90	0.36	1.24	-	-	-	-	-	-	-
2015	1.53	1.14	0.96	1.15	1.00	0.23	1.50	0.53	0.80	0.35	0.98	-	-	-	-	-	-	-
2016	1.42	1.13	0.96	1.18	1.11	0.37	1.70	0.25	1.80	0.25	1.62	0.20	0.13	0.10	0.015	0.010	0.008	-
2017	1.64	1.20	0.98	2.81	0.87	0.29	1.80	0.43	1.10	0.42	1.20	0.22	0.09	0.07	0.010	0.010	0.004	-
2018	1.62	1.18	0.98	0.35	1.06	0.29	1.90	0.60	0.95	0.43	0.74	0.20	0.13	0.07	0.020	0.013	0.005	-
2019	1.42	1.11	0.98	0.16	0.98	0.34	2.50	0.77	2.55	0.50	2.18	0.2	0.07	0.07	0.016	0.010	0.005	-
2020	1.56	1.16	0.98	0.16	1.30	0.33	2.40	0.90	1.50	0.49	1.40	0.24	0.11	0.07	0.027	0.011	0.009	-
2021	1.33	1.10	0.96	0.32	1.02	0.36	2.00	0.87	2.75	0.41	2.00	0.20	0.16	0.07	0.114	0.010	0.004	-
2022	1.56	1.25	0.99	0.19	0.93	0.29	1.80	0.70	1.45	0.44	1.04	0.20	0.05	0.07	0.062	0.010	0.004	-
2023	1.36	1.14	0.98	0.16	0.82	0.34	1.90	0.73	2.75	0.39	3.00	-	-	-	-	-	-	-

Note: "-" indicates parameters that were not measured or for which data were unavailable in the given year.

Nutrient levels show moderate winter enrichment with clear spatial differences. At Trnski Odorovci, nitrite ratios range between 1.30 and 2.50, ammonium between 0.25 and 0.90, and total phosphorus between 0.74 and 3.00, occasionally exceeding Class I thresholds. These increases likely reflect the combined influence of local inputs and reduced biochemical transformation during winter conditions.

Organic indicators (BOD_5, CODMn) remain within expected winter ranges, while dissolved metals stay well below Class I thresholds, confirming the absence of metal-related pressures. Microbiological data were not collected during winter, which limits the interpretation of seasonal microbial variability. Microbiological parameters, particularly total coliforms, were monitored less frequently than physicochemical parameters within the national monitoring program (typically 1–5 measurements per year). Therefore, TC values represent indicative observations rather than continuous monitoring. Although included in the WPI calculation, the limited frequency of microbiological data introduces some uncertainty in assessing microbial contamination in the Jerma River.

Winter represents the most chemically stable period of the year, while still showing moderate nutrient accumulation during lower-flow conditions, particularly at the downstream station.

Seasonal changes in water quality along the Jerma River reflect the catchment's hydrological conditions. The downstream station, Trnski Odorovci, shows more frequent deviations from Class I standards, especially during periods of reduced flow in summer and early autumn. Upstream at Strazimirovci, most parameters remain lower and more stable. After the river crosses the border, additional inputs and local pressures further influence conditions downstream. These differences highlight the combined effects of

longitudinal changes, transboundary influences and seasonal hydrology, underscoring the need for coordinated water-management measures.

3.4. Water Pollution Index (WPI) Analysis

Table 9 presents the annual WPI values and corresponding water quality classes for both monitoring stations on the Jerma River. At the Trnski Odorovci station, water quality fluctuated noticeably over the ten-year period (2014–2023), with WPI values ranging from 0.81 to 2.71. The dominant class was Class II (pure), recorded in five of the analyzed years, while Class III and IV appeared intermittently, indicating episodic deterioration in water quality.

Table 9. Mean annual WPI values and water quality classifications at the analyzed hydrological stations.

Hydrological St Trnski Odorovci	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
WPI	2.71	0.99	0.97	2.27	1.35	0.81	1.52	1.2	0.86	1.44
Cass	IV	II	II	IV	III	II	III	III	II	III
Hydrological St Strazimirovci	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
WPI	-	-	-	-	-	-	-	0.78	0.75	1.41
Class	-	-	-	-	-	-	-	II	II	III

Note: "-" indicates years for which WPI values could not be calculated due to the unavailability of required input parameters.

The poorest water quality was recorded in 2014 and 2017, when the river reached Class IV, indicating a short-term increase in microbiological and organic loading. In contrast, the lowest WPI values were recorded in 2019 (0.81, Class II) and 2022 (0.86, Class II), indicating a temporary return to pure water quality conditions. These oscillations suggest that pollution in the lower part of the Jerma basin is not persistent but occurs primarily in an episodic manner, reflecting localized anthropogenic pressures and seasonal variability in pollution inputs.

The classification shift toward Class IV in 2014 was driven by the fact that total coliforms were sampled only once that year (11,000 N/100 mL), and this value was used as the annual average in the WPI calculation. Consequently, the microbiological component of the index exerted full weighting influence, while other parameters remained within moderate ranges. This confirms that short-term microbiological peaks can significantly affect the final WPI classification, even when the physicochemical status of the water body does not change markedly.

Seasonal WPI values offer a more nuanced understanding of temporal fluctuations in water quality across the Jerma River basin. At the Trnski Odorovci station, the index exhibits marked variability, with high values occurring under different hydrological conditions—including spring runoff (e.g., 2020, WPI = 2.50, Class IV) as well as pronounced summer and early-autumn peaks (e.g., summer 2017, WPI = 6.81, Class V; autumn 2021, WPI = 1.53, Class III). These patterns reflect two dominant seasonal mechanisms: increased nutrient inputs during spring runoff and enhanced concentration effects combined with elevated temperatures during late-summer conditions. Comparable discharge–water-quality interactions have been examined for the Nišava River system, where Leščešen et al. [60] reported weak or site-specific relationships between discharge and overall water quality, indicating that low-flow conditions alone do not fully explain observed variability. Similar seasonally driven degradation patterns have been documented in semi-arid catchments, where high summer temperatures and reduced discharge promote eutrophication and microbiological pressures [61].

Seasonal WPI values at the Trnski Odorovci station indicate pronounced temporal variability across the study period (Figure 2). Spring and autumn were characterized by generally pure water quality conditions, with WPI values most frequently falling within Class

II, but with several notable seasonal exceedances. These include spring 2020 (WPI = 2.50, Class IV) and autumn 2021 (WPI = 1.53, Class III), both of which are associated with elevated phosphorus and coliform concentrations.

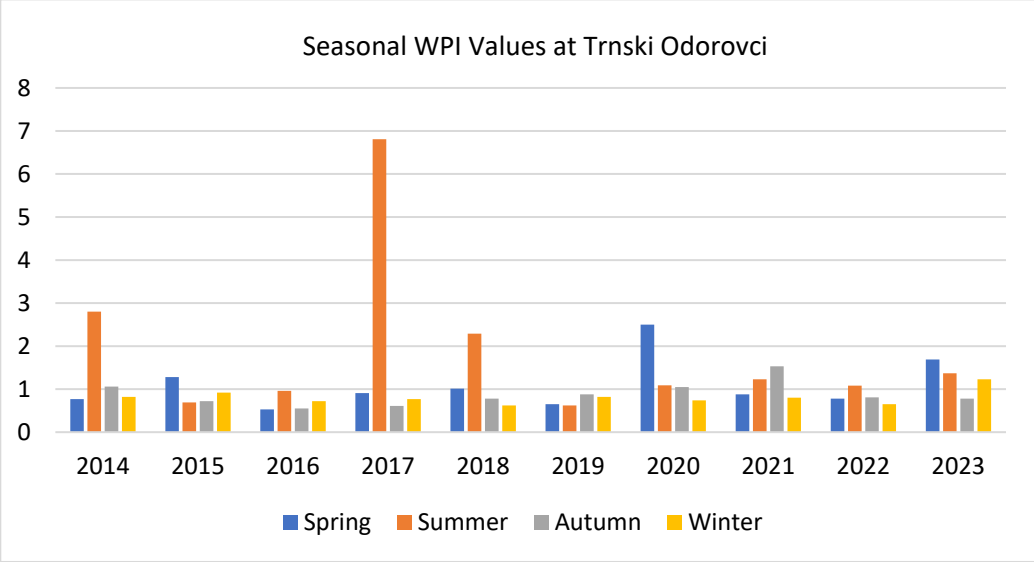


Figure 2. Seasonal WPI values at the Trnski Odorovci hydrological station (2014–2023).

Winter WPI values were generally lower and less variable, most often classified as Class II (pure). However, this apparent stability should be interpreted with caution, as the absence of microbiological data during winter monitoring may contribute to an underestimation of episodic contamination events. Consequently, seasonal comparisons should account for both hydrological conditions and data availability when assessing relative water-quality status.

At the Strazimirovci station, seasonal WPI data are available for the period 2021–2023 (Figure 3). The most favorable conditions were observed in winter, with all three years classified as Class II (pure) (WPI range: 0.47–0.75). As observed at the Trnski Odorovci station, the lack of coliform data during winter likely contributed to these lower values. Spring and summer exhibited greater variability, with WPI values ranging from 0.49 (summer 2022, Class II) to 2.21 (spring 2021, Class IV). The highest seasonal index was recorded in autumn 2023 (WPI = 2.00, Class III), coinciding with elevated nutrient and microbial indicators.

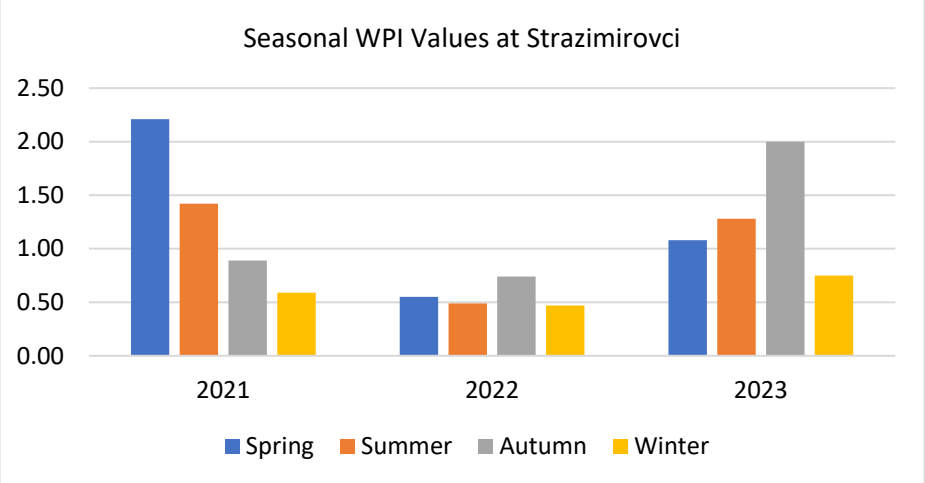


Figure 3. Seasonal WPI values at the Strazimirovci hydrological station (2021–2023).

Taken together, the seasonal WPI analysis confirms that summer and spring are the most vulnerable periods for water-quality deterioration, while winter consistently shows lower index values, partially due to incomplete microbiological data. These findings reinforce the importance of seasonal monitoring and highlight the need for year-round microbiological sampling to ensure accurate classification. The observed patterns suggest that pollution in the Jerma River is episodic and seasonally driven, with localized pressures amplifying during periods of reduced dilution capacity.

3.5. Statistical Relationships Between Water-Quality Parameters and River Discharge

3.5.1. Correlation Analysis

Spearman's rank correlation was applied to assess the relationships between river discharge and individual water-quality parameters, considering the non-normal distribution of the data (Figure 4).

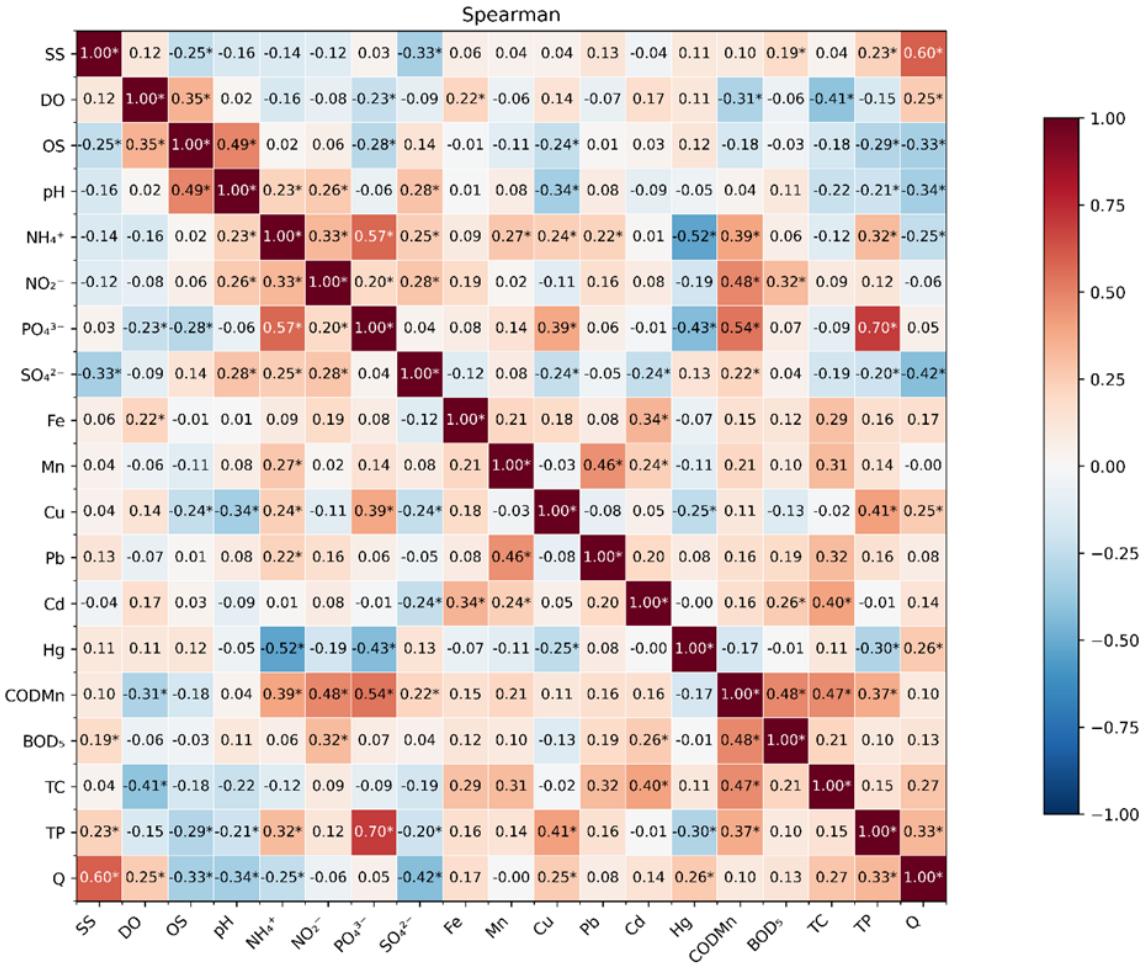


Figure 4. Spearman correlation heatmap of water-quality parameters and river discharge at the Trnski Odorovci station at lag = 0. Note: Statistically significant correlations ($p < 0.05$) are indicated by an asterisk (*). SS—suspended solids (mg/L); DO—dissolved oxygen (mg/L); OS—oxygen saturation (%); pH—potential of hydrogen (dimensionless); NH_4^+—ammonium (mg/L); NO_2^-—nitrites (mg/L); PO_4^{3-}—orthophosphates (mg/L); SO_4^{2-}—sulphates (mg/L); Fe, Mn, Cu, Pb, Cd, Hg—dissolved metals (µg/L); CODMn—permanganate chemical oxygen demand (mg/L); BOD_5—biochemical oxygen demand (mg/L); TC—total coliforms (N/100 mL); TP—total phosphorus (mg/L); Q—river discharge (m^3/s).

Spearman's rank correlation coefficient (r) showed that river discharge (Q) is moderately negatively correlated with several physicochemical and nutrient parameters, in-

cluding pH, NH_4^+, and SO_4^{2-} ($r \approx -0.25$ to -0.42). These relationships indicate higher concentrations of these parameters during low-flow conditions, when dilution is weaker, while their values tend to decrease at higher discharges due to enhanced dilution. In contrast, discharge shows a strong positive correlation with suspended solids (SS; $r \approx 0.60$), reflecting enhanced erosion and solid transport under high-flow conditions.

Most dissolved metals (Fe, Mn, Cu, Pb, Cd, and Hg), as well as nitrite (NO_2^-), orthophosphate (PO_4^{3-}), and total coliforms (TC), do not exhibit statistically significant correlations with discharge. The absence of such relationships suggests that their variability is not primarily controlled by hydrological conditions but is more likely associated with local pollution sources, episodic inputs, chemical transformations, and sediment–water interactions.

Oxygen regime parameters (DO and OS) show weak correlations with discharge ($r \approx 0.25$ to -0.33), suggesting limited direct hydrological control. This indicates that oxygen conditions are primarily influenced by temperature, biological activity, and flow turbulence rather than by short-term changes in river discharge.

In addition to relationships with discharge, significant internal correlations were observed among nutrient parameters (e.g., NH_4^+–PO_4^{3-} and PO_4^{3-}–TP), organic pollution indicators (CODMn–BOD_5), and between dissolved oxygen and oxygen saturation. These patterns point to shared sources and coupled biogeochemical processes that are largely independent of short-term hydrological fluctuations.

3.5.2. Factor Analysis

To further examine the shared processes controlling the variability of hydrochemical parameters, factor analysis was applied. The results indicate the presence of five dominant factors reflecting key processes in the hydrochemical functioning of the Jerma River (Table 10).

Table 10. Factor analysis of water-quality parameters and river discharge at the Trnski Odorovci station. Communality values indicate the proportion of total variance explained by the extracted factors.

	F1	F2	F3	F4	F5	Communality
SS	0.19	0.58	−0.04	0.02	−0.23	0.43
DO	−0.31	−0.13	0.82	−0.35	0.04	0.92
OS	−0.45	−0.21	0.71	0.07	0.26	0.83
pH	−0.36	−0.59	−0.08	0.26	0.19	0.60
NH_4^+	−0.10	−0.63	−0.22	−0.15	0.31	0.57
NO_2^-	0.27	−0.09	0.21	0.43	0.59	0.67
PO_4^{3-}	0.46	0.09	−0.38	−0.66	0.26	0.87
SO_4^{2-}	−0.35	−0.28	0.06	0.36	0.38	0.48
Fe	0.24	0.25	0.06	−0.15	0.18	0.18
Mn	0.86	−0.49	−0.05	−0.05	0.03	0.99
Cu	0.04	0.35	−0.32	−0.49	−0.13	0.49
Pb	0.87	−0.49	0.02	0.01	−0.02	1.00
Cd	0.50	0.17	0.10	−0.26	−0.03	0.35
Hg	0.03	−0.01	0.17	0.30	−0.31	0.22
CODMn	0.84	0.54	0.02	0.02	0.01	1.00
BOD_5	0.76	0.42	0.22	0.00	−0.10	0.81
TC	0.24	0.04	0.01	0.48	0.36	0.42
TP	0.76	0.39	−0.19	−0.24	0.23	0.88
Q	0.43	0.66	0.12	−0.40	−0.25	0.86

The first factor (F1) includes heavy metals (Mn, Pb, and partly Cd), organic pollution indicators (BOD_5 and CODMn), and total phosphorus (TP), showing high loadings and communality values. This factor may reflect anthropogenic pressures, primarily associated with municipal wastewater inputs, without excluding contributions from other diffuse sources.

The second factor (F2) shows a strong association with river discharge (Q) and suspended solids (SS), together with negative loadings of some dissolved nutrients and physicochemical parameters (e.g., NH_4^+ and pH). This factor structure indicates a pronounced influence of hydrological conditions, mainly related to dilution effects and enhanced mixing during periods of higher discharge.

The third factor (F3) is mainly defined by dissolved oxygen (DO) and oxygen saturation (OS), which have the highest loadings on this factor. This factor reflects a stable oxygen regime and aeration processes that are more closely related to physical flow conditions and temperature than to short-term changes in other hydrochemical parameters.

The fourth factor (F4) groups orthophosphate (PO_4^{3-}), nitrite (NO_2^-), and total coliforms (TC), indicating a shared pattern of variability. This grouping suggests the influence of local and episodic pollution sources, such as municipal inflows and short-term inputs of nutrients and microbiological material. Although discharge also contributes to the factor structure, the absence of a statistically significant bivariate correlation between Q and these parameters indicates that their dynamics are not primarily controlled by the hydrological regime but by local processes and sources.

The fifth factor (F5) shows weaker loadings and includes some chemical parameters (e.g., NO_2^- and SO_4^{2-}). It can therefore be interpreted as a secondary factor reflecting local or short-term chemical processes, with a limited contribution to the overall variability of the system.

Taken together, the factor analysis shows that suspended solids and selected nutrient and organic parameters are clearly related to hydrological conditions and dilution effects, whereas the variability of orthophosphate and microbiological indicators is more strongly associated with local sources and episodic inputs.

4. Conclusions

This study presents an integrated assessment of water quality in the Jerma River based on long-term and seasonal Water Pollution Index (WPI) analysis and supporting physicochemical and microbiological data, providing new insights into water-quality dynamics in a transboundary mountain river system. The results show clear spatial and temporal variability, with generally better conditions at the upstream station Strazimirovci and more pronounced pressures at the downstream station Trnski Odorovci.

At Strazimirovci, most physicochemical parameters remained within or close to Class I limits during the analyzed period. Oxygen conditions were stable, suspended solids were low, and nutrient concentrations were generally moderate. However, total phosphorus and total coliforms occasionally exceeded reference values, indicating episodic nutrient and sanitary pressures even in the upper part of the catchment.

Downstream at Trnski Odorovci, water quality showed stronger variability and more frequent departures from Class I conditions. Elevated concentrations of nutrients, particularly nitrites, ammonium, orthophosphates, and total phosphorus, together with high total coliform values, indicate increased anthropogenic pressure. WPI values at this station ranged from Class II to Class IV, confirming episodic but significant deterioration of water quality.

Spring and summer are the most sensitive periods for water-quality degradation, with frequent increases in nutrient parameters and total coliforms. Winter generally shows lower WPI values and greater chemical stability, although this should be interpreted with caution due to the limited availability of microbiological data.

Statistical analysis shows that river discharge selectively influences water quality. Higher flows are associated with increased suspended solids, while some nutrient parameters, such as ammonium, show higher concentrations during low-flow conditions. Total

coliforms do not show a significant relationship with discharge, indicating a dominant influence of local and episodic pollution sources.

These findings demonstrate the importance of long-term and seasonal monitoring for understanding water-quality dynamics in small transboundary river systems. Improving wastewater management, reducing diffuse nutrient inputs, and ensuring year-round microbiological monitoring are key priorities for maintaining and improving the ecological status of the Jerma River.

Although this study examines the Jerma River, the results may also be applicable to other mountain rivers with comparable hydrological conditions. The analysis shows that index-based approaches can effectively combine multiple monitoring parameters and help identify seasonal and spatial patterns in water quality. The findings further highlight the importance of considering hydrological variability when interpreting nutrient and microbiological indicators in torrential river systems.

Author Contributions: Conceptualization, D.M.J., V.N. and A.M.P.; methodology, D.M.J.; validation, D.M.J. and I.N.; formal analysis, D.M.J.; investigation, I.N., J.B., V.N. and A.M.P.; resources, A.M.P.; data curation, D.M.J.; writing—original draft preparation, D.M.J.; writing—review and editing, A.M.P., J.B., I.N., and V.N.; visualization, A.M.P.; supervision, A.M.P.; project administration, V.N. and A.M.P.; funding acquisition, V.N. and A.M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out in the frame of the projects "Geomorphological interpretation of photogrammetry and laser scanning data in the study of torrential watersheds", 337-00-140/2023-05/10 and 451-03-33/2026-03/200172 (Ministry of Science, Technological Development and Innovation, Serbia), № КП-06-Дунав/5, 14.08.2023 (National Science Fund, Bulgaria), and MSMT 8X23015 (Czechia).

Data Availability Statement: Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors gratefully acknowledge Darko Sarvan for his valuable assistance and expertise in the statistical analyses that supported this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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