

Article

Field-Scale Spatial Organization of Water Quality During Floating-Island Operation in a Eutrophic Urban Lake

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Abstract

Eutrophication remains a persistent water-quality problem in shallow lakes, where external inputs interact with internal loading and biogeochemical cycling. Although floating treatment wetlands (FTWs) are increasingly promoted as nature-based solutions for water remediation, their field-scale interpretation in hydrologically complex eutrophic lakes remains challenging. This study examined the spatial organization of water quality during the operation of a floating-island system in a eutrophic urban lake affected by polluted tributary inflow. The study was not designed to quantify isolated FTW removal efficiency, but to evaluate spatial water quality organization during FTW operation under real-use field conditions. Water quality was monitored over two growing seasons across six functionally defined zones, and spatial and temporal patterns were analyzed using descriptive statistics and linear mixed-effects models. The results showed parameter-specific spatial structuring rather than a uniform treatment response. The clearest inlet-lake contrasts were observed for electrical conductivity (EC), suspended matter (SM), and nitrate nitrogen ($\text{NO}_3\text{-N}$), whereas biochemical oxygen demand (BOD_5), ammonium nitrogen ($\text{NH}_4\text{-N}$), and total organic carbon (TOC) showed lower values at the inlet and higher values in downstream zones. Dissolved oxygen (DO), oxygen saturation (SO), chemical oxygen demand (COD), nitrite nitrogen ($\text{NO}_2\text{-N}$), and orthophosphate phosphorus ($\text{PO}_4\text{-P}$) showed moderate or non-robust zonal effects. These findings indicate that FTWs in shallow eutrophic lakes should be evaluated through functional zoning and parameter-specific interpretation rather than as isolated units with uniform removal responses.

Keywords: floating treatment wetlands; shallow lake; eutrophication; nature-based solution; internal loading; biogeochemical cycling

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1. Introduction

Eutrophication remains one of the most persistent water-quality problems in freshwater ecosystems, particularly in shallow lakes where external nutrient inputs interact with sediment resuspension, internal loading, and rapid biogeochemical cycling [1,2]. In such systems, reducing external loading alone does not necessarily produce an immediate ecological response, because nutrients and organic matter stored in sediments may continue to sustain poor water quality and algal productivity for years [1,3]. Shallow eutrophic lakes are therefore difficult to restore and require management approaches that address both inflow-related pollution and in-lake processing [3–5].

Floating treatment wetlands (FTWs), also referred to as constructed floating wetlands or floating islands, have received increasing attention as nature-based solutions for improving water quality in ponds, rivers, reservoirs, and lakes [6–8]. Their main advantages include direct installation in open water, low cost, low land requirements, and the potential to provide water-quality, ecological and aesthetic co-benefits [8–11]. Current understanding indicates that FTWs function through multiple interacting mechanisms, including hydraulic slowing, particulate retention, root-zone filtration, rhizosphere-associated microbial activity, and plant uptake, rather than through a single linear removal pathway [7,10,11]. Recent reviews further emphasize that FTW performance depends strongly on system design, plant establishment, hydraulic conditions, and the broader ecological context of the receiving water body [6–8].

Despite this growing body of research, an important gap remains between the dominant experimental basis of FTW knowledge and the conditions under which these systems are often applied in practice [7,12]. Much of the available evidence has been generated from laboratory, mesocosm, or hydraulically simplified settings [12,13]. Such studies are highly valuable for isolating mechanisms, but they do not fully represent the behavior of FTWs in field-scale lake systems, where tributary inflow, vegetation belts, sediment-water exchange, internal nutrient cycling, hydrodynamics, and retention processes act simultaneously [7,12,13]. Recent studies have therefore pointed to the need for field-based evaluation and improved interpretation of FTW behavior under hydrologically complex conditions [6,7,13].

This issue is both methodological and conceptual. While previous research shows that FTWs can improve selected water-quality parameters, it remains unclear how their contribution should be interpreted in shallow eutrophic lakes where natural and engineered attenuation processes occur simultaneously. In open eutrophic lakes, a reduction in pollutant concentration at one location cannot automatically be attributed to a direct FTW effect, because measured values may also reflect mixing, sediment release, resuspension, in-lake retention, and biological processing [3,4]. The key question is therefore not only whether FTWs can remove pollutants, but how water-quality patterns during FTW operation should be evaluated within a functionally zoned and internally dynamic lake system. This question is particularly relevant for restoration practice, where nature-based interventions are usually implemented in multifunctional water bodies rather than in controlled experimental units [6,12].

The present study addresses this gap through a field-scale assessment of water-quality spatial organization during the operation of a floating-island system installed in Lake Trešnja, a eutrophic urban lake in Serbia affected by polluted inflow from a tributary stream. Rather than treating the lake as a homogeneous water body or applying a simple input-output efficiency framework, the study was designed around repeated monitoring of a functionally defined lake continuum comprising the inlet, reed-belt zone, two floating-island zones, an intermediate middle-lake zone, and the downstream dam zone.

Within this framework, the main aim was to assess how physicochemical water-quality parameters were spatially structured across the lake during two consecutive growing

seasons of floating-island operation. We expected parameters more directly associated with tributary inflow and particulate transport, such as electrical conductivity (EC), suspended matter (SM), and nitrate nitrogen ($\text{NO}_3\text{-N}$), to show clearer inlet-lake contrasts than parameters more strongly controlled by organic matter turnover, redox conditions, sediment–water interactions and internal lake metabolism. Because the study was conducted under real-use field conditions, without an independent untreated control water body and with limited FTW coverage, it was not intended as a controlled before-and-after or treatment-control assessment of isolated FTW efficiency. Accordingly, the study should be interpreted as a field-scale monitoring and interpretation study that evaluates parameter-specific spatial patterns during FTW operation within a functionally zoned, internally dynamic eutrophic lake system.

2. Materials and Methods

2.1. Study Area and Conceptual Framework

This study was conducted at Lake Trešnja, an artificial lake located near Mala Ivanča, in the wider Belgrade area, Serbia. The geographical location of the lake within Serbia and Serbia's position in Europe are shown in Figure 1a. The lake was originally created in 1963 as a fire-protection reservoir and later became a recreational water body. Over time, its ecological condition deteriorated, primarily due to inflow from a tributary stream receiving untreated wastewater from nearby settlements without a sewerage system. The lake is approximately 150 m long, with an average width of about 30 m, a depth ranging from 0.8 m in the shallower northwestern part to 4.5 m near the dam, and a total volume not exceeding 20,000 m³.

The study was designed as a field-scale assessment of water-quality patterns during the operation of floating islands in a eutrophic urban lake. Because the system operated under natural hydrological and ecological conditions, the research design was based on repeated spatial monitoring rather than on a strictly controlled experimental approach. Water was sampled along a functionally defined lake continuum comprising the pollution inflow, a naturally established reed-belt, two floating island zones, an intermediate open-water zone, and the downstream dam zone. The conceptual layout of this lake continuum is shown schematically in Figure 1b.

Conceptually, the monitored lake was treated as an integrated natural-constructed treatment pathway in which multiple attenuation and transformation processes may act simultaneously. These include pollutant inflow from the tributary, partial retention within emergent vegetation, transport and mixing within the lake, sedimentation, sediment–water exchange, and local processes associated with floating islands and their rhizosphere. Accordingly, the floating islands were evaluated as ecotechnological components operating within a coupled lake system, rather than as an isolated treatment unit. Within this framework, the primary objective was to assess spatial and temporal patterns in physico-chemical water quality across the monitored lake zones during floating island operation, while avoiding interpretation in terms of strict removal-efficiency estimates.

2.2. Floating-Island System

The floating islands were implemented over two consecutive growing seasons, with the first installation in May 2019 and the second in June 2020. In total, 50 floating islands were deployed in the lake during each season. The floating island model was based on a previously developed system [9] and adapted to site conditions at Lake Trešnja.

Each individual island had an effective planted area of 1 m² and was constructed as a lightweight high-density polyethylene floating platform filled with inert rock wool, 8 cm thick, which served as the plant growth substrate. The planted vegetation consisted of

a mixture of ornamental and emergent macrophyte species: *Phragmites australis* (Cav.) Trin. ex Steud., *Canna indica* L., *Iris pseudacorus* L., *Iris sibirica* 'Perry's Blue', *Alisma plantago-aquatica* L., and *Lythrum salicaria* L. The same plant composition and planting density were used on all floating islands in both floating-island systems. Each island was planted with 25 nursery-produced plants, corresponding to a density of 25 plants m⁻². The plants were produced in the same year and planted in May, at the beginning of the operational season. Prior to planting, only healthy, visually well-developed individuals were selected, and plants of the same species were chosen to be as uniform in size as possible. Root biomass was not measured destructively before installation, because the islands were established as an operational field-scale system rather than as an experimental plant-growth trial.

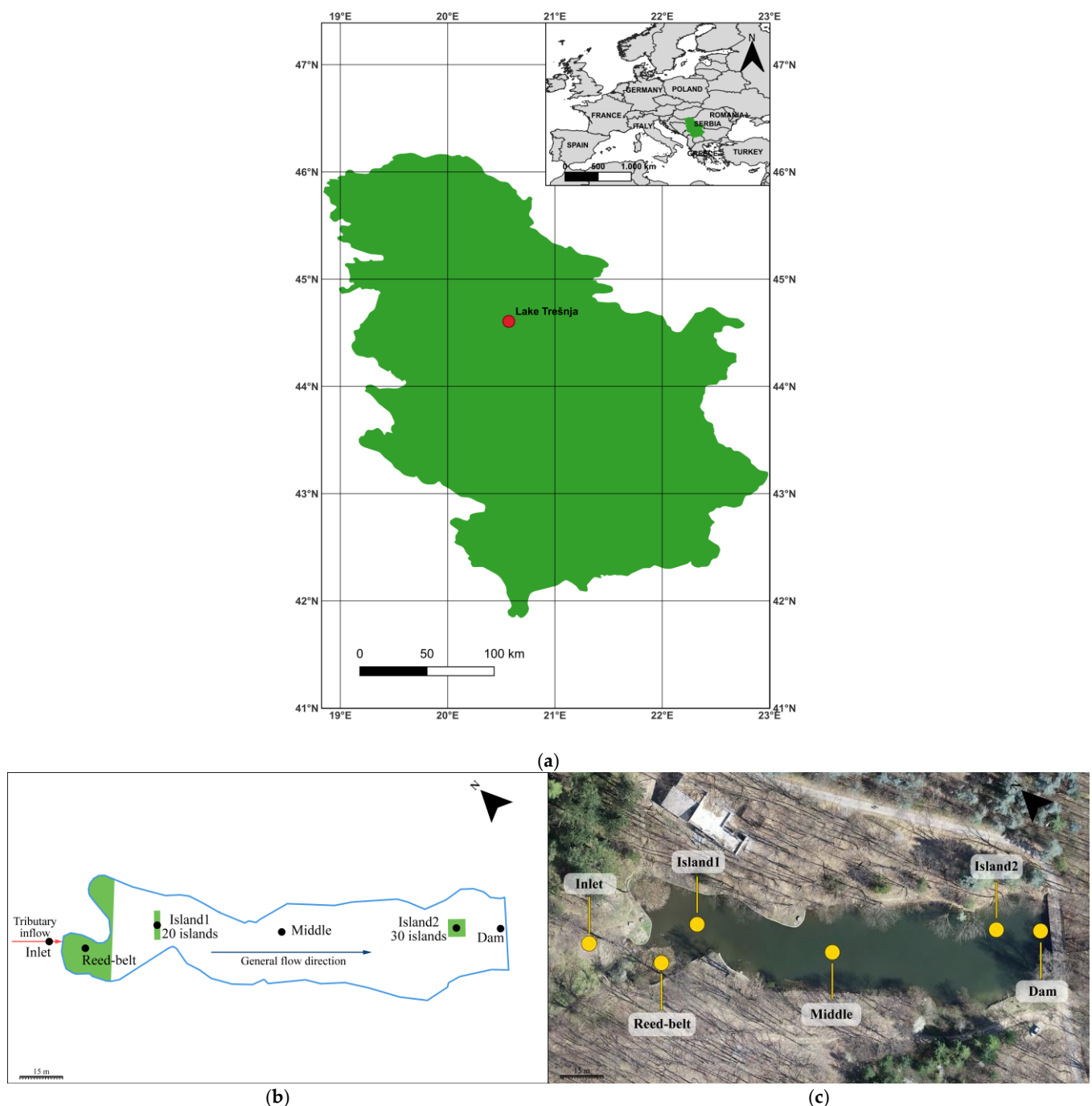


Figure 1. Location and monitoring layout of Lake Trešnja. (a) Location of Lake Trešnja within Serbia and the position of Serbia within Europe. (b) Schematic representation of the monitored lake

continuum, showing the tributary inflow, inlet zone, reed-belt, first floating-island system (Island1), middle lake zone, second floating-island system (Island2), dam zone, and general flow direction. (c) Drone image of Lake Trešnja showing the approximate positions of the six monitoring zones. Drone photograph provided by Nenad Šurjanac; sampling-zone annotations, scale bars, and compass arrows were added by the authors.

The islands were arranged into two main floating island systems. System 1 consisted of 20 interconnected floating islands, arranged in two rows of ten islands and anchored in the northwestern, shallower part of the lake (Figure 2a). System 2 consisted of 30 interconnected floating islands, positioned farther downstream toward the southeastern part of the lake (Figure 2b). These systems formed the basis for defining the two floating island monitoring zones used in the present study.



Figure 2. Floating-island systems installed in Lake Trešnja: (a) System 1, consisting of 20 interconnected floating islands in the shallower northwestern part of the lake; (b) System 2, consisting of 30 interconnected floating islands positioned farther downstream.

During the operational period, the floating-island systems were inspected once per week and after heavy rainfall or storm events by members of the research team. Maintenance included checking the position and anchoring of the islands, removing solid waste or debris that could obstruct water movement or physically damage the structures, and inspecting the general condition of the planted vegetation. During both monitored growing seasons, no invasive or unwanted plant species were observed on the islands, and no visible symptoms of plant pests or diseases were recorded. All planted individuals survived during the monitored periods, and no plant replacement was required in either study year.

2.3. Water Sampling Design

Water sampling was conducted during the field-scale operation of the floating islands over two consecutive growing seasons. Monitoring was carried out once per month from June to September 2019 and from June to September 2020, corresponding to the periods when floating islands were present in the lake. This monitoring window was selected because it corresponded to the operational and growing period of the floating-island systems, when plant establishment, root-zone development, microbial activity, and plant-water interactions were expected to be most relevant. Monitoring outside this period was not included because the islands were removed at the end of each operational season. Sampling was performed in accordance with SRPS ISO 5667-4:2019 [14]. During each sampling campaign, water was collected from six monitoring zones.

The six monitoring zones represented functionally distinct parts of the lake system:

- Inlet zone (Inlet)—located at the end of the main pollution inflow from the tributary stream;

- Reed-belt zone (Reed-belt)—located immediately after the reed belt at the beginning of the lake;
- Floating island zone 1 (Island1)—located at the site of the first floating-island system;
- Middle zone (Middle)—located at the transition/open-water zone between the two floating-island systems;
- Floating island zone 2 (Island2)—located at the site of the second floating-island system;
- Dam zone (Dam)—located in the downstream part of the lake near the dam.

The six monitoring zones and their approximate field positions are shown in Figure 1c. The approximate geographical coordinates of the six monitoring zones are provided in Table 1. Because each monitoring zone was represented by three within-zone subsamples during each sampling campaign, the coordinates refer to the representative central position of each functionally defined zone.

Table 1. Approximate geographical coordinates and functional position of the water-sampling zones in Lake Trešnja.

Monitoring Zone	Abbreviation	Latitude	Longitude	Functional Position
Inlet zone	Inlet	44°36'22.8" N	20°34'10.0" E	End of polluted tributary inflow
Reed-belt zone	Reed-belt	44°36'22.7" N	20°34'10.6" E	Immediately after the reed belt
Floating island zone 1	Island1	44°36'22.6" N	20°34'11.3" E	First floating-island system
Middle zone	Middle	44°36'21.4" N	20°34'12.7" E	Open-water transition zone
Floating island zone 2	Island2	44°36'20.9" N	20°34'14.5" E	Second floating-island system
Dam zone	Dam	44°36'20.1" N	20°34'15.6" E	Downstream dam zone

At each sampling campaign, 3 subsamples were collected per zone to capture within-zone spatial heterogeneity. The spacing among 3 subsamples depended on zone geometry and accessibility: approximately 2 m at the inlet, about 12.5 m across the reed-belt zone, about 5 m across the floating island zone 1, at least 15 m in the middle zone, and approximately 6 m across the floating island zone 2 and the dam zone. In the floating-island zones, samples were collected at approximately 30 cm depth within the root zone.

2.4. Water Quality Parameters and Analytical Procedures

The study focused on the physicochemical water-quality parameters relevant to eutrophication, organic loading, oxygen regime, and nutrient dynamics. The following quantitative variables were included in the analytical framework: water temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), oxygen saturation (SO), biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), ammonium nitrogen (NH₄-N), nitrite nitrogen (NO₂-N), nitrate nitrogen (NO₃-N), total nitrogen (TN), orthophosphate phosphorus (PO₄-P), total organic carbon (TOC), and suspended matter (SM). Water color, odor, and visible turbidity were evaluated descriptively during field observations.

Water temperature, pH, EC, DO, and SO were measured using a portable HACH HQ40d Digital Multi-2-channel Meter with automatic temperature compensation, equipped with Intellical™ PHC101, CDC401, and LDO101 probes for pH, conductivity, and dissolved oxygen, respectively, all supplied by Hach Company (Loveland, CO, USA).

Nutrient concentrations were determined spectrophotometrically using a Jenway™ 6305 UV/Visible spectrophotometer (Cole-Parmer Ltd., Stone, Staffordshire, UK). NH₄-N was analyzed using the Nessler method [15], with absorbance measured at 425 nm. NO₂-N was determined according to SRPS EN 26777:2009 [16], with absorbance read at 540 nm. NO₃-N was determined according to Standard Method 4500-NO₃-B Ultraviolet Spectrophotometric Screening Method [17], using absorbance at 220 nm for nitrate measurement and 275 nm to correct for possible interference from dissolved organic matter. PO₄-P was

determined according to SRPS EN ISO 6878:2008 [18], with absorbance measured at 880 nm.

TN was determined according to SRPS EN 12260:2008 [19] using catalytic combustion in an oxygen atmosphere at a temperature above 700 °C, followed by chemiluminescence detection of nitrogen oxides after reaction with ozone. COD was determined as COD_{Cr} using the dichromate digestion method with a Lovibond analytical system (Tintometer GmbH, Dortmund, Germany) comprising a COD reactor ET 108, an RD 125 Thermoreactor, and a COD Vario photometer, following the manufacturer's instructions. BOD₅ was determined according to SRPS EN 1899-1:2009 [20], using the dilution-and-seeding method with the addition of allylthiourea. SM was determined according to Standard Method 2540 D. Total Suspended Solids Dried at 103–105 °C [21]. TOC was determined according to SRPS ISO 8245:2007 [22] using a LABTOC analyzer (Scientific Analysis Laboratories Limited, Manchester, UK) with infrared detection.

2.5. Data Handling and Statistical Analysis

The mean of the three subsamples collected within each monitoring zone on a given date was used as the primary analytical unit in the inferential statistical analyses. This approach was applied because the three samples represented spatial subsamples within the same zone and sampling campaign, rather than fully independent experimental replicates. Accordingly, each observation used in the main models corresponded to one monitoring zone at one sampling date. Within-zone variability was retained in the descriptive statistics and expressed as standard deviation.

A preliminary pre-installation water-quality screening campaign was conducted to characterize the lake and support plant selection for the floating-island system, but it was not included in the main statistical analysis because it was not designed as a systematic baseline comparable to the repeated June–September monitoring dataset.

Several nutrient variables contained observations reported as being below the analytical limit of detection (LOD). For numerical treatment of these censored values in descriptive and inferential analyses, concentrations below the corresponding LOD were replaced with one-half of the LOD (LOD/2) before analysis. This approach was applied to NH₄-N, NO₂-N, and NO₃-N. However, because more than 50% of TN observations were below the LOD, TN was treated descriptively only and was not included in the main inferential statistical models.

The statistical analysis focused on spatial and temporal variation in water quality during floating island operation. The primary inferential framework was based on linear mixed-effects models (LMMs), selected because the monitoring design involved repeated measurements across zones and sampling dates. For each parameter, sampling zone, month, and year were treated as fixed effects, while sampling date was treated as a random effect to account for repeated monitoring over time. The general model structure was as follows:

$$\text{parameter} \sim \text{zone} + \text{month} + \text{year} + (1 | \text{sampling date}), \quad (1)$$

Interaction terms were not retained in the final model structure because the available dataset was limited in size, and additive models provided a more stable and interpretable framework for the main analyses. Variables showing substantial right-skewness or heteroscedasticity were analyzed after natural logarithmic transformation. In the final inferential framework, this applied to COD, BOD₅, NH₄-N, NO₂-N, NO₃-N, PO₄-P, and TOC. Results, therefore, include both untransformed and ln-transformed variables, depending on the parameter-specific distributional properties and model stability.

For SM, the mixed-effects model yielded an unstable covariance structure in IBM SPSS Statistics. Therefore, this parameter was analyzed using a general linear model

(GLM) with zone, month, and year treated as fixed factors. This approach was adopted because it provided stable and interpretable inferential results, whereas the mixed model for SM could not be reliably retained.

Descriptive statistics were calculated as mean \pm standard deviation for the main annual summaries and as mean, standard deviation, minimum, and maximum in the supplementary descriptive tables. Estimated marginal means and 95% confidence intervals were extracted from the fitted models and used for graphical presentation. Because these confidence intervals were model-derived and based on the fitted error structure, the balanced zone-by-date design, and pooled residual variance, they may appear similar in length across zones and should not be interpreted as raw within-zone variability. Pairwise comparisons among zones were based on the model output and interpreted in conjunction with the overall significance of the zone effect. Pairwise differences were considered secondary when the corresponding overall zone effect was not statistically significant.

The main analysis was based on zone-by-date spatial modeling rather than on site-to-site removal-efficiency calculations, because water quality at each monitoring zone may reflect local floating-island influence, upstream transport, mixing, sedimentation, retention, and internal lake processes. This approach was consistent with the study objective: to evaluate field-scale spatial and temporal water-quality patterns during floating-island operation rather than to calculate strict treatment-only removal efficiencies.

All statistical analyses were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) for data organization and descriptive summaries and IBM SPSS Statistics 26.0.0.0 (IBM Corp., Armonk, NY, USA) for inferential modeling. Statistical significance was assessed at $p < 0.05$.

3. Results

3.1. Descriptive Overview of Spatial Variation

The descriptive statistics for selected water quality parameters across six monitoring zones in 2019 and 2020 are shown in Table 2. The data revealed clear spatial variation within Lake Trešnja, although the direction and consistency of these patterns differed among parameter groups.

Table 2. Descriptive statistics for selected water-quality parameters across monitoring zones in 2019 and 2020, expressed as mean \pm standard deviation.

Parameter	Year	Inlet	Reed-Belt	Island1	Middle	Island2	Dam
EC ($\mu\text{S cm}^{-1}$)	2019	689.6 \pm 16.07	565.6 \pm 23.33	571.4 \pm 24.07	566.5 \pm 17.77	568.2 \pm 16.59	572.3 \pm 21.79
	2020	688.9 \pm 13.15	558.9 \pm 6.00	558.9 \pm 6.54	559.6 \pm 6.56	556.5 \pm 6.98	561.1 \pm 7.82
DO (mg L^{-1})	2019	8.43 \pm 0.39	9.07 \pm 1.99	9.19 \pm 2.23	8.83 \pm 2.35	7.99 \pm 1.85	7.63 \pm 1.18
	2020	8.53 \pm 0.38	6.98 \pm 0.16	7.33 \pm 0.15	7.00 \pm 0.75	7.18 \pm 1.12	6.80 \pm 0.56
SO (%)	2019	95.17 \pm 2.12	109.75 \pm 21.03	111.42 \pm 23.93	105.75 \pm 25.22	95.75 \pm 18.82	89.75 \pm 12.31
	2020	74.17 \pm 35.11	82.75 \pm 6.06	85.50 \pm 6.79	82.75 \pm 13.37	85.50 \pm 17.41	68.42 \pm 22.38
BOD5 (mg L^{-1})	2019	1.54 \pm 0.32	3.96 \pm 2.08	4.78 \pm 1.45	4.20 \pm 1.74	3.63 \pm 1.36	4.60 \pm 1.13
	2020	2.68 \pm 1.33	4.70 \pm 1.56	4.48 \pm 1.64	4.28 \pm 1.3	3.71 \pm 1.05	3.51 \pm 1.12
COD (mg L^{-1})	2019	5.00 \pm 5.38	7.13 \pm 2.14	6.83 \pm 1.22	7.06 \pm 1.88	6.29 \pm 1.58	6.40 \pm 1.37
	2020	9.70 \pm 9.92	9.00 \pm 6.45	8.30 \pm 4.80	7.11 \pm 3.59	6.69 \pm 3.36	6.51 \pm 3.10
NH4-N (mg L^{-1})	2019	0.067 \pm 0.04	0.122 \pm 0.05	0.151 \pm 0.11	0.368 \pm 0.54	0.245 \pm 0.32	0.243 \pm 0.32
	2020	0.102 \pm 0.06	0.172 \pm 0.04	0.163 \pm 0.04	0.169 \pm 0.04	0.168 \pm 0.04	0.196 \pm 0.06
NO2-N (mg L^{-1})	2019	0.007 \pm 0.00	0.022 \pm 0.01	0.022 \pm 0.01	0.023 \pm 0.01	0.024 \pm 0.01	0.025 \pm 0.01
	2020	0.006 \pm 0.00	0.016 \pm 0.03	0.017 \pm 0.03	0.015 \pm 0.03	0.015 \pm 0.03	0.016 \pm 0.03
NO3-N (mg L^{-1})	2019	3.708 \pm 0.21	0.375 \pm 0.17	0.358 \pm 0.18	0.317 \pm 0.15	0.283 \pm 0.14	0.292 \pm 0.15
	2020	3.009 \pm 0.09	0.242 \pm 0.20	0.200 \pm 0.14	0.175 \pm 0.15	0.175 \pm 0.15	0.175 \pm 0.15

PO ₄ -P (mg L ⁻¹)	2019	0.042 ± 0.01	0.051 ± 0.02	0.061 ± 0.02	0.057 ± 0.02	0.051 ± 0.01	0.06 ± 0.02
	2020	0.046 ± 0.02	0.075 ± 0.05	0.075 ± 0.04	0.064 ± 0.02	0.054 ± 0.02	0.047 ± 0.02
TOC (mg L ⁻¹)	2019	2.00 ± 0.12	5.29 ± 0.83	5.38 ± 0.72	5.45 ± 0.68	5.50 ± 0.71	5.74 ± 0.53
	2020	3.81 ± 2.00	8.84 ± 3.75	8.84 ± 3.10	8.20 ± 2.53	7.94 ± 3.02	7.53 ± 3.28
SM (mg L ⁻¹)	2019	114.92 ± 54.75	22.75 ± 21.48	16.67 ± 3.47	15.08 ± 6.6	9.83 ± 3.37	8.08 ± 0.42
	2020	56.92 ± 58.85	18.33 ± 19.25	19.50 ± 7.94	8.75 ± 2.62	6.83 ± 3.68	9.00 ± 3.92

Notes: Values are presented as mean ± SD. Descriptive statistics are based on monthly sampling campaigns conducted during the 2019 and 2020 growing seasons. TN was not included in the main table because more than 50% of observations were below the analytical limit of detection.

The most consistent inlet-lake gradients were observed for EC, NO₃-N and SM. These parameters showed the highest mean values in the inlet zone and substantially lower values in the downstream lake zones during both monitoring years.

In contrast, BOD₅, NH₄-N, NO₂-N, PO₄-P, and TOC showed the opposite descriptive pattern. The lower mean values were measured at the inlet, whereas higher values were generally observed in the reed-belt, floating-island, middle-lake, and dam zones in both years.

The remaining variables, DO, SO, and COD, exhibited more variable spatial behavior. For DO, the spatial pattern differed between years. In 2019, mean DO values at the inlet were lower than those in the reed-belt, Island1, and middle zones, whereas in 2020, the inlet showed higher DO values than the downstream zones. SO was generally higher in the reed-belt, both floating-island zones, and the middle zone during both years. In 2019, values above 100% indicated episodes of oxygen supersaturation in several lake zones. COD also showed contrasting annual behavior, with lower mean values at the inlet than in the downstream zones in 2019, but higher inlet values than most downstream zones in 2020.

Overall, the descriptive statistics indicate that Lake Trešnja did not exhibit a uniform spatial pattern across all monitored water-quality variables. Instead, the data show the coexistence of a strong inflow signal for some parameters and more complex downstream patterns for others.

3.2. Field Observation and Supplementary Descriptive Variables

Field observations showed that the lake water was brownish grey during the monitoring period. Water odor was weak, no foam was observed, and turbidity caused by sediment particles was low. These qualitative observations were broadly consistent throughout the two-year monitoring period and provided additional contextual information on the appearance of lake water during floating-island operation.

Supplementary descriptive statistics are provided in Tables S1 and S2. Water temperature was lowest in the inlet zone and higher in the reed-belt, both floating-island, middle-lake, and dam zones. This pattern was consistent with spatial differences between tributary inflow and in-lake water conditions. In contrast, pH showed only limited variation among zones and between years, remaining within a relatively narrow range throughout the monitoring period.

TN is shown only in the supplementary descriptive tables (Tables S1 and S2) because more than 50% of observations were below the analytical LOD. Although the descriptive data suggest generally higher TN values at the inlet than in the downstream zones, this variable was not included in the main inferential statistical models and should therefore be interpreted cautiously.

3.3. Summary of Inferential Models

The inferential statistical results are summarized in Table 3. Sampling zone was the dominant explanatory factor for most analyzed variables, whereas neither month nor year showed a significant effect for any parameter included in the main models.

Strong zonal effects were observed for EC, SM, $\ln(\text{BOD}_5)$, $\ln(\text{NH}_4\text{-N})$, $\ln(\text{NO}_3\text{-N})$, and $\ln(\text{TOC})$. A modest but statistically significant zonal effect was observed for DO. In contrast, SO, $\ln(\text{COD})$, $\ln(\text{NO}_2\text{-N})$, and $\ln(\text{PO}_4\text{-P})$ showed no significant overall zonal effects.

Table 3. Results of inferential statistical models testing the effects of sampling zone, month, and year on selected water-quality parameters.

Parameter	Model	Transformation	Zone F	Zone <i>p</i>	Month F	Month <i>p</i>	Year F	Year <i>p</i>
EC	LMM	none	193.151	<0.001	0.397	0.766	0.693	0.466
SM	GLM	none	11.372	<0.001	1.939	0.140	2.436	0.127
DO	LMM	none	2.587	0.043	0.648	0.635	1.769	0.276
SO	LMM	none	2.324	0.064	1.173	0.449	5.046	0.11
COD	LMM	ln	1.703	0.16	1.627	0.35	0.055	0.83
BOD ₅	LMM	ln	12.232	<0.001	0.054	0.981	0.041	0.853
NH ₄ -N	LMM	ln	4.587	0.003	1.036	0.489	0.355	0.593
NO ₂ -N	LMM	ln	1.310	0.282	1.756	0.328	3.719	0.149
NO ₃ -N	LMM	ln	128.261	<0.001	1.484	0.377	2.206	0.234
PO ₄ -P	LMM	ln	1.923	0.115	2.109	0.278	0.292	0.626
TOC	LMM	ln	67.635	<0.001	0.366	0.784	1.963	0.256

Notes: LMM, linear mixed-effects model; GLM, general linear model; ln, natural logarithm. Mixed-effects models were applied with sampling date as a random effect, where model convergence was satisfactory. SM was analyzed using GLM because the mixed-effects model yielded an unstable covariance structure.

3.4. Physicochemical Parameters

A linear mixed-effects model showed a significant effect of sampling zone on EC ($F = 193.151$, $p < 0.001$), whereas the effects of month ($F = 0.397$, $p = 0.766$) and year ($F = 0.693$, $p = 0.466$) were not significant (Table 3). Estimated marginal means indicated that the inlet zone had the highest EC values, while all downstream zones showed relatively similar lower values (Figure 3a). Pairwise comparisons confirmed that the inlet differed significantly from the reed-belt, both floating-island, middle-lake, and dam zones, whereas no significant differences were detected among the downstream zones.

For SM, the general linear model showed a significant effect of sampling zone ($F = 11.372$, $p < 0.001$), whereas month ($F = 1.939$, $p = 0.140$) and year ($F = 2.436$, $p = 0.127$) were not significant (Table 3). Estimated means indicated that SM was highest in the inlet zone and substantially lower in all other zones (Figure 3d). Pairwise comparisons showed that the inlet differed significantly from all downstream zones, whereas no significant differences were observed among the downstream zones.

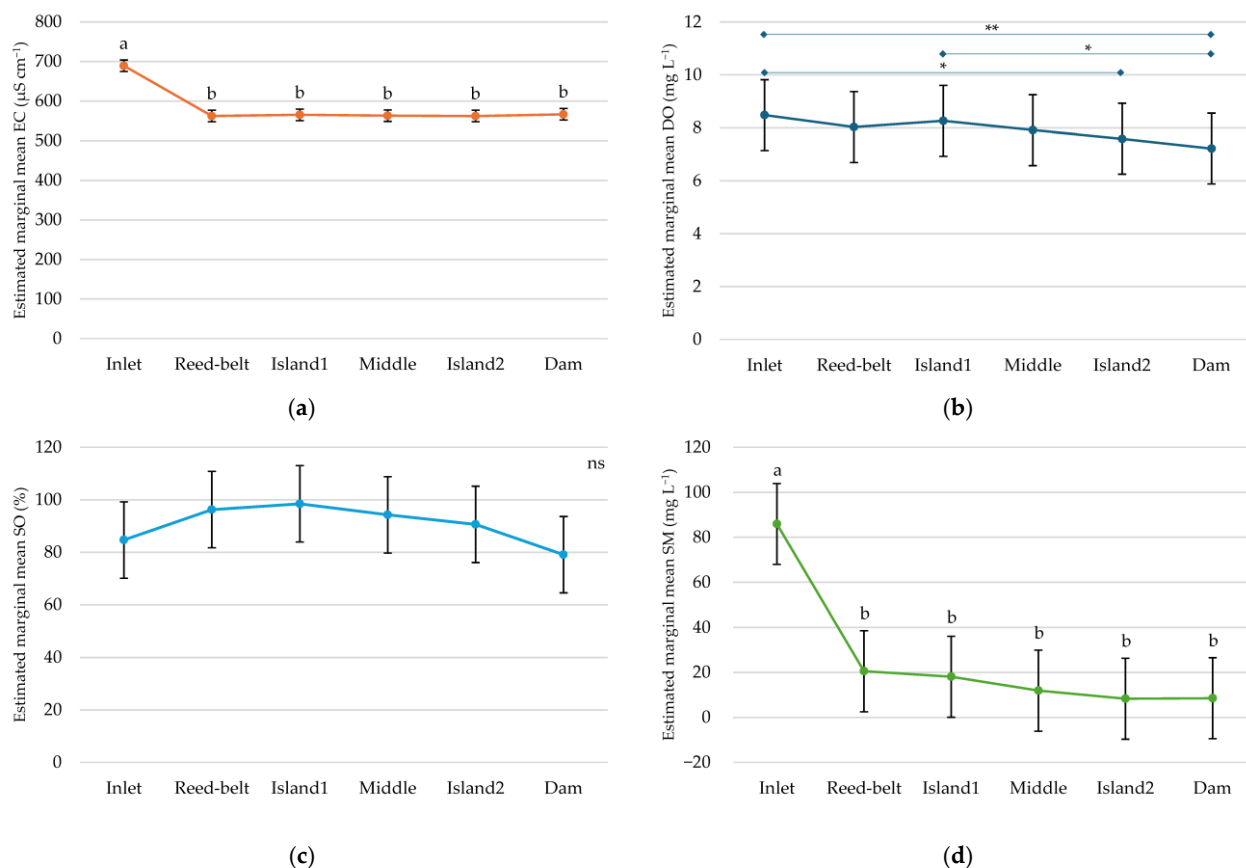


Figure 3. Estimated marginal means \pm 95% confidence intervals of selected physicochemical parameters across the six monitoring zones in Lake Trešnja. Panels show (a) electrical conductivity, EC ($\mu\text{S cm}^{-1}$), (b) dissolved oxygen, DO (mg L^{-1}), (c) oxygen saturation, SO (%), and (d) suspended matter, SM (mg L^{-1}). Different lowercase letters indicate statistically significant differences among monitoring zones for variables with a significant overall zone effect and clear grouping structure. In panel (b), significant pairwise differences are indicated by horizontal connector lines and asterisks because the zonal effect for DO was moderate and did not form a simple grouping pattern. The panel marked “ns” indicates that the overall zone effect was not statistically significant. Values are estimated marginal means \pm 95% confidence intervals derived from the fitted models and should not be interpreted as raw mean \pm standard deviation. * $p < 0.05$; ** $p < 0.01$.

The zonal effect was significant but moderate for DO ($F = 2.587$, $p = 0.043$), while month ($F = 0.648$, $p = 0.635$) and year ($F = 1.769$, $p = 0.276$) were not significant (Table 3). Estimated marginal means indicated the highest DO values in the inlet and Island1 zones and the lowest values at the dam zone (Figure 3b). Pairwise comparisons showed significant differences between the dam and inlet zones, between the dam and Island1, and between the inlet and Island2, whereas the remaining contrasts were not significant.

For SO, the effects of zone ($F = 2.324$, $p = 0.064$), month ($F = 1.173$, $p = 0.449$) and year ($F = 5.046$, $p = 0.110$) were not significant (Table 3). Estimated marginal means suggested lower oxygen saturation in the dam zone and higher values in the Island1, middle-lake, and reed-belt zones (Figure 3c). However, the absence of a significant overall zonal effect indicates that SO did not show robust spatial structuring across the monitored lake continuum.

Overall, EC and SM exhibited the clearest contrast between the inlet zone and all downstream lake zones, whereas DO showed a weaker but statistically significant zonal pattern, and SO lacked a robust overall zonal effect.

3.5. Organic Matter-Related Variables

A linear mixed-effects model applied to $\ln(\text{BOD}_5)$ values showed a significant effect of sampling zone ($F = 12.232$, $p < 0.001$), whereas month ($F = 0.054$, $p = 0.981$) and year ($F = 0.041$, $p = 0.853$) were not significant (Table 3). Estimated marginal means indicated the lowest values in the inlet zone, while all downstream zones showed higher and relatively similar values (Figure 4a). Pairwise comparisons confirmed that the inlet differed significantly from the reed-belt, both floating-island, middle-lake, and dam zones, whereas no significant differences were detected among the downstream zones.

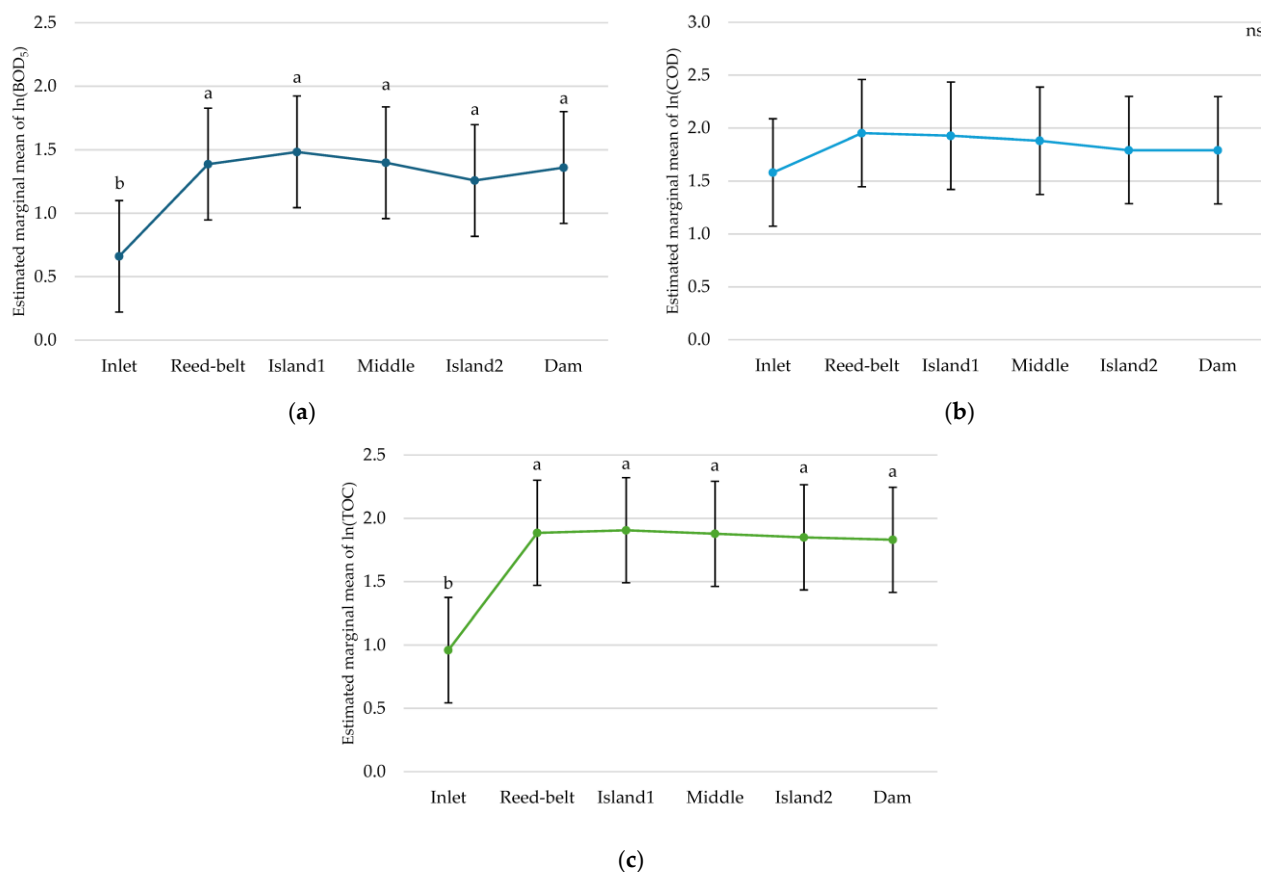


Figure 4. Estimated marginal means \pm 95% confidence intervals of organic matter-related indicators across the six monitoring zones in Lake Trešnja. Panels show (a) \ln -transformed biochemical oxygen demand, $\ln(\text{BOD}_5)$, (b) \ln -transformed chemical oxygen demand, $\ln(\text{COD})$, and (c) \ln -transformed total organic carbon, $\ln(\text{TOC})$. Original concentrations were measured in mg L^{-1} before natural-log transformation. Different lowercase letters indicate statistically significant differences among monitoring zones for variables with a significant overall zone effect. The panel marked “ns” indicates that the overall zone effect was not statistically significant. Values are estimated marginal means \pm 95% confidence intervals derived from the fitted models and should not be interpreted as raw mean \pm standard deviation.

For $\ln(\text{COD})$, no significant effects of zone ($F = 1.703$, $p = 0.160$), month ($F = 1.627$, $p = 0.350$), or year ($F = 0.055$, $p = 0.830$) were detected (Table 3). Estimated marginal means suggested some variation among zones, with lower values in the inlet zone and somewhat higher values in the reed-belt and Island1 zones (Figure 4b). However, because the overall zonal effect was not statistically significant, COD was not interpreted as showing robust spatial differentiation during floating-island operation.

A strong zonal effect was detected for $\ln(\text{TOC})$ ($F = 67.635$, $p < 0.001$), whereas month ($F = 0.366$, $p = 0.784$) and year ($F = 1.963$, $p = 0.256$) were not significant (Table 3). Estimated

marginal means showed the lowest values at the inlet and higher, relatively similar values across the dam, Island1, Island2, middle-lake, and reed-belt zones (Figure 4c). Pairwise comparisons confirmed that the inlet differed significantly from all downstream zones, while no significant differences were observed among the downstream zones.

Overall, BOD₅ and TOC were lowest at the inlet and higher in downstream lake zones, while COD showed no robust overall spatial differentiation.

3.6. Nitrogen and Phosphorus Variables

For $\ln(\text{NH}_4\text{-N})$, the zonal effect was significant ($F = 4.587$, $p = 0.003$), whereas month ($F = 1.036$, $p = 0.489$) and year ($F = 0.355$, $p = 0.593$) were not significant (Table 3). Estimated marginal means indicated the lowest values in the inlet zone and higher, relatively similar values in all downstream zones (Figure 5a). Pairwise comparisons confirmed that the inlet differed significantly from the dam, Island1, Island2, middle-lake, and reed-belt zones, whereas no significant differences were detected among the downstream zones.

A linear mixed-effects model applied to $\ln(\text{NO}_2\text{-N})$ showed no significant overall effect of zone ($F = 1.310$, $p = 0.282$), month ($F = 1.756$, $p = 0.328$), or year ($F = 3.719$, $p = 0.149$) (Table 3). Estimated marginal means suggested somewhat lower values in the inlet zone than in the remaining zones (Figure 5b). However, in the absence of a significant overall zonal effect, $\text{NO}_2\text{-N}$ was not considered to show robust spatial structuring across the monitored zones.

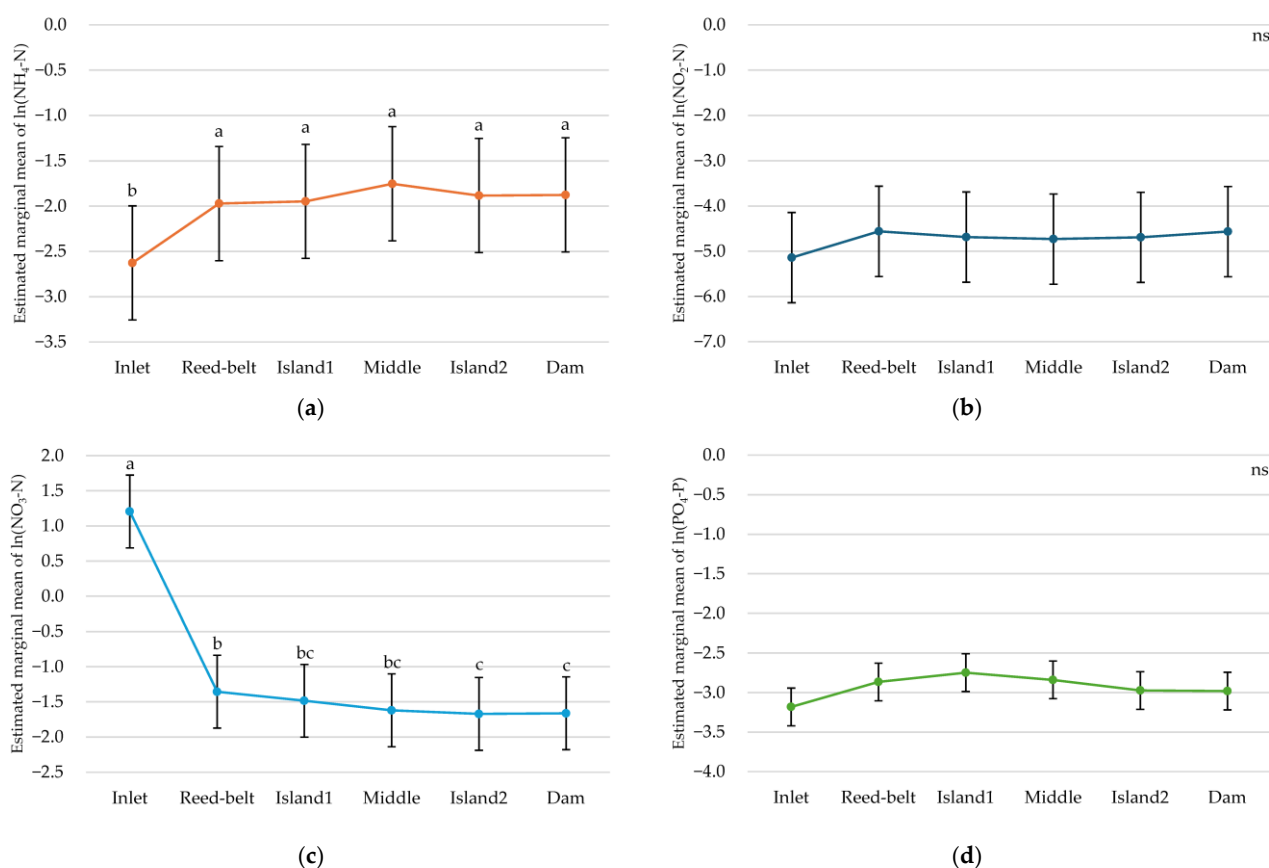


Figure 5. Estimated marginal means \pm 95% confidence intervals of nutrient-related variables across the six monitoring zones in Lake Trešnja. Panels show (a) \ln -transformed ammonium nitrogen, $\ln(\text{NH}_4\text{-N})$, (b) \ln -transformed nitrite nitrogen, $\ln(\text{NO}_2\text{-N})$, (c) \ln -transformed nitrate nitrogen, $\ln(\text{NO}_3\text{-N})$, and (d) \ln -transformed orthophosphate phosphorus, $\ln(\text{PO}_4\text{-P})$. Original concentrations were measured in mg L^{-1} before natural-log transformation. Different lowercase letters indicate statistically significant differences among monitoring zones for variables with a significant overall zone

effect. Panels marked “ns” indicate that the overall zone effect was not statistically significant. Values are estimated marginal means \pm 95% confidence intervals derived from the fitted models and should not be interpreted as raw mean \pm standard deviation.

A highly significant zonal effect was observed for $\ln(\text{NO}_3\text{-N})$ ($F = 128.261$, $p < 0.001$), whereas month ($F = 1.484$, $p = 0.377$) and year ($F = 2.206$, $p = 0.234$) were not significant (Table 3). Estimated marginal means indicated substantially higher values in the inlet zone than in all downstream lake zones (Figure 5c). Pairwise comparisons confirmed that the inlet differed significantly from the dam, Island1, Island2, middle-lake, and reed-belt zones. Additional significant differences were also detected between the dam and reed-belt zones and between Island2 and the reed-belt zone.

For $\ln(\text{PO}_4\text{-P})$, the overall effects of zone ($F = 1.923$, $p = 0.115$), month ($F = 2.109$, $p = 0.278$), and year ($F = 0.292$, $p = 0.626$) were not significant (Table 3). Estimated marginal means suggested somewhat lower values in the inlet zone and higher values in the Island1, middle-lake, and reed-belt zones (Figure 5d). However, because the overall zonal effect was not significant, $\text{PO}_4\text{-P}$ was interpreted as lacking robust spatial differentiation during the monitored period.

Overall, the nutrient variables showed contrasting behavior. $\text{NO}_3\text{-N}$ exhibited a pronounced inlet-lake contrast, $\text{NH}_4\text{-N}$ showed a weaker but significant zonal pattern with lower values at the inlet, while $\text{NO}_2\text{-N}$ and $\text{PO}_4\text{-P}$ showed no robust overall zonal effects.

4. Discussion

4.1. General Interpretation of System Response

The present study shows that water quality in Lake Trešnja during floating-island operation was spatially structured, but not according to a uniform treatment-response pattern. Instead, three main response groups were identified. EC, SM and $\text{NO}_3\text{-N}$ showed the strongest and most consistent inlet-lake contrasts, with the inlet zone differing significantly from the downstream lake zones. BOD_5 , $\text{NH}_4\text{-N}$, and TOC followed opposite patterns, with the lowest values at the inlet and higher values in the lake body. The remaining parameters, including DO, SO, COD, $\text{NO}_2\text{-N}$, and $\text{PO}_4\text{-P}$, showed weaker, moderate or non-robust zonal effects.

These differences indicate that Lake Trešnja functioned as a coupled eutrophic system in which external inflow, retention, sediment–water interactions, organic matter turnover and nutrient cycling acted simultaneously. The floating islands were part of this system, rather than separate treatment units. This interpretation is consistent with current understanding of FTWs as systems driven by multiple interacting mechanisms, including hydraulic slowing, particulate retention, root-zone filtration, rhizosphere-associated microbial transformation and plant uptake [3,7,8,10,23]. However, the present results further show that, under field-scale lake conditions, these mechanisms are difficult to separate from tributary input, reed-belt retention, hydrodynamic mixing, and internal lake processes.

The main contribution of this study is therefore the field-scale interpretation of water-quality organization during floating-island operation, rather than quantification of isolated FTW removal efficiency. The strongest break in the data occurred between the tributary inlet and the lake body, while downstream zones often showed similar values. This supports functional zoning as a useful framework for evaluating FTW installations in small eutrophic lakes where engineered and natural attenuation processes operate together.

4.2. Parameters Showing Strong Inlet-Lake Contrasts

Among all analyzed variables, SM, EC and $\text{NO}_3\text{-N}$ showed the clearest and most stable spatial patterns. For all three parameters, the inlet zone differed significantly from all downstream zones, whereas differences among the reed-belt, floating-island, middle-lake and dam zones were generally weak or absent. This indicates that the dominant spatial discontinuity occurred at the transition between the polluted tributary inflow and the lake body, rather than between individual downstream zones.

For SM, the observed pattern is consistent with attenuation processes expected in low-energy vegetated and partially engineered lake systems. Suspended particles can be reduced through hydraulic slowing, sedimentation, entrapment within root systems, and retention by biofilm-associated surfaces [7,8,10]. In Lake Trešnja, the sharp decline in SM after the inlet suggests strong particulate attenuation along the inlet-lake transition. Because the downstream zones did not differ significantly from one another, the observed pattern is best interpreted as a lake-scale retention gradient involving the reed belt, floating-island areas, reduced flow velocity and in-lake sedimentation, rather than as a sharply localized response restricted to individual island zones.

EC showed a similarly stable inlet-lake contrast, although its interpretation differs from that of SM. EC is an integrative indicator of dissolved ionic load, and the higher values at the inlet most likely reflect the chemical signature of the incoming tributary water. The lower and relatively uniform EC values across all downstream zones suggest rapid dilution and mixing within the lake body, combined with broader retention and sediment–water interactions [3,23,24]. This pattern supports the interpretation that EC functioned primarily as a tracer of inflow influence and lake-scale homogenization, rather than as a direct indicator of FTW-specific removal.

$\text{NO}_3\text{-N}$ also exhibited a pronounced inlet-lake contrast, with substantially higher concentrations at the inlet and much lower values in all downstream zones. This pattern indicates strong nitrogen transformation or attenuation within the lake continuum during floating-island operation. Nitrate reduction in FTW and wetland systems can occur through denitrification in anoxic biofilm and rhizosphere microzones, while plant uptake and assimilatory microbial pathways may also contribute [7,25–27]. In a shallow eutrophic lake, these processes are likely to operate alongside dilution, retention, sediment–water exchange, and microbial transformation within the broader lake body. Therefore, the $\text{NO}_3\text{-N}$ pattern is best interpreted as evidence of strong inlet-lake nitrogen differentiation during operation of the natural-constructed system, rather than as a quantified measure of isolated FTW nitrate removal.

Because a substantial proportion of $\text{NO}_3\text{-N}$ measurements were below the analytical limit of detection, the exact magnitude of the $\text{NO}_3\text{-N}$ effect should not be overinterpreted. Nevertheless, the direction of the pattern was consistent throughout the monitoring period and remained one of the clearest indicators of spatial differentiation between the polluted tributary inflow and the downstream lake environment.

4.3. Parameters Showing Enrichment in Downstream Lake Zones

In contrast to SM, EC, and $\text{NO}_3\text{-N}$, several variables associated with organic matter and reduced nitrogen showed higher values in the lake body than at the inlet. BOD_5 , TOC and $\text{NH}_4\text{-N}$ consistently had the lowest values at the inlet and higher values across the reed-belt, floating-island, middle-lake and dam zones. This pattern indicates that these variables were governed primarily by internal lake processes rather than by the direct chemical signature of the tributary inflow.

The downstream increases in BOD_5 and TOC are consistent with active organic matter production, retention, and recycling in eutrophic shallow lakes. In such systems, algal production, macrophyte growth and decomposition, microbial processing, sediment

resuspension and sediment–water exchange can maintain substantial dissolved and particulate organic matter pools within the lake body [3,4,28–31]. The higher values observed in downstream zones, therefore, indicate intensified organic matter turnover within the lake interior, rather than a simple longitudinal pollution gradient from the inlet to the dam.

A similar interpretation applies to $\text{NH}_4\text{-N}$. Ammonium concentrations in shallow eutrophic lakes reflect the balance between ammonification, nitrification, plant and microbial uptake, and redox-sensitive nitrogen transformations [26,31,32]. Higher $\text{NH}_4\text{-N}$ values in the downstream lake zones are therefore consistent with internal nitrogen regeneration, particularly where retained organic matter and microbial mineralization contribute to ammonium production. This pattern also helps explain why $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ behaved differently. Nitrate showed a strong inlet-lake depletion pattern, whereas ammonium reflected internal transformation and regeneration processes within the lake body.

The floating-island zones may have contributed to these biogeochemical processes by increasing local structural complexity and providing root and biofilm surfaces for microbial activity. Constructed wetland and FTW studies have shown that plant roots and associated biofilms provide attachment surfaces for microorganisms, create biogeochemically active microzones, and support organic matter retention and nutrient transformation [33,34]. However, because similar downstream values were also observed outside the island zones, the BOD_5 , TOC and $\text{NH}_4\text{-N}$ patterns are best interpreted as lake-scale indicators of organic matter and nitrogen cycling within the natural-constructed system, rather than as localized responses restricted to the floating islands.

Overall, the enrichment of BOD_5 , TOC and $\text{NH}_4\text{-N}$ in downstream zones highlights the importance of interpreting FTW operation within the metabolic context of the receiving water body. In eutrophic shallow lakes, higher organic matter and $\text{NH}_4\text{-N}$ concentrations within the lake body may reflect internal production, retention and regeneration processes [3,4,26,31,32] even when strong inlet-lake attenuation is observed for other parameters, such as SM and $\text{NO}_3\text{-N}$.

4.4. Parameters with Weak or Non-Robust Spatial Structuring

Oxygen-related variables showed weaker and less spatially coherent patterns than EC, SM, $\text{NO}_3\text{-N}$, BOD_5 , TOC and $\text{NH}_4\text{-N}$. DO showed a statistically significant but modest zonal effect, whereas SO did not show a significant overall zonal effect. This indicates that oxygen conditions in Lake Trešnja were spatially heterogeneous but not organized along a simple inlet-lake or floating-island gradient.

This behavior is expected in shallow eutrophic systems, where oxygen dynamics are regulated by interacting processes such as photosynthesis, respiration, sediment oxygen demand, organic matter decomposition, water-column mixing and temperature-dependent solubility [31,35,36]. In floating-island and wetland root zones, plant-mediated oxygen release may create local aerobic microsites, while retained organic matter and biofilm activity may simultaneously increase microbial oxygen demand [25,33,35–37]. Therefore, a uniform increase in DO or SO across the lake would not be expected under field-scale eutrophic conditions. The oxygen results are better interpreted as evidence of locally variable metabolic conditions than as a direct indicator of treatment performance.

$\text{NO}_2\text{-N}$, COD, and $\text{PO}_4\text{-P}$ did not show significant overall zonal effects. These results suggest that the monitored spatial design did not capture stable zonal structuring for these parameters during the study period. This is consistent with their process behavior in eutrophic shallow lakes. $\text{NO}_2\text{-N}$ is a transient intermediate in nitrogen cycling and is usually rapidly produced and consumed during nitrification and denitrification [26,38]. COD represents an aggregate measure of oxidizable substances rather than a single source-specific fraction, and may therefore integrate multiple inputs and transformation pathways,

including tributary inflow, algal production, macrophyte detritus, microbial decomposition and sediment–water exchange [10,39]. $\text{PO}_4\text{-P}$ is strongly affected by internal phosphorus loading, sediment release, adsorption-desorption processes, particulate resuspension and redox-sensitive sediment–water interactions [3,4,28,31,40].

Taken together, the weak or non-robust spatial structuring of DO, SO, COD, $\text{NO}_2\text{-N}$ and $\text{PO}_4\text{-P}$ indicates that these parameters were governed more by transient transformation processes and whole-lake biogeochemical variability than by stable zonal differentiation. This distinction is important for field-scale FTW monitoring because not all water-quality indicators are equally suitable for detecting spatial organization in low-coverage floating-island systems.

4.5. Implications for Monitoring Low-Coverage FTW Systems

The results of this study have several implications for field-scale evaluation of FTWs in shallow eutrophic lakes. The most informative patterns were not uniform downstream reductions, but parameter-specific spatial contrasts. EC, SM and $\text{NO}_3\text{-N}$ provided the clearest evidence of inlet-lake differentiation. BOD_5 , TOC and $\text{NH}_4\text{-N}$ reflected internal organic matter processing and nitrogen regeneration within the lake body, processes commonly linked to sediment–water exchange, organic matter mineralization and nitrogen cycling in eutrophic shallow systems [3,4,26,31,32]. DO and SO were more closely related to variable metabolic conditions, including photosynthesis, respiration, oxygen demand and mixing [31,35,36]. COD, $\text{NO}_2\text{-N}$, and $\text{PO}_4\text{-P}$ were less suitable as stable spatial indicators because they are influenced by aggregate organic matter pools, transient nitrogen transformations, and internal phosphorus loading [3,4,26,38,39].

These findings show that low-coverage FTW systems should not be evaluated only through conventional treatment-efficiency logic. FTWs operate through multiple interacting mechanisms, including hydraulic slowing, particulate retention, root-zone filtration, microbial transformation and plant uptake [7,8,10]. However, in open eutrophic lakes, these mechanisms are embedded within a broader natural-constructed continuum that also includes tributary inflow, reed-belt retention, hydraulic mixing, sedimentation, sediment–water exchange and internal nutrient cycling [3,4,23,31]. Under such conditions, functional zoning provides a more appropriate monitoring framework than simple inlet-outlet comparison, because it allows different parameter groups to be interpreted according to their dominant controlling processes.

The absence of robust zonal effects for some parameters should therefore be treated as useful monitoring information rather than an analytical failure. It indicates that certain variables are poor indicators of stable spatial differentiation under field-scale conditions with limited FTW coverage. Future monitoring would benefit from denser temporal sampling, hydrological information, sediment or pore-water measurements, and designs that include comparable island and non-island zones. Such additions would improve the separation of local FTW effects from whole-lake attenuation and internal cycling.

4.6. Limitations

Several limitations define the level of inference this study supports. The design did not include an independent, untreated control water body, so the results cannot quantify the isolated contribution of the floating islands or fully separate it from reed-belt retention, sedimentation, hydrodynamic mixing, and other lake-scale attenuation processes. A preliminary water-quality screening campaign was conducted before the operational monitoring period to assess the initial condition of the lake and to inform the selection of plant species for the floating-island system. However, it was not designed as a systematic pre-installation baseline with the same temporal replication and monitoring framework and was therefore not used for before-and-after statistical comparison. FTW coverage was

relatively low in relation to the total lake surface, reflecting a conservative field implementation in a recreational water body, and this may have limited the magnitude of detectable whole-lake responses. The effective sample size was also constrained by the monitoring design. Three within-zone subsamples were averaged to avoid pseudoreplication, and the final models used an additive structure, without zone \times month or zone \times year interactions. Finally, several nitrogen variables included censored observations, and LOD/2 substitution provided a pragmatic basis for analysis but limited the precision of nitrogen-related effect estimates.

These limitations do not invalidate the observed spatial patterns, but they define their interpretation. The study supports inferences about the field-scale spatial organization of water quality during floating-island operation, not about the isolated FTW removal efficiency. Within that scope, the dataset provides useful evidence for evaluating FTW systems as components of a broader natural-constructed restoration pathway in shallow eutrophic lakes.

5. Conclusions

This study shows that water-quality responses during floating-island operation in a eutrophic urban lake were strongly parameter-dependent. EC, SM and NO₃-N captured the clearest influence of polluted tributary inflow, while BOD₅, TOC and NH₄-N reflected stronger processing within the lake body. COD, NO₂-N and PO₄-P showed limited spatial separation, indicating that some commonly measured variables are less suitable for detecting stable field-scale patterns in this type of system.

These findings should therefore be interpreted as evidence of spatial water-quality organization during floating-island operation, rather than as a controlled estimate of isolated FTW treatment efficiency. Overall, the results support functional zoning as a practical approach for interpreting FTW installations in open eutrophic lakes. Floating islands should be monitored as part of the receiving lake system, where their effects interact with retention, mixing, sediment–water exchange and internal nutrient cycling. Future studies combining spatial sampling with hydrological, sediment and rhizosphere measurements would allow stronger separation of local FTW effects from whole-lake processes.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/w18121485/s1>. Table S1: Descriptive statistics of all monitored parameters across sampling zones in 2019, expressed as mean, standard deviation, minimum, and maximum; Table S2: Descriptive statistics of all monitored parameters across sampling zones in 2020, expressed as mean, standard deviation, minimum, and maximum.

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Abbreviations

The following abbreviations are used in this manuscript:

BOD ₅	Biochemical oxygen demand after 5 days
COD	Chemical oxygen demand
DO	Dissolved oxygen
EC	Electrical conductivity
FTW	Floating treatment wetland
GLM	General linear model
LMM	Linear mixed-effects model
LOD	Limit of detection
NH ₄ -N	Ammonium nitrogen
NO ₂ -N	Nitrite nitrogen
NO ₃ -N	Nitrate nitrogen
PO ₄ -P	Orthophosphate phosphorus
SM	Suspended matter
SO	Oxygen saturation
TN	Total nitrogen
TOC	Total organic carbon

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