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Research Article

Comparative nutrient analysis of two freshwater lakes located in the pre-deltaic and deltaic areas with natural hydrological regimes

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Abstract

This study aims to provide a comparative analysis of nutrient concentrations in two lakes with controlled hydrological regimes that are directly influenced by the Danube River. The lakes are differentiated by their distinct geographical settings: one located in a pre-deltaic area and the other within the deltaic zone. Eight chemical indicators were analysed in surface water samples collected seasonally between 2019 and 2023. The results show higher concentrations of nitrates and nitrites in Lake Fortuna, associated with its natural hydrological connectivity, whereas Lake Parcheș exhibited a higher proportion of organic nitrogen and phosphorus and better self-purification capacity. These findings suggest that the hydrological regime plays a significant role in nutrient dynamics and potential eutrophication risk.

Key words: Comparative analysis, Danube Delta, eutrophication, fresh water lakes, nutrients

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Introduction

Eutrophication, caused by high levels of nutrient concentrations, such as nitrogen and phosphorus in aquatic ecosystems, represents a significant ecological concern with severe consequences. This process results from anthropogenic activities, such as agricultural runoff, urban wastewater discharge and industrial pollution, which add excessive nutrients into water bodies (Schindler 2006). Increasing nutrient levels promote algal blooms, which can reduce oxygen levels through bio-chemical processes, leading to hypoxia or anoxic conditions. Water quality and aquatic life degrade under these changes leading to an unbalanced ecosystem. Additionally, the aesthetic and recreational value of lakes is affected by eutrophication impacts, thus activities such as swimming, fishing and tourism are affected and health risks to people increase through the production of harmful algal toxins.

Carbon, nitrogen and phosphorus represent nutrients that are the fundamental building blocks for all living organisms, as they are involved in all the metabolic processes. These essential elements exist in both organic (proteins, nucleic acids and carbohydrates) and inorganic (nitrates, ammonium, phosphates and carbon dioxide) forms. Carbon is the most important component of organic

molecules, while nitrogen and phosphorus play a crucial role in protein synthesis and energy transfer within cells. These nutrients are critical indicators when it comes to water quality, as their concentrations and ratios directly influence the productivity and ecological balance of aquatic systems (Kenneth 2023).

In the case of the Danube Delta ecosystem, where nutrient inputs are heavily influenced by the Danube River, natural cycling of nutrients is further complicated by these inputs. Significant loads of nutrients are delivered by the river in both organic and inorganic forms, which are then redistributed within the delta through its network of channels and lakes. This process is particularly pronounced in lakes with controlled hydrological regimes, where human intervention via water intake and discharge systems changes the natural flow and retention of nutrients (Burada et al. 2015; Iticescu et al. 2016).

Such interventions can amplify nutrient accumulation, which may trigger eutrophication, alter species composition and reduce water quality. Shifts in nutrient dynamics can disrupt the delicate ecological balance, impacting both primary producers, such as algae and aquatic plants and higher trophic levels, including fish and macroinvertebrates. Mastering these dynamics is critical for developing sustainable management strategies to preserve the ecological integrity of the Danube Delta, while maintaining a balance between human and environmental needs (Bogdan 2008; Burada et al. 2015).

According to Șalaru et al. (2007), enrichment of nutrients in surface water with limited circulation significantly accelerates the eutrophication process. Lakes with restricted water flow are the most vulnerable, as eutrophication develops under these conditions.

Nutrient accumulation is amplified during flood events for the ecosystems that are under the direct influence of the Danube River, as these mobilise contaminants from adjacent terrestrial areas into the watercourse (Burada et al. 2015; Iticescu et al. 2016). Seasonal phenomena such as snowmelt and spring rainfall can also influence the quantitative and qualitative changes. These natural processes transport unabsorbed fertilisers by washing the agricultural lands and transporting them into the water systems, contributing to the nutrient load of the Danube River (Burada et al. 2015) and increasing the risks of eutrophication, ultimately endangering the fragile ecological balance.

This study aims to conduct a comprehensive analysis of nutrient concentrations in two distinct lakes with naturally controlled hydrological regime, located in distinct geographical and ecological areas of the Danube Delta – Lake Parcheș, located in the pre-deltaic area and Lake Fortuna which is a deltaic lake. A better understanding of the interplay between natural processes and anthropogenic influences on nutrient dynamics and water quality can provide critical insights for developing sustainable management strategies to preserve the ecological integrity of the Delta while addressing the challenges posed by nutrient pollution and hydrological alterations.

This research seeks to answer two questions relevant to the management and conservation of deltaic ecosystems:

1. How do nutrient concentrations (e.g. nitrogen, phosphorus and organic carbon) compare between lakes in pre-deltaic regions, which are directly influenced by floodplain processes and those in deltaic regions, characterised by a more complex hydrological network and natural connectivity?

2. What are the primary environmental and anthropogenic factors that drive variations in nutrient concentrations, including water temperature, hydrological inputs (e.g. floods, snowmelt, rainfall) and land-based activities such as agricultural runoff?

A primary effect of the eutrophication process in aquatic ecosystems is the degradation of recreational functions, including increased water turbidity and unpleasant odours, which make the water unappealing for leisure activities. This is often followed by fish mortality and/or proliferation of invasive species (Husaru 2010). At the same time, dissolved oxygen levels in surface waters decline significantly due to oxidation of organic and inorganic substances. Oxygen depletion affects higher life forms, which rely on adequate oxygen level for survival (Shmeis 2018).

The inorganic form of nitrogen includes ammonium, nitrites and nitrates, which are found as dissolved species in water, while total nitrogen represents the sum of inorganic and organic nitrogen (including amino acids, proteins, peptides, urea and nucleic acids). Nitrate is the most stable form amongst these nitrogen species, whereas the presence of ammonium in water, the unstable form, indicates a source of recent pollution. An intermediate form in the nitrogen cycle is nitrite, which is produced through the reduction of nitrates or the oxidation of ammonia by bacteria (Shmeis 2018). Understanding these nitrogen dynamics is essential for assessing nutrient cycling and identifying pollution sources in aquatic ecosystems.

Materials and methods

Study area

This study focuses on two representative lakes located in the region where the Danube River meets the Black Sea: Lake Parcheș, situated in the pre-deltaic zone with a controlled hydrotechnical regime and Lake Fortuna, located in the fluvial-deltaic zone and characterised by a naturally regulated hydrological system (Fig. 1). These lakes were selected due to their distinct geographical and hydrological characteristics, which provide a unique opportunity to analyse nutrient dynamics and ecosystem variability. The study covered the monitoring period from 2019 to 2023, with sampling stations strategically established during the early stages of the fieldwork.

Lake Parcheș is part of the Somova-Parcheș lake complex, a pre-deltaic area in the western section of the Danube Delta Biosphere Reserve (DDBR). This complex covers approximately 9,000 hectares, with around 2,000 hectares consisting of waterbodies, including interconnected lakes and channels. The northern boundary of the complex is defined by the Danube River and the western section of the Tulcea branch, while the southern and western edges are bordered by the Northern Dobrogea Plateau. To the east lies the city of Tulcea, which exerts a significant urban influence on the area's ecological dynamics (Török 2006). The hydrological regime of Lake Parcheș is regulated by the Danube, with fixed intake and discharge structures ensuring regular, largely one-way renewal. Nevertheless, water levels vary with the Danube's hydrographical characteristics, making the lake a model system for studying anthropogenic and natural interactions in pre-deltaic ecosystems.

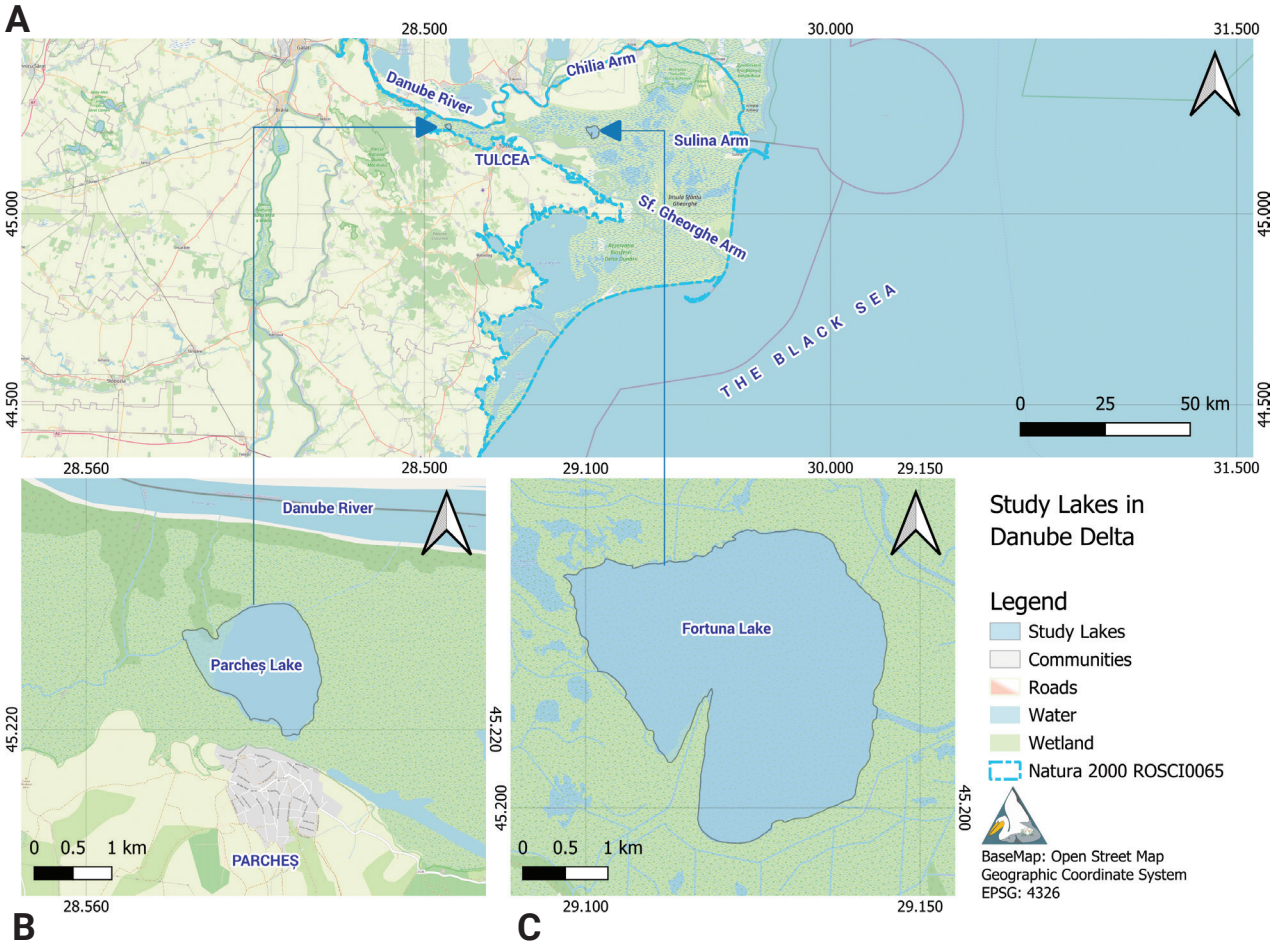

Figure 1. Study area: **A.** The Danube Delta; **B.** Parcheș Lake; **C.** Fortuna Lake.

Lake Fortuna, part of the Șontea-Fortuna complex, is located in the fluvial-deltaic zone of the Danube Delta. It is bordered to the south by the Sulina branch and to the east by the Great M Channel, with the Șontea Channel flowing through the lake as its primary hydrological artery. Fortuna Lake covers an area of approximately 900 hectares and lies at an elevation between 0 and -0.5 metres relative to sea level. Its strong connectivity to both the Sulina branch and the Șontea Channel through smaller channels which facilitate dynamic water exchange, making it an ideal site for studying nutrient transport and ecological interactions in deltaic ecosystems (Gâștescu 1971).

The study area experiences a temperate-continental transitional climate, typical of Central Europe, with significant influences from the Black Sea. This exerts a Pontic influence, shaping a distinctive climatic pattern. Precipitation levels decrease progressively from west to east, influenced by the proximity of the Black Sea and the surrounding terrain. These climatic conditions affect hydrological processes, nutrient cycling and overall ecosystem dynamics, adding complexity to the interactions observed in these lakes (Bogdan 2008).

Sampling methods

Water samples were collected using standardised methods in accordance with SR ISO 5667-4/2020 – Water quality – Sampling – Part 4: Guidance on sampling from lakes, natural and man-made (ASRO – Romanian Standards Association

2020). In the case of the two lakes, detailed analyses were carried out on their central, representative points during three seasonal campaigns (spring, summer and autumn) for the period 2019–2023. At each campaign, one water sample and in-situ measurements were taken at each site, resulting in three samples per year for each site and a total of 15 samples for each lake over the monitoring period. This approach was chosen to capture the most relevant hydrological and ecological dynamics, as winter is characterised by ice cover and limited accessibility, while nutrient and ecological processes are less active. Annual averages of the three seasonal measurements and calculated parameters were then determined to provide a reliable assessment of water quality trends.

In addition to chemical and nutrient assessments, supplementary measurements were performed to improve understanding of the lake's physical characteristics. These included evaluating water depth and transparency, using a Secchi disc, which is critical for assessing light penetration, primary productivity and overall ecosystem health.

Field measurements of physical and chemical parameters were conducted at each sampling point using a high-precision multiparameter device, YSI EXO2, equipped with sensors for temperature, pH, algal biomass, dissolved oxygen and conductivity.

Laboratory analyses

Molecular absorption spectrophotometry, one of the earliest and most widely used methods in physical and chemical laboratory analysis, was employed to determine the concentrations of $N\text{-}NH_4$, $N\text{-}NO_2$, $N\text{-}NO_3$, NT, $P\text{-}PO_4$ and PT. Based on the collected data, concentrations of the organic forms of phosphorus and nitrogen were calculated as the difference between the measured total forms (TP, TN) and the total inorganic forms (TIP, TIN).

The selected nutrients were transformed via wet-chemical treatment into coloured compounds with high molar absorptivity, allowing very low detection and quantification limits. These samples were subsequently analysed using a UV-VIS PerkinElmer Lambda 650 S spectrophotometer, capable of measuring wavelengths between 190 and 900 nm.

Results and discussion

Analysis of the collected data reveals significant interannual variability in the depth and transparency of Parcheș and Fortuna Lakes, reflecting the influence of hydrological and ecological dynamics specific to these systems.

Figs 2, 3 present the results of depth and transparency measurements, physical parameters that indirectly reflect chemical dynamics by influencing light penetration, primary productivity and associated nutrient and oxygen processes in Parcheș and Fortuna Lakes. These combined datasets provide a holistic overview of the ecological conditions of the lakes, supporting the evaluation of nutrient dynamics and water quality trends over the monitoring period.

The maximum recorded depth in Lake Parcheș was 186 cm in 2023, likely indicating an increased water inflow or favourable hydrological conditions. In contrast, the minimum depth of 60 cm in 2022 suggests reduced hydrological inputs or drier climatic conditions during that year.

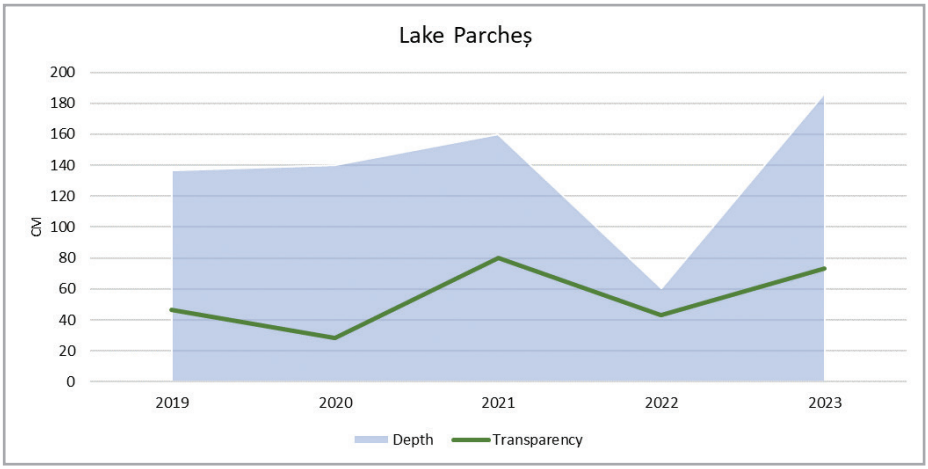

Figure 2. The average annual depth and transparency of Lake Parcheș.

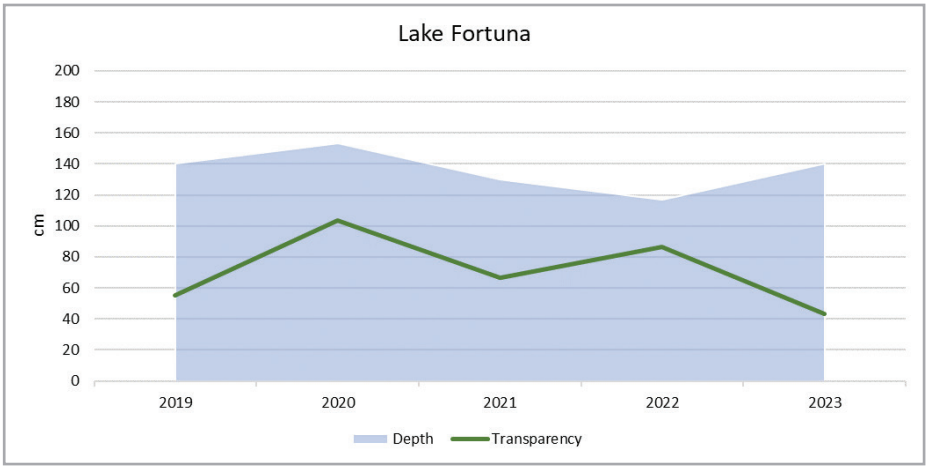

Figure 3. The average annual depth and transparency of Lake Fortuna.

In 2021 and 2022, transparency levels exceeded 50%, suggesting reduced turbidity and improved water clarity, likely due to lower sediment inputs or stabilised nutrient levels. Between 2019 and 2021, transparency was lower, ranging from 20% to 43%, indicating higher turbidity potentially driven by algal blooms, suspended particles or inflows rich in organic matter.

The average depth in Lake Fortuna ranged from a minimum of 116 cm in 2022 to a maximum of 153 cm in 2020, reflecting variations driven by hydrological connectivity, particularly exchanges with the Sulina branch and Șontea Channel.

In 2019, 2021 and 2023, transparency values ranged between 30% and 51%, indicating moderate clarity, likely influenced by sediment re-suspension or increased algal activity. In 2020 and 2022, transparency improved significantly, reaching 67% to 74%, probably due to reduced nutrient input, favourable hydrological conditions or efficient water exchange that enhanced sediment settling.

The depth and transparency variations observed in both lakes underscore the dynamic interplay between hydrological processes, climatic factors and anthropogenic influences. Parcheș exhibited more pronounced fluctuations in transparency, suggesting greater susceptibility to external inputs, whereas

Fortuna maintained higher transparency during certain years, reflecting its hydrological connectivity and stabilising influences. These findings highlight the importance of long-term, systematic monitoring for understanding and managing nutrient dynamics, water quality and ecological health within the Danube Delta's aquatic ecosystems.

Fig. 4 presents the annual average concentrations of dissolved oxygen for the two lakes showing that all recorded values exceed the minimum threshold of 7 mg/l, corresponding to the second Class of quality standards.

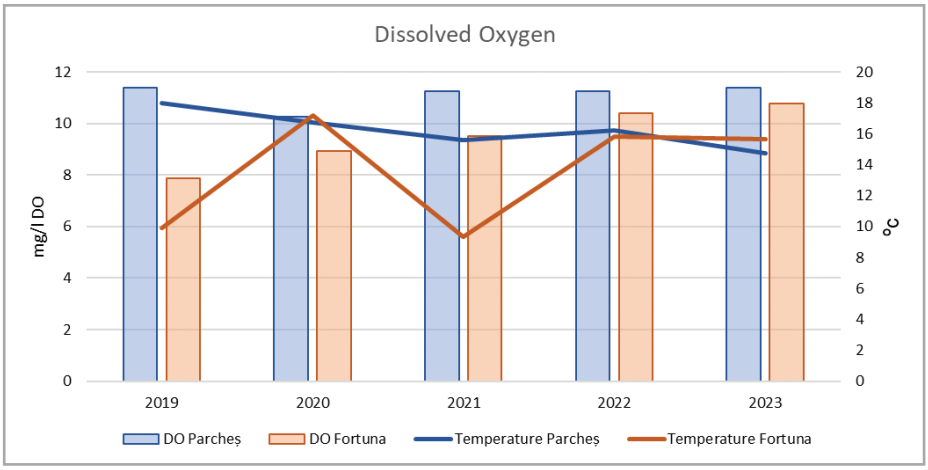

Figure 4. Annual average values of dissolved oxygen concentration and temperature.

For Lake Parcheș, the annual average dissolved oxygen levels ranged from a minimum of 10.27 mg/l in 2020 to a maximum of 11.41 mg/l for 2019, indicating stable and favourable oxygenation conditions throughout the monitoring period.

In Lake Fortuna, the annual average dissolved oxygen levels were slightly lower, ranging from a minimum of 7.86 mg/l in 2019 to a maximum of 10.76 mg/l in 2023. These variations reflect the natural hydrological connectivity and ecosystem dynamics specific of the deltaic region.

Oxygen saturation in water bodies is influenced by re-aeration, atmospheric pressure, chemical and biological oxygen demand and, also, oxygen concentration decreases as salinity increases (Husaru 2010).

In addition to dissolved oxygen, water temperature can be a decisive factor in the oxidation processes of nitrogen forms (Weon et al. 2004).

The lowest annual average temperatures for both lakes were recorded in 2023, at 14.7 °C for Parcheș and, in 2021, 9.3 °C for Fortuna, while the highest annual averages were observed in 2019 for Parcheș (18 °C) and, in 2020, for Fortuna (17.6 °C). These variations likely reflect the climatic influences and hydrological conditions during the monitoring period.

The data underscore stable dissolved oxygen levels in both lakes, maintaining ecological quality standards, while temperature variations highlight distinct climatic and hydrological influences. Lake Parcheș demonstrates consistent conditions typical of a managed hydrological system, whereas Lake Fortuna showcases the natural variability characteristic of its deltaic environment. These findings provide a valuable basis for understanding the ecological dynamics and water quality of these aquatic systems.

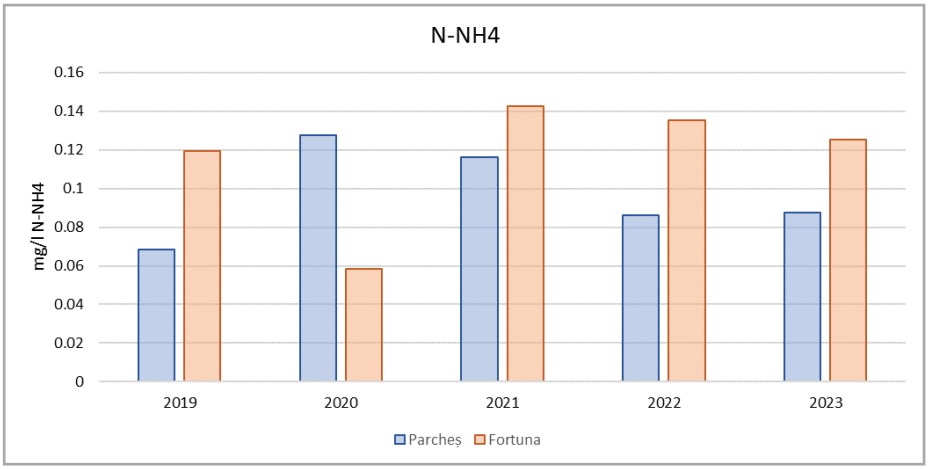

Figure 5. Annual average values of ammoniacal nitrogen concentration.

Amongst the eutrophication indicators, ammoniacal nitrogen in Lake Parcheș showed a declining trend over the monitoring period (Fig. 5) suggesting reduced nutrient inputs or improved nitrogen cycling within the system.

In contrast, Lake Fortuna exhibited fluctuating values for ammoniacal nitrogen, ranging from a minimum of 0.058 mg/l recorded in 2020 to a maximum of 0.14 mg/l in 2021. These oscillations may reflect varying external inputs, such as seasonal nutrient influxes or differences in hydrological connectivity and water exchange within the deltaic environment.

These patterns highlight the contrasting nutrient dynamics between the managed hydrological regime of Lake Parcheș and the more naturally variable conditions of Lake Fortuna.

Despite interannual depth fluctuations, Parcheș is situated in the pre-deltaic Somova-Parcheș complex and is fed more directly by the Danube main stream, which generally supplies more diluted water and lower external nutrient loads. By contrast, Fortuna lies within the deltaic network and is supplied through sinuous channels that accumulate and re-mobilise nutrient-rich suspended matter and fine sediments. The external influence on Parcheș appears to be lower than in the case of Fortuna, with the exception of the 2020 annual average.

When assessed against the Class I water quality threshold of 0.4 mg/l for ammoniacal nitrogen, as established by Order 161/2006 in Annex 2, it is evident that concentrations in Parcheș remained well below this limit throughout the monitoring period. This indicates a very good status for this specific parameter, but does not, on its own, imply that the overall ecological status of the Lake is Class I, as such classification requires the assessment of multiple physical, chemical and biological indicators. Over the last four years, ammoniacal nitrogen levels in Lake Parcheș declined from 2020 to 2022 and then remained relatively stable through 2023.

The consistency of ammoniacal nitrogen concentrations, even in the context of varying hydrological conditions, suggests that Parcheș Lake's ecosystem may have self-regulating mechanisms, such as efficient nitrogen uptake by aquatic vegetation, microbial nitrification-denitrification processes and sediment nutrient buffering, which together reduce the sensitivity of water column concentrations to changes in depth. This highlights the importance of sustained monitoring to ensure that nutrient dynamics remain within acceptable

limits, safeguarding the Lake's ecological health and compliance with water quality standards.

The primary (nitrites) and final (nitrates) forms of organic nitrogen oxidation in surface waters showed significantly lower annual average concentrations in Parcheș Lake compared to Fortuna Lake (Figs 6, 7). These findings reflect distinct nitrogen cycling processes in the two ecosystems, influenced by their hydrological regimes, connectivity and external nutrient inputs.

In Parcheș Lake, the controlled hydrological regime likely limits the influx of nitrogen compounds and promotes more stable conditions for nitrogen transformation. As a result, the concentrations of nitrites and nitrates remain lower, indicating reduced external loading or efficient internal cycling processes. This may also suggest limited organic matter decomposition and a lower degree of eutrophication risk compared to Fortuna Lake.

In contrast, Fortuna Lake, characterised by its natural hydrological connectivity and dynamic water exchange with surrounding channels, exhibits higher concentrations of nitrites and nitrates. This could be attributed to greater nutrient influxes from surrounding areas, including agricultural runoff or organic matter transported during periods of increased hydrological activity. The higher levels of these nitrogen forms may also reflect more active decomposition and

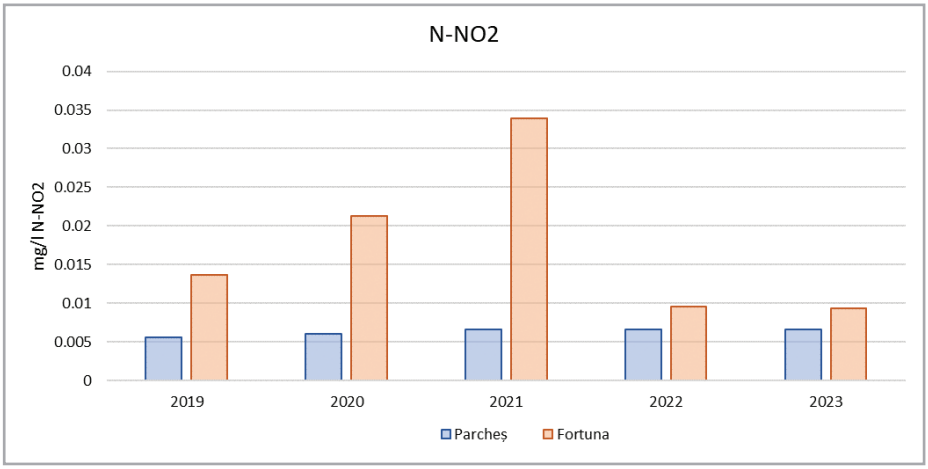

Figure 6. Annual average values of nitrite concentrations.

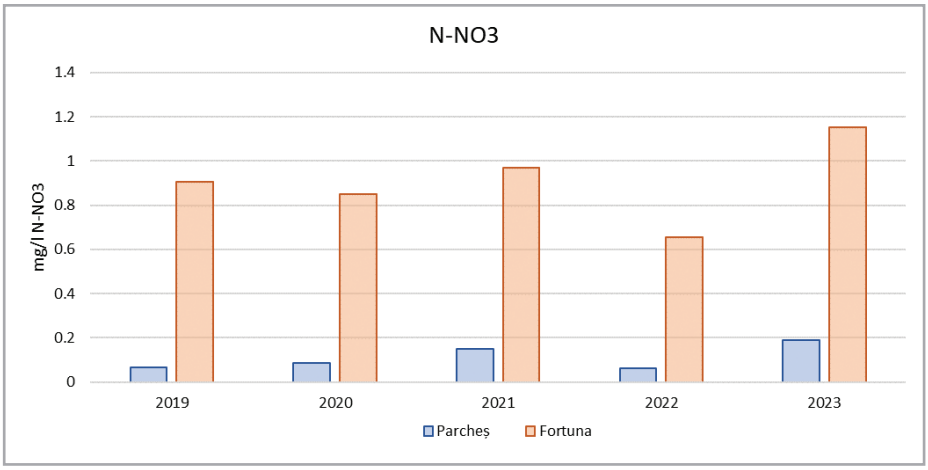

Figure 7. Annual average values of nitrate concentrations.

nitrification processes within the Lake, potentially influenced by its deltaic setting. Furthermore, the biodiversity differences between the two lakes could play a role, as large populations of colonial water-birds are known to contribute significant nutrient inputs through guano deposition, a phenomenon documented in similar ecosystems (e.g. Verstijnen et al. (2021)).

These differences underscore the importance of understanding local hydrological and ecological factors when assessing nitrogen dynamics in aquatic ecosystems. They also highlight the need for targeted management strategies to address nutrient loading and ensure the ecological health of these distinct lake systems within the Danube Delta Biosphere Reserve.

In the case of Lake Parcheș, the direct input of fresh water from the Danube River is reflected in the relatively low concentrations observed during the sampling campaigns, as also reported in the study conducted in 2017 by Catianis et al. (2019). This suggests a dilution effect caused by the direct inflow of river water. In contrast, Fortuna Lake, which is fed through a network of sinuous channels, receives water carrying accumulated nutrient loads along its deltaic path before discharging into the lake. This process results in higher concentrations of nitrates and nitrites in Lake Fortuna, highlighting the influence of its hydrological connectivity and nutrient transport dynamics.

While it is less abundant in nature compared to nitrogen, phosphorus is crucial for the growth and development of living organisms. In its absence, biological productivity is constrained, making it a key limiting nutrient. However, excessive phosphorus levels, often related to anthropogenic sources such as agricultural runoff and wastewater treatment plants, can stimulate algal blooms, disrupt aquatic ecosystems and accelerate the eutrophication of water bodies (Kenneth 2003).

The stable form of organic phosphorus, phosphates, generally complied to Class I water quality standards according to Order 161/2006, with the exception of the year 2019 (Fig. 8). In that year, both Parcheș and Fortuna Lakes recorded higher phosphorus from orthophosphate concentrations – 0.048 mg/l for Parcheș and 0.047 mg/l for Fortuna – which deviated from the trend observed in other years. Despite this anomaly, the phosphate concentrations in both lakes generally remained within the acceptable limits of the first class of quality, indicating a very good ecological status.

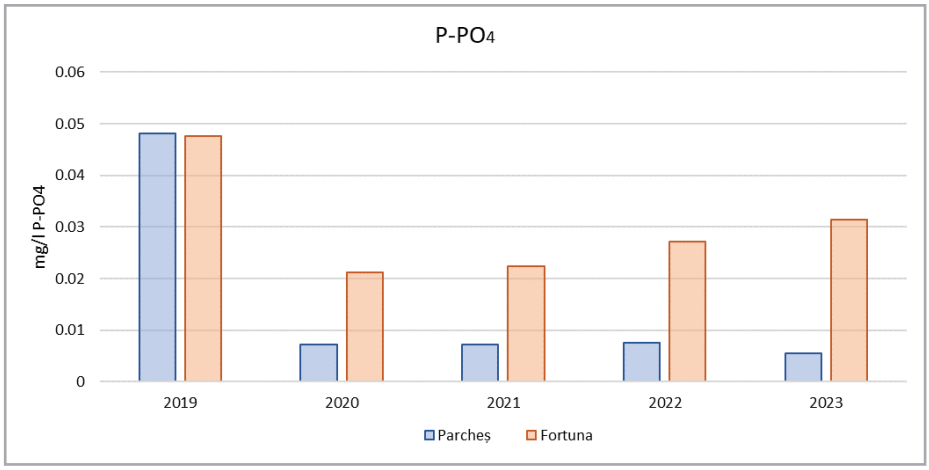

Figure 8. Annual average values of phosphate concentrations.

For Lake Parcheș, located in the pre-deltaic zone, the data show a slight decreasing trend in phosphate concentrations over the monitoring period. This could be attributed to factors such as improved nutrient cycling, reduced external nutrient inflows or natural variations in hydrological conditions. The decrease in phosphate levels for Lake Parcheș suggests that the Danube-controlled hydrological regime may be effectively limiting nutrient accumulation, thereby helping to maintain good water quality over time.

On the other hand, Lake Fortuna, located in the fluvial deltaic zone, exhibits a sharp decrease in 2020 followed by a gradual increase until 2023. These changes may be linked to variations in water inflow from the Sulina branch, which influence both dilution capacity and the transport of nutrient-rich suspended matter. The 2020 drop could reflect a period of higher water exchange and flushing efficiency, reducing phosphate accumulation, while the gradual increase until 2023 may be associated with reduced hydrological connectivity during certain periods, allowing greater retention of phosphorus from upstream channels. Despite this gradual increase, phosphate levels in Fortuna Lake still remain within the Class I water quality range for this parameter, reflecting the Lake's ability to maintain good ecological health, with some nutrient accumulation.

These differing trends between the two lakes highlight the influence of their distinct hydrological conditions, nutrient dynamics and geographical position. Lake Parcheș, with its controlled hydrological regime, shows stabilisation or reduction in phosphate levels, while Lake Fortuna, with its natural deltaic connectivity, experiences a gradual increase in nutrients. However, both Lakes continue to meet the standards for very good ecological status, underscoring the importance of maintaining balanced nutrient inputs to preserve water quality in aquatic ecosystems.

In the case of total nitrogen, the two lakes exhibited differences ranging from 2.77 mg/l in 2019 to 4.95 mg/l in 2022, with both extremes recorded in Lake Parcheș. The annual average concentrations were higher in Fortuna Lake, except for the years 2021 and 2022, when the annual average values for Lake Fortuna were lower by 0.26 mg/l and 0.15 mg/l, as shown in Fig. 9. These differences show lower concentrations in 2019, 2020 and 2023 and higher in 2021 and 2022 for Parcheș, where water supply and discharge are directly controlled by the Danube River, in contrast to Fortuna, where the water intake and discharge process occurs through more sinuous channels with a lower water flow. For total phosphorus (Fig. 10), both Lakes exhibited oscillating values, with the exception of 2022 for both Lakes. In the case of Lake Parcheș, the concentrations ranged from a maximum of 0.160 mg/l in 2020 to a minimum of 0.044 mg/l in 2023. Lake Fortuna showed values ranging from 0.044 mg/l in 2023 to a maximum of 0.091 mg/l in 2019.

These trends highlight the different nutrient dynamics in the two Lakes, influenced by their respective hydrological regimes. The higher total nitrogen and total phosphorus concentrations in Lake Parcheș can be attributed nitrogen and phosphorus natural cycles, due to its higher water retention time, while Lake Fortuna, with its natural deltaic connectivity and more complex water pathways, exhibits lower concentrations overall. Nonetheless, both Lakes show evidence of nutrient fluctuations, suggesting the influence of seasonal, climatic, biological and hydrological factors on nutrient cycling within these ecosystems.

The N:P ratio for the total forms of nitrogen and phosphorus in Parcheș ranges between 18 and 79, exhibiting an oscillating trend. In contrast, Fortuna is

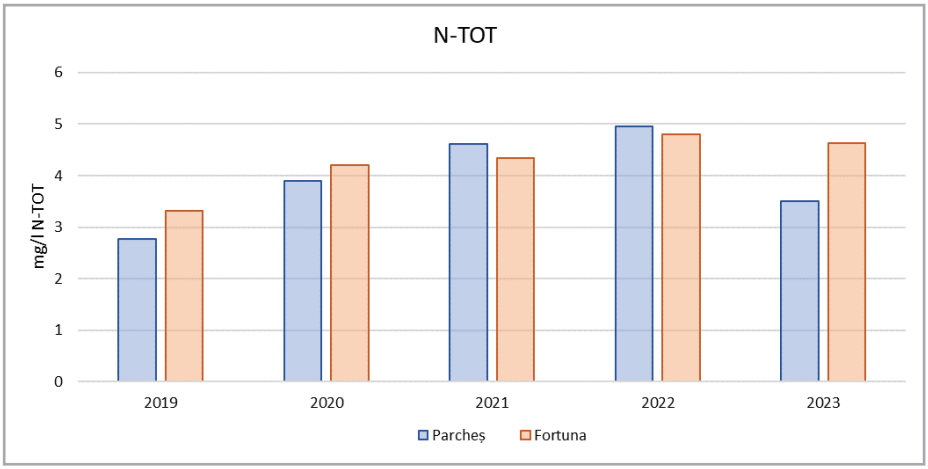

Figure 9. Annual average values of total nitrogen concentrations.

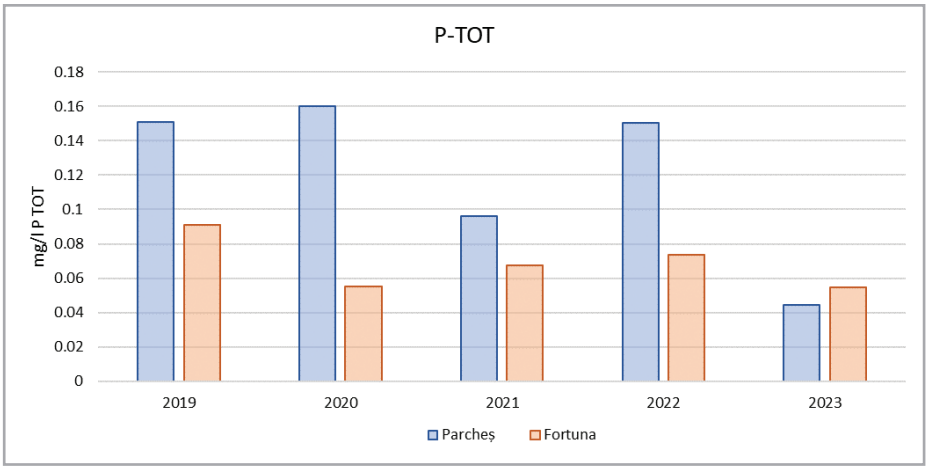

Figure 10. Annual average values of total phosphorus concentrations.

characterised by a ratio between 36 and 84, showing a similar oscillating trend. These variations in the N:P ratio between the two Lakes reflect different nutrient dynamics, with Lake Parcheș showing a generally lower nitrogen-to-phosphorus ratio compared to Lake Fortuna. The oscillating trends in both Lakes suggest seasonal or hydrological factors influencing nutrient availability and cycling, potentially related to water inflows, temperature variations or external nutrient inputs.

In Figs 11, 12, the graphs representing the organic forms of nitrogen and phosphorus are shown. Compared to the total forms of these elements, it is evident that, in Parcheș, the percentage of organic nitrogen relative to the total nitrogen averaged approximately 97% during the years 2019–2022, decreasing to 73% in 2023. In Fortuna, this percentage hovers around 75%, with a deviation of 10 percentage points for the years 2022 (85%), falling to 65% in 2023.

These variations indicate that nutrient dynamics in both Lakes change over time, with Lake Parcheș showing a consistently high proportion of organic nitrogen relative to total nitrogen, suggesting a relative stable nitrogen cycle. In contrast, Lake Fortuna displays greater variability, possibly due to changes in nutrient inputs or internal processes influencing organic nitrogen levels.

In the case of phosphorus, the organic fraction represents on average 87% of the total form in the pre-deltaic lake compared to about 56% for the fluvial zone

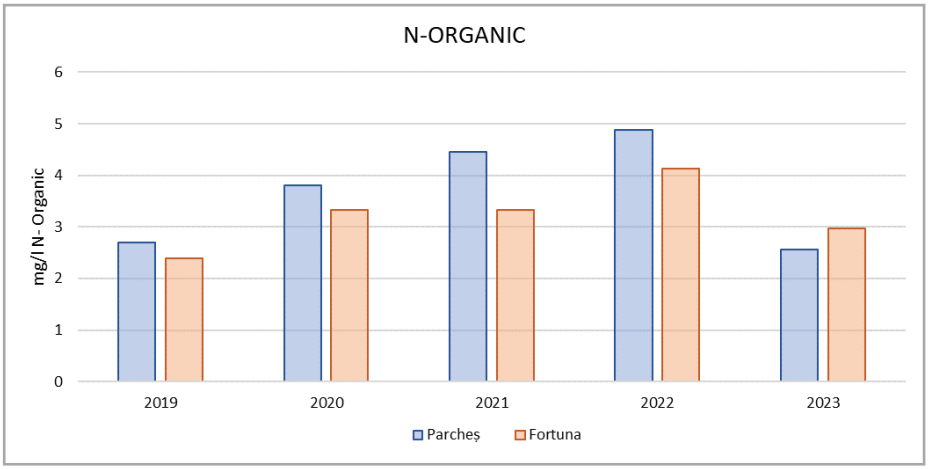

Figure 11. Annual average values of organic nitrogen concentrations.

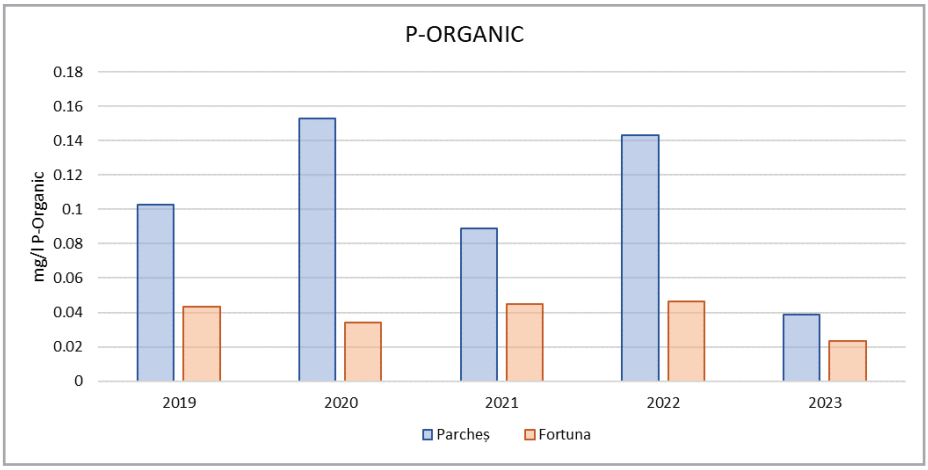

Figure 12. Annual average values of organic phosphorus concentrations.

of the Delta. In both Lakes, there is a variation of 10 percentage points over the analysed five-year period.

This significant difference suggests that Lake Parcheș, located in the pre-deltaic zone, has a much higher proportion of organic phosphorus relative to total phosphorus, likely indicating a more stable phosphorus cycle dominated by organic forms and possibly lower external nutrient inputs. On the other hand, Lake Fortuna, located in the fluvial zone of the Danube Delta, exhibits a more dynamic phosphorus cycling, with a lower and more variable proportion of organic phosphorus, possibly influenced by higher sediment re-suspension, nutrient inputs from surrounding channels or increased anthropogenic pressures.

Conclusions

The comparative analysis of nutrient concentrations in Parcheș and Fortuna Lakes highlighted that, in the deltaic zone, the concentrations of intermediate nitrogen forms are higher, likely driven by inflows from the sinuous channels of the Danube Delta. In contrast, the pre-deltaic lake (Parcheș) showed lower values for nitrates and nitrites.

Lake Fortuna, located in the deltaic area, is more susceptible to nutrient accumulation due to the complex network of channels and the relatively lower fresh water inflow. The observed nutrient accumulation in this Lake may be linked to hydrological connectivity, which likely facilitates the transfer of nutrient-rich waters from surrounding areas. On the other hand, Lake Parcheș shows a higher self-purification capacity, as indicated by higher dissolved oxygen concentrations and a greater proportion of organic forms of nitrogen and phosphorus, indicating greater resilience to nutrient loading and eutrophication.

Both Lakes fall under Class II water quality, according to Order 161/2006, indicating a good ecological status, with one exception observed in Lake Fortuna for $N\text{-}NO_2$ in 2021, which was classified as Class III for water quality. The elevated nutrient concentrations in Fortuna indicate an increased risk of eutrophication in this area. To maintain water quality in both Lakes, continuous monitoring and careful management of nutrient inputs are essential, particularly during flood events and snowmelt periods, when nutrient loading peaks. This highlights the importance of managing the nutrient balance to prevent ecosystem degradation and preserve the ecological health of these important water bodies.

The comparative assessment highlighted that nutrients differ substantially between pre-deltaic and deltaic lakes. Lake Fortuna, located in the deltaic zone, showed consistently higher levels of inorganic nitrogen, a pattern driven by its strong hydrological connectivity and external nutrient inputs. In contrast, Lake Parcheș, situated in the pre-deltaic area, was characterised by higher organic forms and oxygen levels, reflecting greater self-purification capacity and resilience against eutrophication.

Variations in nutrient concentrations, as reflected in the annual averages, were primarily driven by hydrological and climatic factors such as floods, snowmelt and rainfall, which influenced the magnitude and timing of nutrient inputs. These natural drivers were complemented by anthropogenic pressures, from agricultural and urban influences, whose effects were more pronounced in the deltaic setting of Lake Fortuna.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

Petre Bogdan Gheorghe, study design and data collection, wrote the manuscript with the support of Cristina Despina, Mihaela Țigănuș, Daniela Seceleanu-Odor, Iasemin Suliman, Orhan Ibraim and Nicoleta Matei. Adrian Burada supervised the article. All co-authors reviewed and edited the manuscript draft.

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Data availability

The data supporting the findings of this study are available upon reasonable request from the corresponding author. The dataset includes measurements collected during the research period and is stored in a secure repository. Due to confidentiality agreements and data protection regulations, certain restrictions may apply to the accessibility of the full dataset. Where applicable, a subset of anonymised data may be shared for academic and research purposes.

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