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Water Pollution Index (WPI) as an Indicator of Vertical and Spatial Water Quality Patterns in the Gruža Reservoir

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Abstract

This study analyzes the vertical structure of physicochemical parameters and the Water Pollution Index (WPI) in the Gruža Reservoir, located in central Serbia. Three profiles were sampled at depths from 50 to 950 cm. The upper and intermediate sampled layers generally showed smaller vertical differences than the deepest samples. Oxygen conditions differed among profiles, with the highest surface DO recorded in Profile B and lower values in Profiles A and C. NH_4–N concentrations were generally low in these layers, while PO_4–P concentrations in Profiles A and B ranged mainly from 0.013 to 0.022 mg P/L. Nitrate ranged from 0.3 to 0.7 mg N/L, while nitrite remained around 0.008 mg N/L. The original WPI values generally ranged from 1.02 to 1.45 and were assigned to Class III based on the unrounded values. Conditions in the deeper sampled layers differed among profiles. Profiles A and B showed higher nutrient concentrations in some of their deeper samples. NH_4–N reached 0.37 mg N/L, PO_4–P reached 0.064 mg P/L, and TP reached 0.11 mg P/L. Their original WPI values reached 2.00 in Profile A and 1.59 in Profile B, with all samples assigned to Class III based on the unrounded values. Profile C showed the most pronounced deterioration in its two deepest samples. At C/950, NH_4–N reached 2.98 mg N/L, PO_4–P reached 0.547 mg P/L, TP reached 0.778 mg P/L, and DO decreased to 0.50 mg/L. The original WPI values were 5.00 at C/800 and 11.07 at C/950, corresponding to Classes V and VI. The parameter-contribution analysis showed that NH_4–N, PO_4–P, and TP were the main drivers of the high original WPI values at C/800 and C/950. In all three sensitivity scenarios, C/950 remained the highest-ranked sample and C/800 remained the second-highest sample. The combination of severe oxygen depletion and elevated ammonium and phosphorus concentrations is consistent with oxygen-depleted conditions and possible nutrient enrichment near the sediment–water interface. However, the available measurements do not directly confirm the sources or mechanisms responsible for this pattern. The results show that deeper layers should be included in reservoir monitoring. Surface measurements alone may not reveal water-quality deterioration at greater depths. The findings represent a spatial and vertical snapshot from one monitoring campaign and should not be interpreted as seasonal or annual patterns in the reservoir.

Keywords: water quality; Water Pollution Index; vertical profiling; physicochemical parameters; Gruža Reservoir; Serbia

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1. Introduction

Water quality in lakes and reservoirs represents one of the key indicators of ecological stability and the sustainable use of water resources. These systems provide water supply, support aquatic organisms, and contribute to recreational and tourism activities. They are

therefore sensitive to various natural and anthropogenic influences. Changes in inflow, climatic conditions, agricultural activities, local pressures, and seasonal fluctuations can lead to the deterioration of water quality, which emphasizes the need for regular monitoring and timely management [1,2].

In Serbia, a large number of artificial lakes are used for water supply, tourism, fishing, and the preservation of natural values [3], and their broader socio-economic importance has recently been emphasized through studies on sustainable tourism valorization [4]. Their ecological stability directly affects local development, so assessing water quality is important for spatial planning and management. The management of reservoirs in Serbia also has an important spatial-planning dimension, since water quality and the sustainability of water supply are directly linked to land use and the protection of the surrounding area [5]. Although some reservoirs have been investigated in more detail, certain lakes remain insufficiently covered by systematic monitoring, especially regarding the vertical distribution of parameters and the processes occurring along the depth of the water column [6–8].

The Gruža Reservoir represents an important natural and functional resource within the local ecosystem. Its role in water supply, recreational activities, and tourism development makes it particularly sensitive to changes that may occur due to increased anthropogenic pressure or natural fluctuations. Vujadinović et al. [9] state that the catchment of the Gruža Reservoir is a protected drinking-water source of national importance and that the construction of the reservoir ensured water supply for the city of Kragujevac and numerous surrounding settlements. Previous studies have related the eutrophication of the Gruža Reservoir to its predominantly shallow morphology, surrounding agricultural land, wastewater inputs, and other anthropogenic pressures [9,10]. They also reported elevated phosphate concentrations, occasional oxygen depletion, and increased ammonium and nitrite concentrations, particularly under summer conditions [9]. However, depth-resolved comparisons of integrated water-quality conditions among different reservoir profiles remain limited.

Water quality indices are widely applied in studies of lakes, reservoirs, and rivers because they enable a simple and comparable assessment of water-quality conditions. For this purpose, methodologies that combine multiple physicochemical parameters into a single value are used [11–15]. The Water Pollution Index (WPI) is a simple and practical tool for assessing the overall water load relative to reference values. Applying WPI across depths provides an overview of the vertical structure of water quality and allows the identification of layers with different WPI values, which cannot be observed when only the surface part of the water column is analysed.

Building on previous investigations of water quality and eutrophication in the Gruža Reservoir, the present study compares physicochemical conditions and WPI values at discrete depths across three sampling profiles. Its specific contribution is the depth-resolved application of WPI, supplemented by parameter-contribution and sensitivity analyses to examine the interpretation and robustness of the integrated assessment.

This study aims to assess vertical and spatial differences in the physicochemical water quality of the Gruža Reservoir. WPI was calculated at different depths across three sampling profiles. The study also examines which parameters contributed most to the original WPI values. Contribution and sensitivity analyses were used to examine the effects of different treatments of DO, OS, and pH. The results describe the conditions recorded during the September 2024 monitoring campaign and show the importance of including deeper layers in reservoir monitoring.

2. Materials and Methods

2.1. Study Area

The study area is located in the central part of Serbia and encompasses the Gruža Reservoir, an artificial lake formed in 1984 by damming the Gruža River, a right tributary of the Zapadna Morava. The Gruža River is 62 km long and drains a catchment area of 622 km^2, predominantly covered by arable land, meadows, pastures, and patches of sparse forest vegetation. The dam is positioned approximately 32 km upstream from the river's confluence with the Zapadna Morava. The average discharge of the Gruža River at its mouth is 1.96 m^3/s [16].

Gruža Reservoir spans roughly 900 ha and stores about 64.6 × 10^6 m^3 of water. The mean depth is approximately 6.5 m, while the deepest sections exceed 30 m. Nearly 80% of the reservoir's total volume lies within the upper 10 m of the water column, reflecting the predominantly shallow morphology of the reservoir. During summer, surface waters warm up to 26 °C, supporting recreational activities and well-developed sport fishing [3].

Reservoir conditions are shaped by catchment morphology, land-use structure, and climate. The prevalence of agricultural land increases nutrient inflow and promotes seasonal eutrophication, emphasizing the necessity of regular water-quality monitoring for sustainable management. Given its role in regional water supply, continuous monitoring of water quality in the Gruža Reservoir is essential for ensuring safe and sustainable use.

Long-term monitoring data were not available for the present analysis, which highlights the need for systematic water-quality monitoring, particularly given the importance of the Gruža Reservoir for regional water supply and recreational use.

2.2. Data Sources and Analytical Methods

Water-quality sampling was carried out by the Serbian Environmental Protection Agency at multiple monitoring locations in the Gruža Reservoir. For this study, three individual sampling stations, referred to as Profiles A, B, and C, were selected for detailed vertical analysis. The sampling profiles were georeferenced using the Gauss–Krüger coordinate system:

Profile A: 4860621 N, 7477215 E.
Profile B: 4861969 N, 7476836 E.
Profile C: 4863457 N, 7475211 E.

The sampling profiles were located in the southern and central parts of the reservoir. Profile A was located in the southern part and was the closest of the three analysed profiles to the dam. Profile B was located farther north, in the central–southern part of the reservoir. Profile C was located in the central part of the reservoir. The three profiles therefore represent different positions along the reservoir. However, they do not provide complete spatial coverage and are not considered representative of all reservoir zones. Their locations are shown in Figure 1.

Vertical sampling included eight discrete depths at each profile. Profiles A and B were sampled at 50, 200, 300, 400, 500, 600, 850, and 950 cm, whereas Profile C was sampled at 50, 200, 300, 400, 500, 600, 800, and 950 cm.

The available monitoring documentation does not report the local water depth at each profile or the distance between the deepest sample and the sediment surface. Therefore, the analysed samples are not described as near-bottom samples or as samples from the deepest zones of the reservoir. The terms upper, intermediate, and deeper sampled layers are used throughout the manuscript.

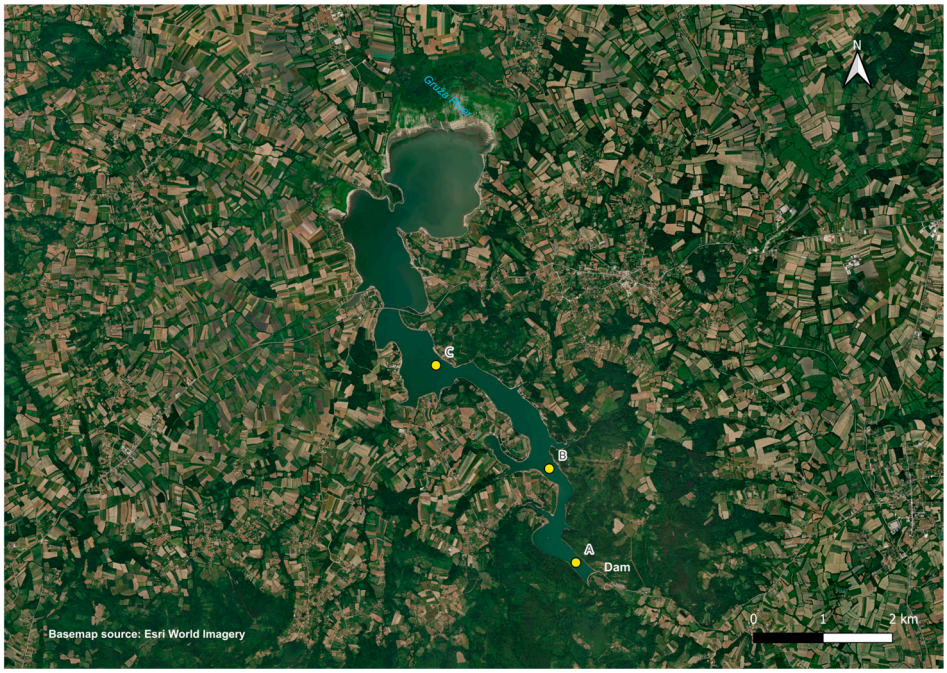


Figure 1. Location of the Gruža Reservoir and the three analysed sampling profiles (A–C), including the main inflow and the dam. Basemap source: Esri World Imagery.

All samples were collected during the official monitoring campaign conducted by the Serbian Environmental Protection Agency [17] from 23 to 25 September 2024. The three profiles were sampled on consecutive days. Therefore, the observed differences among profiles cannot be interpreted as exclusively spatial. Short-term variation during the three-day sampling period may also have contributed. The analysis was limited to these three profiles because they provided measurements at multiple depths, allowing a consistent comparison of vertical water-quality patterns among the sampled locations. The assessment therefore represents a spatial and vertical snapshot of conditions during this monitoring campaign rather than a comprehensive characterisation of seasonal or annual reservoir dynamics.

The analysed parameters include fundamental water-quality indicators relevant for limnological studies: dissolved oxygen (DO), oxygen saturation (OS), pH, electrical conductivity (EC), total organic carbon (TOC), ammonium nitrogen (NH_4–N), nitrate nitrogen (NO_3–N), nitrite nitrogen (NO_2–N), orthophosphate phosphorus (PO_4–P), and total phosphorus (TP). All data were obtained from the official monitoring program conducted by the Serbian Environmental Protection Agency [17].

The selected parameters represent key indicators of the chemical and biogeochemical functioning of lake ecosystems. The oxygen regime, assessed through DO and OS, provides information on differences in oxygen conditions along the sampled water column. The pH and EC parameters provide insight into general hydrochemical conditions and changes in water mineralization. TOC reflects the level of organic loading, while different forms of nitrogen and phosphorus (NH_4–N, NO_3–N, NO_2–N, PO_4–P, TP) indicate the intensity of biological processes, nutrient inputs, and the potential for eutrophication. Together, these parameters provide a basis for describing the physicochemical water-quality conditions recorded during the monitoring campaign.

The analytical methods were reported according to the official SEPA monitoring documentation. Where more than one method is listed for an analyte, the documentation does not identify which method was applied to each individual sample from the Gruža Reservoir.

The methods reported in the monitoring documentation were: Dissolved oxygen (DO)—SRPS ISO 5813:1994 [18]; Oxygen saturation (OS)—SRPS H.Z1.160:1987; pH—SRPS H.Z1.111:1987; Electrical conductivity (EC)—EPA Method 120.1:1982; Ammonium (NH_4–N)—HACH Method 8155; Nitrate (NO_3–N)—SEV:1973; Nitrite (NO_2–N)—HACH Method 8507/EPA 353.2; Orthophosphate phosphorus (PO_4–P)—HACH Method 8048/EPA 365.1; Total phosphorus (TP)—APHA AWWA WEF 4500 (A, B, E); Total organic carbon (TOC)—SRPS ISO 8245:2007 [19], determination using NDIR detection [17].

2.3. Water Pollution Index (WPI)

The Water Pollution Index (WPI) was applied as an integrated indicator of the deviation between the measured physicochemical values and the selected Class I reference values. The original WPI was calculated as the arithmetic mean of the ratios between the measured value of each parameter and its corresponding reference value:

$$WPI_{\text{original}} = \frac{1}{n}\sum_{i=1}^{n}\frac{C_i}{S_i}$$

where C_i is the measured value of parameter i, S_i is the corresponding Class I reference value, and n is the number of parameters included in the calculation.

The symbol S_i denotes the reference value selected for parameter i. In earlier regional applications of the WPI, the same reference value was designated as SFQS, referring to the standard value for Class I surface-water quality. The difference between S_i and SFQS is terminological and does not represent a different calculation procedure. The original WPI formulation was retained to facilitate comparison with previous regional applications. However, because the methodology permits the inclusion of different parameter sets, comparisons among studies should consider differences in parameter selection, reference values, and water-body characteristics.

The WPI methodology does not prescribe a fixed number or universal set of parameters. The parameter set may be selected according to the objectives of the assessment, the characteristics of the investigated water body, data availability, and the applicability of the selected reference values. In the present study, the original WPI calculation included ten available physicochemical parameters: dissolved oxygen (DO), oxygen saturation (OS), pH, electrical conductivity (EC), total organic carbon (TOC), ammonium nitrogen (NH_4–N), nitrate nitrogen (NO_3–N), nitrite nitrogen (NO_2–N), orthophosphate phosphorus (PO_4–P), and total phosphorus (TP). All included parameters received equal weight in the arithmetic mean.

The reference values were obtained from Annex 1 of the Serbian Regulation on Limit Values of Pollutants in Surface Waters, Groundwaters and Sediment and Deadlines for Their Achievement [20]. The values for pH, DO, TOC, NH_4–N, NO_3–N, PO_4–P, and TP were selected from Annex 1, Table 2 of the regulation [20], which defines the limit values for excellent ecological status corresponding to Class I surface waters. The selected regulatory category includes lakes situated above 200 m a.s.l. that are classified as medium-depth lakes (10–30 m) or deep lakes (>30 m). Gruža Reservoir is situated above 200 m a.s.l. and has a maximum depth exceeding 30 m. The Class I reference values for this category were therefore selected based on the elevation and maximum depth of the reservoir and were applied in the original WPI calculation. The reference values for OS, NO_2–N, and EC were obtained from Annex 1, Table 1 of the same regulation. All reference values are presented in Table 1 of this manuscript. For pH, the upper limit of 8.5 was used in the WPI calculation.

Table 1. Class I reference values used in the original WPI calculation [20].

Parameter	Unit	Si (Class I Reference Value)	Source
Dissolved Oxygen (DO)	mg/L	8.52	Annex 1, Table 2
Oxygen Saturation (OS)	%	90	Annex 1, Table 1
pH	–	6.5–8.5	Annex 1, Table 2
Total Organic Carbon (TOC)	mg/L	2	Annex 1, Table 2
Ammonium nitrogen (NH_4–N)	mg N/L	0.05	Annex 1, Table 2
Nitrate nitrogen (NO_3–N)	mg N/L	1.5	Annex 1, Table 2
Nitrite nitrogen (NO_2–N)	mg N/L	0.01	Annex 1, Table 1
Orthophosphate phosphorus (PO_4–P)	mg P/L	0.02	Annex 1, Tables 1 and 2
Total phosphorus (TP)	mg P/L	0.05	Annex 1, Table 2
Electrical conductivity (EC)	µS/cm	1000	Annex 1, Table 1

For OS, the original calculation used 90% as the reference value. The regulation provides different Class I oxygen-saturation ranges depending on the position within the water column and the presence of stratification. Because temperature profiles were not included in the present analysis, the samples could not be independently assigned to epilimnetic, hypolimnetic, or unstratified regulatory categories. Therefore, the single OS reference value was retained in the original WPI calculation. This methodological limitation was examined through the sensitivity analysis.

Orthophosphate was reported in the SEPA monitoring dataset as orthophosphate phosphorus (PO_4–P, mg P/L). Annex 1, Table 1 of the regulation also expresses orthophosphate in mg P/L and refers, through footnote 8, to Table 2 for the corresponding Class I limit. Therefore, the measured concentrations and the reference value of 0.02 mg P/L were expressed on the same phosphorus basis, and no conversion was required.

Table 2. Water quality classes derived from the Water Pollution Index.

Class	Water Quality Class Description	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: The dash indicates the range between the stated class boundaries. Exact boundary values were assigned to the higher-quality class. Water-quality classes were determined using unrounded WPI values.

The categorization of water quality based on WPI values follows a commonly used approach, previously applied in regional studies [21–23], and is presented in Table 2.

The Class I reference values applied to individual parameters, the descriptive classes derived from WPI, and a formal assessment of ecological status represent different assessment concepts. Therefore, the WPI classes reported in this study should not be interpreted as an independent formal classification of the ecological status of Gruža Reservoir.

2.4. Methodological Limitations of the Original WPI Formulation

An important limitation of the original WPI is the direct Ci/Si normalisation. This approach assumes that higher measured values always indicate greater water-quality deterioration. This is appropriate for parameters with upper reference limits, such as nutrients, TOC, and EC. However, it is not appropriate for DO and OS under oxygen-depleted conditions. For these parameters, lower values indicate greater deterioration.

For example, the deepest sample at Profile C had a DO concentration of 0.50 mg/L and an oxygen saturation of 2%. However, direct Ci/Si normalisation produced ratios of only 0.059 and 0.022, respectively. As a result, severe oxygen depletion decreased the original WPI instead of increasing it.

The original calculation also used the upper pH limit of 8.5 as the reference value. However, pH is evaluated within an acceptable range of 6.5–8.5 rather than against a single upper limit. Therefore, this calculation does not account for values below the lower limit. It also produces different ratios for pH values that may all be within the acceptable range.

DO and OS represent closely related aspects of the oxygen regime. Their simultaneous inclusion in an equally weighted arithmetic mean may overrepresent oxygen-related information. PO_4–P and TP are also related indicators. However, they represent different phosphorus fractions and were therefore retained in the original calculation.

The original WPI was retained to allow comparison with previous regional studies. However, the results were supplemented by parameter-contribution and sensitivity analyses. These analyses were used to test whether the main sample ranking and the observed vertical pattern depended on the treatment of DO, OS, and pH.

2.5. Parameter-Contribution Analysis

The relative contribution of each parameter to the original WPI was calculated as:

$$Contribution_{\mathrm{i}}(\%) = \frac{R_{\mathrm{i}}}{\sum_{\mathrm{j}=1}^{\mathrm{n}} R_{\mathrm{j}}} \times 100$$

where $R_i = C_i/S_i$ is the original normalised ratio of parameter i, j is the summation index representing all included parameters, and n is the total number of parameters included in the original WPI calculation.

The contribution analysis was used to identify the parameters that primarily determined the WPI value at each profile and depth. Because the original WPI represents the arithmetic mean of the included ratios, the proportional contribution of each parameter can be expressed as its individual ratio divided by the sum of all included ratios.

2.6. Sensitivity Analysis

Three alternative calculations were performed to evaluate the stability of the sample ranking and the observed vertical pattern. These calculations were treated as sensitivity scenarios rather than as validated replacements for the original WPI formulation.

Scenario 1: Direction-Corrected DO and OS

In the first scenario, the direction of normalisation was reversed for DO and OS so that lower oxygen values produced higher ratios:

$$R_{\mathrm{DO}} = \frac{S_{\mathrm{DO}}}{C_{\mathrm{DO}}}$$

$$R_{\mathrm{OS}} = \frac{S_{\mathrm{OS}}}{C_{\mathrm{OS}}}$$

For parameters evaluated against upper reference values, the original relationship was retained:

$$R_{\mathrm{i}} = \frac{C_{\mathrm{i}}}{S_{\mathrm{i}}}$$

For pH, a range-based sensitivity factor was used:

$$R_{\mathrm{pH}} = \begin{cases} 1, & 6.5 \le \mathrm{pH} \le 8.5 \\ \frac{pH}{8.5}, & \mathrm{pH} > 8.5 \\ \frac{6.5}{pH}, & \mathrm{pH} < 6.5 \end{cases}$$

This procedure assigned a neutral factor of 1 to measurements within the acceptable pH interval and a value greater than 1 to measurements outside the interval.

The first sensitivity scenario included all ten parameters:

$$WPI_{S1} = \frac{R_{DO} + R_{OS} + R_{pH} + R_{EC} + R_{TOC} + R_{NH4-N} + R_{NO3-N} + R_{NO2-N} + R_{PO4-P} + R_{TP}}{10}$$

Scenario 2: One Oxygen-Related Parameter

The second scenario retained the direction-corrected DO ratio but excluded OS to reduce the potential duplication of oxygen-related information:

$$WPI_{S2} = \frac{R_{DO} + R_{pH} + R_{EC} + R_{TOC} + R_{NH4-N} + R_{NO3-N} + R_{NO2-N} + R_{PO4-P} + R_{TP}}{9}$$

Scenario 3: Reduced Parameter Set

The third scenario excluded DO, OS, and pH from the composite calculation. These parameters remained part of the overall water-quality assessment but were not included in the reduced sensitivity index:

$$WPI_{S3} = \frac{R_{EC} + R_{TOC} + R_{NH4-N} + R_{NO3-N} + R_{NO2-N} + R_{PO4-P} + R_{TP}}{7}$$

The six descriptive classes presented in Table 2 were applied only to the original WPI formulation. They were not assigned to the three sensitivity scenarios because changing the direction of normalisation or the number of included parameters may alter the scale and distribution of the index values. The sensitivity results were therefore interpreted as continuous comparative values used to evaluate the stability of the sample ranking and the observed vertical pattern.

3. Results and Discussion

3.1. Vertical and Spatial Patterns of Physicochemical Parameters

Measured dissolved oxygen concentrations in September 2024 showed a pronounced vertical gradient across all three lake profiles, with values ranging from 9.32 mg/L in the surface layer of Profile B to only 0.50 mg/L at 950 cm in Profile C. Oxygen conditions in the upper sampled layers differed among the three profiles. Profile B had the highest values, with DO concentrations above 9 mg/L, whereas lower values were recorded in Profiles A and C. The higher values in Profile B may reflect atmospheric exchange and photosynthetic oxygen production in the upper sampled layer. In contrast, the deeper sampled layers of all three profiles exhibited substantial oxygen depletion. This vertical pattern may reflect several processes, including limited oxygen renewal, water-column organic matter decomposition, and increased oxygen demand near the sediment–water interface. However, the absence of contemporaneous temperature profiles prevents direct confirmation of thermal stratification. Profile A showed relatively small differences in DO concentrations down to 500 cm (4.41–4.65 mg/L), followed by a sharp decline below 600 cm, where the concentration decreased to 1.29 mg/L at 950 cm. Profile B displayed the steepest vertical decrease, transitioning from well-oxygenated surface waters to hypoxic conditions (<2 mg/L) already at 600 cm. Profile C maintained moderate oxygenation in the upper 300–400 cm (7.13–5.64 mg/L), but its deepest layers were the most depleted, with concentrations falling below 1 mg/L.

Ratio values relative to the selected Class I reference value further emphasised these gradients. In the upper and intermediate sampled layers, the original DO ratios ranged from 0.52 to 0.92 in Profiles A and C. In Profile B, the ratios were above 1.0 in the upper 200 cm, reflecting measured DO concentrations above the selected Class I reference value.

At depths greater than 600 cm, the original DO ratios ranged from 0.06 to 0.33. These low ratios reflected the low measured DO concentrations in the deeper sampled layers. However, direct C_i/S_i normalisation does not maintain a consistent direction of impairment for DO because lower oxygen concentrations produce lower ratios.

Organic matter decomposition and oxygen-consuming processes near the sediment–water interface may have contributed to this pattern [24]. However, the available data do not allow the effects of these processes to be determined separately.

The parameter-specific normalised ratios (C_i/S_i) for all profiles and sampling depths are presented in Table 3, whereas the corresponding measured physicochemical values are provided in Supplementary Table S1.

Table 3. Original normalised ratios (C_i/S_i) of measured physicochemical parameter values to the selected Class I reference values.

Profile/Depth	DO	OS	pH	EC	TOC	NH_4–N	NO_3–N	NO_2–N	PO_4–P	TP
A/50	0.52	0.56	0.93	0.32	4.35	1.20	0.27	0.80	0.65	0.66
A/200	0.55	0.57	0.93	0.32	4.70	1.60	0.33	0.80	0.80	0.82
A/300	0.52	0.54	0.94	0.32	4.45	2.00	0.33	0.80	0.65	0.76
A/400	0.52	0.54	0.93	0.31	6.10	2.20	0.47	0.80	0.65	0.84
A/500	0.52	0.54	0.93	0.32	4.70	2.40	0.27	0.80	0.95	0.78
A/600	0.30	0.32	0.91	0.32	4.60	3.40	0.27	0.80	1.45	0.74
A/850	0.18	0.19	0.90	0.32	4.70	6.60	0.27	0.80	2.40	1.26
A/950	0.15	0.14	0.90	0.36	4.55	7.40	0.27	0.80	3.20	2.20
B/50	1.09	1.16	1.01	0.31	5.50	1.20	0.27	0.80	0.95	0.94
B/200	1.06	1.12	1.00	0.32	5.00	1.20	0.27	0.80	0.80	0.94
B/300	0.96	1.01	0.98	0.32	4.75	1.80	0.27	0.80	0.95	1.04
B/400	0.91	0.96	0.98	0.31	4.45	2.00	0.27	0.80	0.80	0.86
B/500	0.48	0.50	0.93	0.31	4.50	1.80	0.33	0.80	1.10	0.90
B/600	0.18	0.19	0.90	0.31	4.65	1.60	0.27	1.00	0.95	1.00
B/850	0.17	0.17	0.89	0.31	4.60	2.20	0.33	1.00	0.95	0.70
B/950	0.16	0.16	0.89	0.33	4.20	4.60	0.27	0.80	2.70	1.80
C/50	0.92	0.96	0.96	0.31	4.15	1.20	0.27	0.80	3.50	1.40
C/200	0.87	0.90	0.96	0.31	4.30	1.20	0.20	0.80	1.75	1.04
C/300	0.84	0.88	0.96	0.32	4.30	1.40	0.20	0.80	1.90	0.92
C/400	0.66	0.69	0.94	0.31	4.05	1.60	0.20	0.90	1.60	1.00
C/500	0.56	0.58	0.94	0.31	4.35	2.00	0.20	0.80	1.30	1.00
C/600	0.33	0.34	0.91	0.31	4.40	4.00	0.20	0.80	2.10	1.00
C/800	0.11	0.11	0.88	0.31	5.35	27.40	0.20	0.80	9.75	5.04
C/950	0.06	0.02	0.85	0.40	5.90	59.60	0.20	0.80	27.35	15.56

Across all profiles, oxygen saturation declined markedly with depth, ranging from 104% in the upper sampled layer of Profile B to just 2% at 950 cm in Profile C. The upper water column was generally well oxygenated, particularly in Profile B, where saturation exceeded 100%. These values may reflect atmospheric exchange and photosynthetic oxygen production in the upper sampled layer. Profiles A and C exhibited oxygen saturation values of 49–86% between 50 and 500 cm, followed by a marked decline at greater sampled depths. Below approximately 500–600 cm, all profiles showed a marked decrease in saturation. This decline indicates progressively stronger oxygen depletion in the deeper sampled layers. Such a pattern may occur under conditions of restricted oxygen renewal and increased oxygen consumption, although thermal stratification cannot be directly confirmed without corresponding temperature profiles. The deepest layers were strongly depleted, with saturation falling to 13% in Profile A, 14% in Profile B, and only 2% in Profile C. These values indicate pronounced oxygen depletion at greater sampled depths and may reflect restricted oxygen renewal and increased oxygen consumption. Similar deep-water patterns

have been reported in previous studies of the Gruža Reservoir, where reducing conditions and the release of phosphorus and ammonium from sediments were identified as key drivers of eutrophication [9,10].

Ratio values relative to Class I thresholds followed the same vertical pattern. In Profile B, surface ratios exceeded 1.0, confirming oxygen conditions above Class I requirements. Profiles A and C remained below the Class I benchmark in the upper layers (0.54–0.96), but still within a range typical for moderately oxygenated waters. At depths greater than 600 cm, all profiles showed ratios between 0.02 and 0.34. These values indicate severe oxygen depletion in the deeper sampled layers, particularly at Profile C. The observed vertical pattern is consistent with restricted oxygen renewal at greater depths. However, the thermal structure of the water column could not be directly evaluated because temperature profiles were not included in the present analysis.

Measured pH values ranged from 7.23 at C/950 to 8.55 at B/50. Values generally decreased with depth, with the most pronounced change observed in Profile C, from 8.20 at 50 cm to 7.23 at 950 cm. Most measurements were within the selected Class I interval of 6.5–8.5, while the surface value at B/50 slightly exceeded the upper boundary. Because pH is evaluated against an acceptable interval rather than a single upper reference value, the original C_i/S_i ratios were interpreted with caution and were further examined through the sensitivity analysis.

Electrical conductivity showed limited variation across most profiles and depths, with values generally ranging from 308 to 326 µS/cm. Higher values were recorded in some of the deepest samples, particularly at C/950, where EC increased to 396 µS/cm. The corresponding original normalised ratios remained below the selected Class I reference value at all sampled depths.

TOC concentrations varied from 8.1 to 12.2 mg/L across all profiles and depths, without a consistent increase towards the deepest samples. The highest value was recorded at A/400 (12.2 mg/L), while C/950 also had a relatively high concentration of 11.8 mg/L. In the surface samples, TOC concentrations were 8.7 mg/L in Profile A, 11.0 mg/L in Profile B, and 8.3 mg/L in Profile C. Profiles A and B showed variable values across depth, whereas Profile C increased from 8.8 mg/L at 600 cm to 10.7 mg/L at 800 cm and 11.8 mg/L at 950 cm. These results indicate profile-specific vertical patterns rather than a general increase in TOC towards the bottom. The original normalised TOC ratios ranged from 4.05 to 6.10 and exceeded 1.0 at all sampled depths, indicating that all measured concentrations were above the selected Class I reference value.

NH_4–N concentrations generally increased with depth, although the magnitude of this increase differed among profiles. In the upper and intermediate sampled layers, concentrations ranged mainly from 0.06 to 0.17 mg/L in Profile A, from 0.06 to 0.10 mg/L in Profile B, and from 0.06 to 0.20 mg/L in Profile C. Higher concentrations were recorded in some of the deeper samples, reaching 0.37 mg/L at A/950, 0.23 mg/L at B/950, 1.37 mg/L at C/800, and 2.98 mg/L at C/950. The corresponding original normalised ratios reached 7.40 in Profile A, 4.60 in Profile B, and 59.60 in Profile C. The pronounced NH_4–N accumulation in the two deepest samples of Profile C coincided with severe oxygen depletion and elevated PO_4–P and TP. A depth-related increase in ammonium, with the highest concentrations in bottom waters, was also reported for the Longyangxia Reservoir [25]. This pattern is consistent with changes in nitrogen transformation processes and possible ammonium enrichment under oxygen-depleted conditions, although the available measurements do not directly confirm the responsible mechanisms or the contribution of the sediment.

Nitrate and nitrite concentrations were very low and showed minimal variation across all profiles and depths. NO_3–N ranged narrowly between 0.3 and 0.7 mg/L, with slightly higher mid-depth values in Profiles A and B. Conversely, Profile C showed the smallest

differences among the sampled depths, with NO_3–N concentrations consistently around 0.3 mg N/L. Nitrite concentrations were even more uniform (mostly 0.008 mg N/L). Only minor increases to 0.009–0.01 mg N/L were observed in deeper samples from Profiles B and C.

The ratios relative to the selected Class I reference values ranged from 0.20 to 0.47 for NO_3–N and from 0.80 to 1.00 for NO_2–N. Although nitrate and nitrite concentrations showed relatively small vertical differences, these patterns alone do not demonstrate favourable oxidative conditions, steady nitrification, or the absence of external nitrogen inputs. Low nitrate and nitrite concentrations may reflect different combinations of biological uptake, transformation, and transport, which cannot be distinguished using the available measurements. Moreover, the pronounced ammonium accumulation and oxygen depletion in the deeper samples of Profile C indicate that nitrogen-related conditions were not uniform throughout the sampled water column.

PO_4–P concentrations showed clear differences among profiles and depths. Profiles A and B had relatively low concentrations in the upper and intermediate sampled layers, generally ranging from 0.013 to 0.022 mg P/L. Profile C had a higher surface concentration of 0.070 mg P/L, followed by 0.035–0.042 mg P/L between 200 and 600 cm. Concentrations increased in some of the deeper samples, reaching 0.064 mg P/L at A/950, 0.054 mg P/L at B/950, 0.195 mg P/L at C/800, and 0.547 mg P/L at C/950. The corresponding original normalised ratios reached 3.20 in Profile A, 2.70 in Profile B, and 27.35 in Profile C. The pronounced increase in the two deepest samples of Profile C occurred together with severe oxygen depletion and elevated NH_4–N and TP. This pattern is consistent with possible phosphorus enrichment near the sediment–water interface under oxygen-depleted conditions, although the available measurements do not directly confirm its source or mechanism [26].

TP concentrations varied across profiles and sampling depths. In the upper and intermediate sampled layers, most values were between 0.033 and 0.052 mg P/L. The surface sample at C/50 was an exception, with a concentration of 0.070 mg P/L. Higher concentrations were recorded in some of the deeper samples, particularly at Profile C. TP reached 0.110 mg P/L at A/950 and 0.090 mg P/L at B/950, compared with 0.252 mg P/L at C/800 and 0.778 mg P/L at C/950. The highest original normalised ratios were 2.20 in Profile A, 1.80 in Profile B, and 15.56 in Profile C. At the two deepest sampling depths of Profile C, the increase in TP coincided with severe oxygen depletion and elevated NH_4–N and PO_4–P. These conditions may indicate nutrient enrichment near the sediment–water interface. However, the available data do not allow the relative influence of internal processes and external nutrient inputs to be determined. Previous studies of the Gruža Reservoir also reported reducing conditions and sediment-related release of phosphorus and ammonium as factors contributing to eutrophication [10].

Oxygen conditions differed among the three profiles, including in the upper sampled layers. Profile B had the highest surface DO, whereas lower values were recorded in Profiles A and C. All profiles showed oxygen depletion at greater depths, accompanied by increases in NH_4–N, PO_4–P, and TP in some of the deeper samples. The magnitude of these changes differed among the profiles. Profiles A and B showed moderate increases in these nutrients, whereas Profile C showed a substantially stronger and simultaneous increase at C/800 and C/950. The observed patterns are consistent with restricted oxygen renewal and enhanced organic matter decomposition, but the available data do not allow these processes to be confirmed directly. External nutrient inputs, local hydrodynamic conditions, proximity to the sediment, and processes occurring near the sediment–water interface may also have contributed. Although temperature measurements were available in the original monitoring documentation, temperature profiles were not included in the present analysis. Therefore, thermal stratification could not be directly evaluated. In addition,

the absence of redox-potential and sediment-flux measurements prevents direct confirmation of sediment-derived nutrient release.

Previous studies have identified agricultural land and wastewater from nearby settlements as potential sources of phosphorus and nitrogen inputs to the Gruža Reservoir [10]. These sources may contribute to the overall nutrient load and eutrophication of the reservoir. However, the available data do not allow their contribution to the elevated nutrient concentrations in individual deeper samples to be determined.

Vujadinović et al. [9] state that various pollution sources exist in the Gruža catchment. The main point sources include wastewater from settlements around the lake and certain industrial facilities. Diffuse sources include septic tanks, unmanaged waste disposal sites, runoff from agricultural land, soil erosion and the impact of livestock. These factors may contribute to eutrophication and increased organic matter input. However, their effects cannot be separated from possible internal processes near the sediment–water interface using the available data.

Similar depth-related deterioration has also been reported in other Serbian reservoirs. In the Garaši Reservoir, marked decreases in dissolved oxygen and increases in ammonium were recorded in deeper waters during some monitoring periods, while the Ribnica Reservoir study also demonstrated variation in water-quality parameters and index results among sampling depths [7,8]. A depth-related increase in ammonium, with the highest concentrations in bottom waters, was also reported for the Longyangxia Reservoir [25]. Water-quality index applications in other countries have shown considerable differences among reservoirs. Dam-water samples examined in Greece were classified as excellent using the CCME WQI, whereas a modified WQI indicated medium water quality in one lowland reservoir and poor water quality in three reservoirs in Poland [27,28]. These findings support the use of integrated indices for identifying differences among reservoirs. However, direct numerical comparison with the original WPI values obtained for the Gruža Reservoir is limited because the studies used different indices, parameter sets, reference values, sampling designs, and classification scales.

3.2. WPI Results

The original WPI shows clear vertical and between-profile differences, which generally correspond to the patterns identified for the other physicochemical parameters (Figure 2). In Profiles A and B, the values show only small differences in the upper sampled layers. They remain relatively uniform through much of the sampled water column, with higher values recorded at the greatest sampled depths. In Profile A, the original WPI increased to 1.762 at 850 cm and 1.997 at 950 cm. Based on the unrounded values, all samples from Profile A were assigned to Class III. Profile B shows relatively small differences from 50 to 300 cm, with original WPI values of 1.25–1.32. The values decrease to 1.10–1.23 between 400 and 850 cm and increase to 1.59 at 950 cm. All samples from Profile B belong to Class III. This pattern coincides with moderate increases in NH_4–N, PO_4–P, and TP and with lower dissolved oxygen in the deeper sampled layers.

Profile C shows a different vertical pattern. Up to 600 cm, the values range from 1.2 to 1.4 (Class III), which is broadly comparable to the other profiles. However, at 800 cm the original WPI sharply increases to 5.00 (Class V), and at 950 cm to 11.07 (class VI). These values deviate several-fold from all other measurements.

The sharp increase in WPI at C/800 and C/950 coincided with severe oxygen depletion and the highest concentrations of NH_4–N, PO_4–P, and TP. At the same time, electrical conductivity increases to 396 µS/cm, and TOC reaches 11.8 mg/L. This combination of parameters is consistent with oxygen-depleted conditions, enhanced mineralisation of organic matter, and possible nutrient enrichment near the sediment–water interface. These

conditions may have contributed to the high original WPI values. Previous studies of the Gruža Reservoir reported oxygen depletion and nutrient enrichment in deeper waters, including possible sediment-related nutrient release under reducing conditions [9].

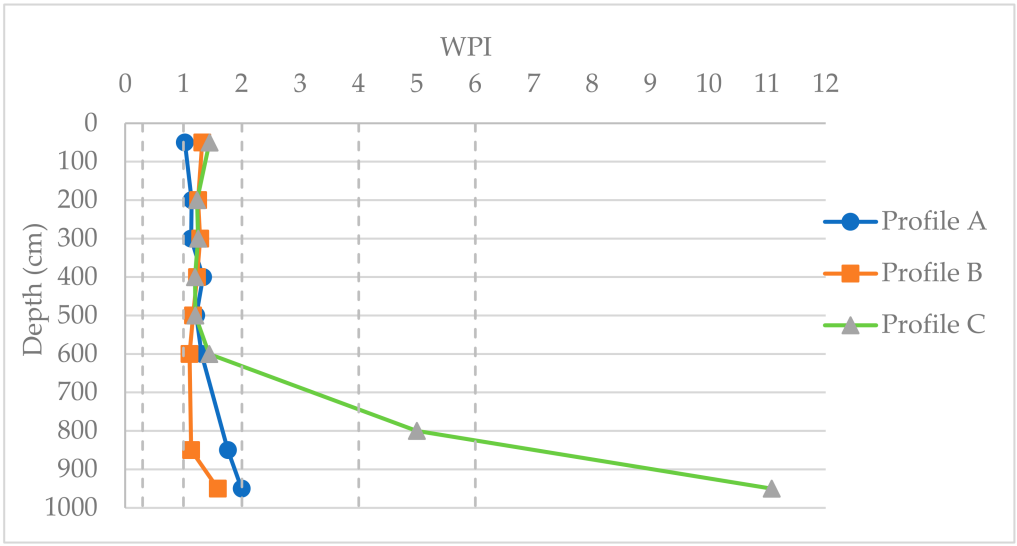


Figure 2. Vertical distribution of the Water Pollution Index (WPI) at the three sampling profiles in the Gruža Reservoir. Vertical dashed lines indicate the boundaries between WPI classes I–VI at 0.3, 1, 2, 4, and 6.

Several factors may have contributed to the difference between the deepest samples of Profile C and those of Profiles A and B. These include local morphometric and hydrodynamic conditions, external nutrient inputs, organic matter decomposition, proximity to the sediment, and processes occurring near the sediment–water interface. However, local bathymetric data, sediment characteristics, sediment–water fluxes, and hydrodynamic measurements were not included in the present analysis. These factors are therefore considered only as possible explanations. Their individual effects cannot be determined from the available data.

In summary, the original WPI values corresponded to Class III at all sampled depths of Profiles A and B and between 50 and 600 cm in Profile C. The two deepest samples of Profile C had substantially higher values, corresponding to Classes V and VI. This pattern indicates that the most pronounced water-quality deterioration occurred at C/800 and C/950.

The present analysis is based solely on the monitoring campaign conducted from 23 to 25 September 2024. Therefore, the results represent a spatial and vertical snapshot of conditions at the three sampled profiles rather than a seasonal or annual assessment of the reservoir. Biological indicators were not included, so the results are limited to the analysed physicochemical parameters and the original WPI assessment. Although temperature measurements were available in the original monitoring documentation, temperature profiles were not included in the present analysis; therefore, the thermal structure of the water column and the presence of stratification could not be directly evaluated. Accordingly, the terms upper, intermediate, and deeper sampled layers were used instead of epilimnion and hypolimnion. In addition, the available data do not allow external nutrient inputs to be distinguished from possible internal nutrient enrichment near the sediment–water interface. Sediment characteristics, redox potential, porewater concentrations, and sediment–water nutrient fluxes were not measured. Consequently, the sources and mechanisms responsible for the elevated ammonium and phosphorus concentrations in the deeper samples of Profile C could not be directly determined.

3.3. Parameter Contributions and Sensitivity Analysis

The parameter-contribution analysis showed that the ten parameters did not contribute equally to the original WPI. TOC was the main contributor in most upper and intermediate samples. Its relative contribution decreased in several deeper samples, where NH_4–N and phosphorus compounds became more important. NH_4–N was the main contributor in the deepest samples of Profiles A and B.

The strongest nutrient contribution was found in the two deepest samples of Profile C. At C/800, NH_4–N contributed 54.8% to the sum of the original normalised ratios. PO_4–P and TP contributed 19.5% and 10.1%, respectively. Together, these three parameters accounted for 84.5% of the total. At C/950, NH_4–N contributed 53.8%, while PO_4–P and TP contributed 24.7% and 14.1%, respectively. Their combined contribution was 92.6%. Therefore, the high original WPI values at C/800 and C/950 were mainly driven by ammonium and phosphorus compounds.

Three sensitivity scenarios were used to examine the effect of oxygen-related normalisation, pH treatment, and parameter selection. The original WPI values and the results of these scenarios for all 24 samples are presented in Table 4.

Table 4. Original WPI values and results of the three sensitivity scenarios at the sampled depths of Profiles A, B, and C.

Profile/ Depth	Original WPI	Original Class	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)
A/50	1.025	III	1.295	1.239	1.178
A/200	1.141	III	1.397	1.356	1.338
A/300	1.132	III	1.405	1.357	1.330
A/400	1.337	III	1.612	1.587	1.624
A/500	1.220	III	1.498	1.460	1.459
A/600	1.311	III	1.898	1.764	1.653
A/850	1.762	III	2.814	2.538	2.335
A/950	1.997	III	3.330	2.931	2.682
B/50	1.323	III	1.276	1.321	1.424
B/200	1.251	III	1.215	1.251	1.332
B/300	1.287	III	1.295	1.329	1.417
B/400	1.233	III	1.264	1.288	1.356
B/500	1.165	III	1.485	1.428	1.392
B/600	1.104	III	2.168	1.821	1.397
B/850	1.132	III	2.309	1.899	1.442
B/950	1.589	III	2.839	2.440	2.099
C/50	1.446	III	1.477	1.525	1.661
C/200	1.233	III	1.287	1.306	1.372
C/300	1.251	III	1.317	1.337	1.406
C/400	1.196	III	1.363	1.353	1.380
C/500	1.203	III	1.448	1.417	1.423
C/600	1.440	III	1.975	1.872	1.831
C/800	4.996	V	6.822	6.58	6.979
C/950	11.074	VI	17.285	14.205	15.687

Note: Scenario 1 used direction-corrected normalisation for DO and OS and a range-based factor for pH. Scenario 2 excluded OS but retained direction-corrected DO and the range-based pH factor. Scenario 3 excluded DO, OS, and pH. The original WPI classes were applied only to the original WPI values. They were not applied to the three sensitivity scenarios.

In Scenario 1, the direction of normalisation was corrected for both DO and OS. The pH values were evaluated against the acceptable range. This scenario produced values of 6.82 at C/800 and 17.28 at C/950. In Scenario 2, OS was excluded, while direction-corrected DO

was retained. The corresponding values were 6.58 and 14.21. Scenario 3 excluded DO, OS, and pH. It produced values of 6.98 at C/800 and 15.69 at C/950.

Although the absolute values differed among the calculations, the main sample ranking remained unchanged. C/950 had the highest value and C/800 the second-highest value in the original calculation and all three sensitivity scenarios. This finding shows that their ranking did not depend only on the original treatment of DO, OS, or pH.

The sensitivity results were not assigned to the original WPI classes. The scenarios were used only to compare samples and test the stability of their ranking. The modified calculations used different parameter sets and have not been validated against the original class boundaries. Therefore, the six descriptive classes were retained only for the original WPI.

The contribution and sensitivity analyses support the main pattern observed in the study. The two deepest samples of Profile C had the highest calculated values in the original WPI and in all three sensitivity scenarios. However, the absolute index values depended on the selected parameters and the normalisation method. The WPI should therefore be interpreted together with the measured physicochemical values. It should not be treated as an independent formal assessment of the ecological status of the reservoir.

4. Conclusions

This study provides a depth-resolved assessment of vertical and between-profile differences in water quality across three profiles in the Gruža Reservoir during the September 2024 monitoring campaign. The upper and intermediate sampled layers generally showed smaller vertical differences than the samples collected at the greatest sampled depths. Oxygen conditions differed among profiles. Profile B had the highest surface DO, while lower values were recorded in Profiles A and C. Across the upper and intermediate sampled layers, the original WPI values generally ranged from 1.02 to 1.45 and were assigned to Class III based on the unrounded values.

Conditions in the deeper sampled layers also differed among the three profiles. Profiles A and B showed higher nutrient concentrations in some of their deeper samples. NH_4–N reached 0.37 mg N/L, PO_4–P reached 0.064 mg P/L, and TP reached 0.110 mg P/L. The original WPI values reached 1.997 in Profile A and 1.589 in Profile B, with all samples assigned to Class III based on the unrounded values. Profile C showed the most pronounced deterioration at its two greatest sampled depths. At C/950, NH_4–N reached 2.98 mg N/L, PO_4–P reached 0.547 mg P/L, TP reached 0.778 mg P/L, and DO decreased to 0.50 mg/L. The original WPI values were 5.00 at C/800 and 11.07 at C/950.

The combination of severe oxygen depletion and elevated ammonium and phosphorus concentrations at the two greatest sampled depths of Profile C is consistent with oxygen-depleted conditions and possible nutrient enrichment near the sediment–water interface. However, the available measurements do not directly confirm the sources or mechanisms responsible for this pattern. Water-column organic matter decomposition, external inputs, local hydrodynamic conditions, and proximity to the sediment may also have contributed.

The main contribution of this study is the comparison of physicochemical conditions and WPI values at discrete depths across three sampling profiles. The parameter-contribution analysis showed that NH_4–N, PO_4–P, and TP were the main drivers of the high original WPI values at C/800 and C/950. The sensitivity analysis confirmed the same main ranking across all three scenarios. C/950 had the highest value, while C/800 had the second-highest value in each scenario. However, the absolute values depended on the selected parameters and the normalisation method. The WPI should therefore be interpreted together with the measured physicochemical values.

The results highlight the importance of including deeper sampled layers in reservoir monitoring because surface measurements alone may not represent deterioration at greater

depths. However, the study is based on a single monitoring campaign and three profiles. The findings therefore represent a spatial and vertical snapshot of the sampled conditions rather than seasonal, annual, or long-term patterns. Biological indicators, temperature profiles, sediment characteristics, redox potential, and sediment–water nutrient fluxes were not included. Therefore, the processes responsible for the elevated ammonium and phosphorus concentrations in the deeper samples of Profile C could not be directly determined. Future studies should include additional locations, seasonal sampling, biological indicators, temperature profiles, and sediment-related measurements. These data would support a more complete interpretation of the processes affecting water quality and strengthen the basis for reservoir management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/limnolrev26040069/s1, Table S1: Measured physicochemical water-quality parameters at the sampled depths of Profiles A, B, and C in the Gruža Reservoir.

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