



SPATIOTEMPORAL WATER QUALITY DYNAMICS IN A TROPICAL AGRICULTURAL RESERVOIR DRIVEN BY CATCHMENT RUNOFF AND INTERNAL PROCESSES

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ABSTRACT

Sustainable reservoir management requires seasonally targeted mitigation measures to control sediment and nutrient inputs. However, such efforts are often constrained by limited understanding of how seasonal runoff pulses interact with internal mixing processes to shape water quality dynamics. This study investigates the spatiotemporal variability of water quality in Cileunca Reservoir, a tropical agricultural reservoir in West Java, Indonesia, with a focus on the coupling between catchment runoff and in-reservoir processes. Field observations during the wet and dry seasons (2023–2024) included vertical profiling, spatial transect sampling, and laboratory analyses. Multivariate statistical techniques, including Principal Component Analysis and Cluster Analysis, combined with spatial interpolation, were applied to characterise variability in key parameters. The results revealed pronounced seasonal contrasts and marked spatial heterogeneity. During the wet season, Total Suspended Solids (TSS) increased by up to 21-fold relative to the dry season, while the relationship between TSS and turbidity depended on seasonal changes in particle size distribution and composition. Total Nitrogen (TN) and Total Phosphorus (TP) increased by 125% and 100%, respectively, particularly near inflow zones, indicating strong catchment-driven inputs. In the dry season, reduced surface turbidity but persistent bottom oxygen depletion indicated active internal nutrient recycling. The reservoir remained consistently eutrophic, with mean Trophic State Index values of 57.8 (wet) and 60.4 (dry). These findings demonstrate that interactions between external loading and internal processes sustain water quality variability. Improved understanding of these dynamics is essential for designing effective seasonal mitigation strategies to support sustainable reservoir management.

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Introduction

Hilly agricultural landscapes dominate many tropical upland regions and exert strong influences on freshwater ecosystems. In such environments, steep slopes, intensive cultivation, and seasonal rainfall enhance overland flow and soil erosion, resulting in substantial transport of suspended sediments, particulate organic matter,

and associated nutrients into downstream water bodies (Zhang *et al.*, 2015). These catchment-derived inputs play a critical role in shaping reservoir water quality by increasing turbidity, reducing light penetration, altering thermal structure, and stimulating internal biogeochemical processes, ultimately affecting

ecosystem functioning and water-use services such as hydropower, irrigation, and recreation (Donohue & Garcia Molinos, 2009).

Tropical reservoirs located in steep agricultural catchments are further characterised by strong hydrological variability driven by monsoonal rainfall. Wet-season inflows typically introduce large pulses of sediments and nutrients, whereas dry-season conditions are associated with reduced inflow and increased water residence time, which can facilitate internal biogeochemical transformations (Wiranegara *et al.*, 2023; Bieroza *et al.*, 2024). These dynamics generate both vertical gradients (e.g., temperature, dissolved oxygen, and nutrients) and horizontal heterogeneity along inflow–outflow and littoral–pelagic axes, creating pronounced spatiotemporal variability in water quality.

Despite increasing attention to sediment and nutrient dynamics in tropical reservoirs, important knowledge gaps remain. In particular, the extent to which seasonal runoff pulses interact with internal mixing processes to control both vertical stratification and horizontal heterogeneity is still poorly constrained. This limitation is exacerbated by monitoring approaches that rely on single-depth or spatially limited sampling, which are insufficient to capture the coupled vertical–horizontal variability typical of slope-dominated systems (Borovská *et al.*, 2022; Wang *et al.*, 2022). As a result, our ability to understand how external loading and internal processes jointly regulate water quality dynamics remains limited.

This knowledge gap has direct implications for reservoir management. Sustainable management requires seasonally targeted mitigation measures to control sediment and nutrient inputs; however, the lack of process-based understanding constrains the development of effective strategies. Without resolving how runoff-driven inputs and internal processes interact across seasons, management interventions—such as sediment control, nutrient reduction, and operational adjustments—cannot be optimally designed or timed.

The Cileunca reservoir (locally known as Situ Cileunca), located in the upper Citarum watershed, West Java, Indonesia, provides a representative example of a tropical agricultural reservoir influenced by steep catchment topography and intensive land use (Nahib *et al.*, 2024). The reservoir is situated at high elevation (approximately 1,420–2,091 m above sea level) and is primarily operated for hydropower generation, with water levels regulated through controlled inflow and outflow. These characteristics create a dynamic system in which hydrological inputs, operational controls, and internal processes interact to shape water quality. Given its exposure to strong seasonal runoff and regulated hydrology, Cileunca Reservoir offers an ideal setting to investigate the coupling between external loading and in-reservoir processes.

This study addresses these gaps by examining the spatiotemporal variability of water quality through integrated vertical and horizontal observations across wet and dry seasons. Physical parameters (e.g., temperature, conductivity, turbidity, and particulate matter), chemical variables (dissolved oxygen and nutrient concentrations), and biological indicator (chlorophyll-a) were analysed to link catchment-derived inputs with in-reservoir processes. Specifically, this study aims to: (1) Characterise seasonal patterns of vertical gradients and mixing behaviour; (2) quantify horizontal variability in suspended solids, nutrients, and dissolved oxygen; and (3) evaluate how external loading and internal processes interact to control trophic status and water quality dynamics.

We hypothesise that (i) wet-season inflows enhance lateral heterogeneity and surface nutrient enrichment, particularly near inflow zones, while (ii) dry-season conditions promote vertical gradients and hypolimnetic oxygen depletion due to reduced mixing. By integrating spatial and temporal perspectives, this study provides new insights into how catchment forcing and in-reservoir processes interact to shape water quality in tropical agricultural reservoirs, supporting the development of more

effective and seasonally adaptive management strategies.

Materials and Methods

Study Area

The Cileunca Reservoir lies within the Pangalengan Subdistrict of Bandung Regency, West Java, situated roughly 45 kilometres to the south of Bandung City. In geographical terms, the reservoir is positioned at coordinates 107°33'04" E and 7°11'31" S. Cileunca Reservoir forms a series of waterbodies or a cascade system with the Cipanunjang Reservoir, where Cileunca is situated downstream and receives outflow from Cipanunjang. Both reservoirs primarily function as part of a hydropower system. The area experiences a humid tropical climate, characterised by yearly temperatures varying from 16°C to 25°C and an average precipitation total of about 1,996 mm per year, equivalent to 5.47 mm per day (Malik *et al.*, 2019).

Based on daily rainfall data from 2017 to 2019, the wet season occurs from January to April, with the peak average monthly rainfall generally in March. The dry season occurs between June and September, with monthly rainfall declining to near-zero levels close to zero (Figure 1). Moreover, the Cileunca Reservoir functions as a multipurpose water body, supporting activities such as hydroelectric power production, agricultural irrigation, municipal water distribution (PDAM), and recreational tourism.

From a geomorphological perspective, the Cileunca Reservoir lies within a hilly drainage basin covering approximately 2,091 hectares, with terrain elevations varying between 1,420 metres and 2,070 metres above mean sea level. The reservoir is encompassed by diverse land uses, including pine forest ecosystems, tea plantations, intensive vegetable cultivation areas, and residential settlements. Agricultural land constitutes 56.1% of the catchment area (Figure 1), indicating the predominance of farming activities within the catchment area. The surface area is approximately 1,400 hectares.

The elongated shape follows the contours of the river valley, producing a sinuous shoreline. Several small bays located in the central part of the reservoir contribute to habitat diversity. Water depth typically ranges between 6 m and 10 m, with the deepest point reaching ~between 17 m and 18 m, and the effective storage volume is estimated at ~10.66 million m³ (Tjahjo & Purnamaningtyas, 2017). The shoreline is generally shallow, forming a wide littoral zone that supports the growth of aquatic vegetation. The Cileunca Reservoir exhibits an average annual outflow rate of approximately 5.5 m³ s⁻¹ and a typical hydraulic residence time of about 22 days.

Data Acquisition and Analytical Procedures

Water samples were collected from five designated locations that characterise distinct hydrological zones within the reservoir. While the number of sampling sites is limited relative to the reservoir area, this design prioritises representation of the main functional zones (inlets, outlet, and transitional zone) that control dominant horizontal gradients driven by inflow–outflow processes. Therefore, the horizontal dynamics described in this study should be interpreted as first-order, zone-based patterns rather than fine-scale spatial heterogeneity. The inlet zone was represented by Cibunihayu and Cipanunjang, the transitional zone by Cangkring, and the outlet zone by Palayangan, which drains into the river, and Pulosari, which supplies water to the hydroelectric power plant. Geographic positions for all sampling locations were determined using a Garmin GPS device with UTM Zone 48S coordinate system, which is set in relation to the WGS 84 system. The obtained coordinates were then visualised through Geographic Information System (GIS) mapping software (Figure 2).

Physicochemical parameters were assessed through *in situ* measurements and laboratory analyses conducted during 2023–2024, representing both the wet (April 2023, October 2023, April 2024, and December 2024) and dry (August 2023, September 2023, May 2024,

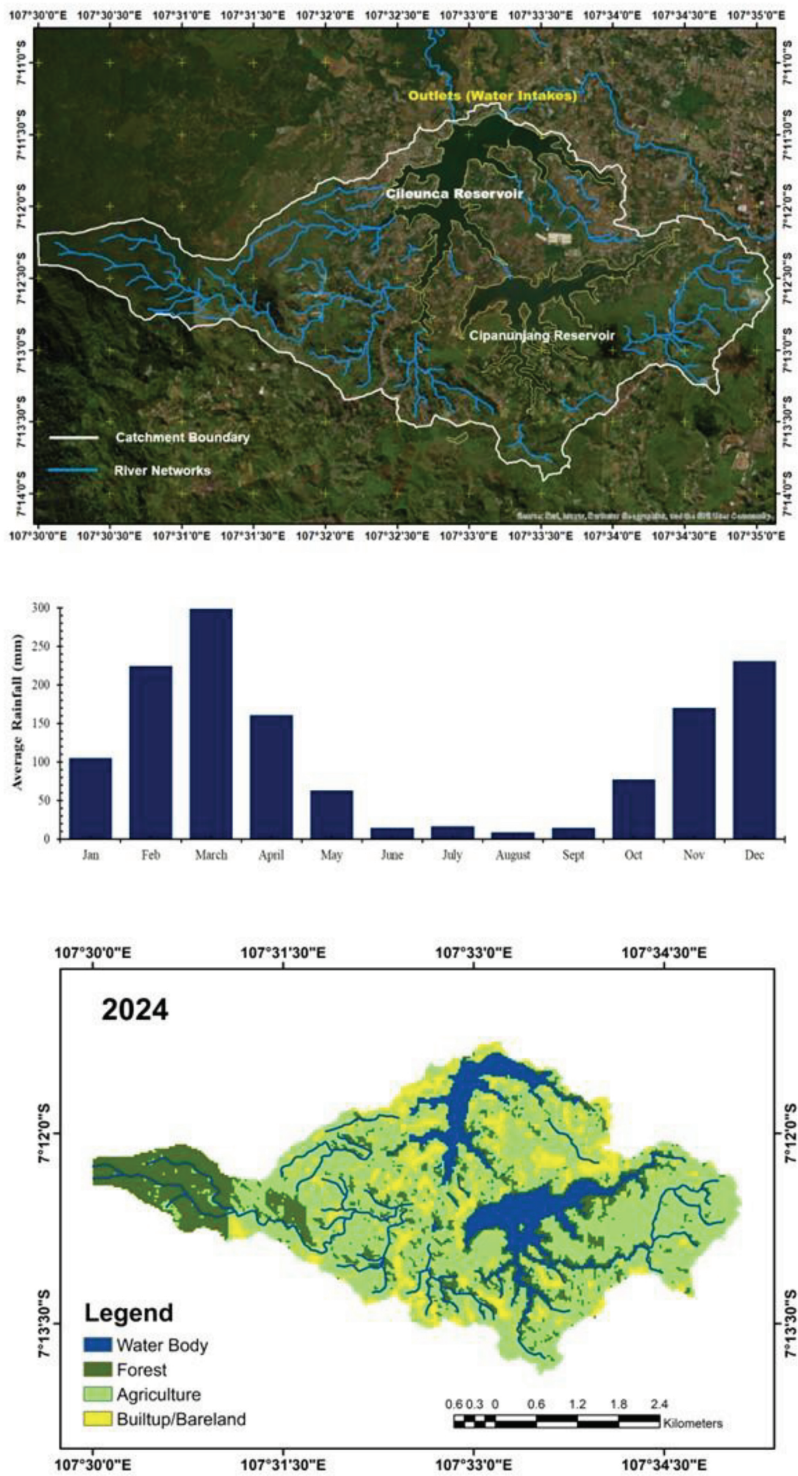


Figure 1: Catchment area of the cileunca–cipanunjang reservoirs (top panel), average monthly rainfall distribution (middle panel), and land use within the catchment (bottom panel)

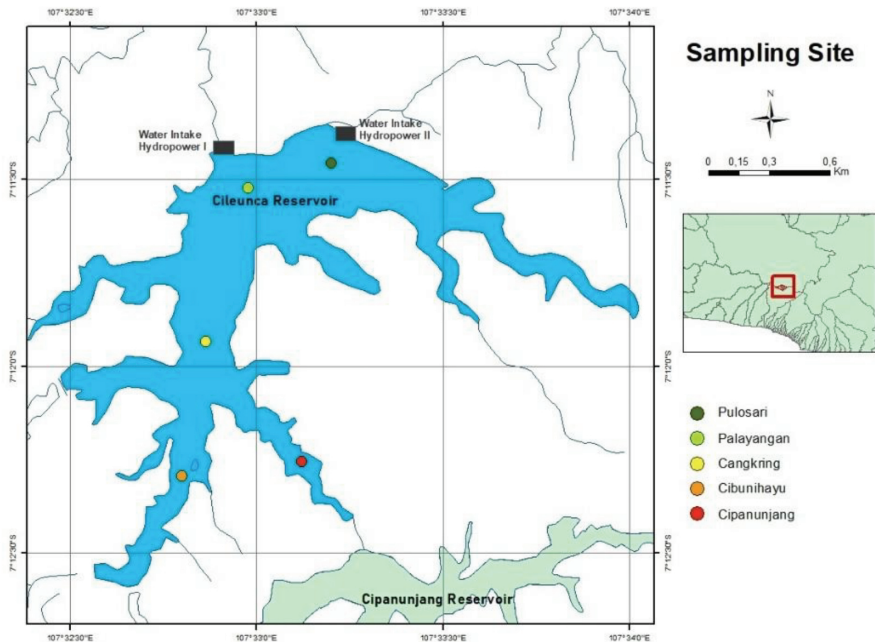


Figure 2: Distribution of *in situ* measurements and water sampling locations in Cileunca Reservoir

and August 2024) seasons. Water sampling was conducted at three depth strata (surface, 50%, and 95% of total depth) using a Van Dorn sampler. In situ measurements of temperature, DO, pH, turbidity, EC, TDS, and chlorophyll-*a*

were obtained using a CTD profiler. Laboratory analyses were conducted to determine TSS, TN, and TP. Measurement procedures and analytical methods are summarised in Table 1.

Table 1: Equipment and methodology used for determining water quality parameters

No.	Parameters	Method Measurements	References	Range/Min. Detectable
1	Water depth	Depth meter	Depth sounder Hondex Ps-7	0.6 m to 80 m
2	Water Temperature (WT)	Logger CTD profiler	Rinko-Profiler ASTD102	-3°C to 45°C
3	Dissolved Oxygen (DO)	Logger CTD profiler	Rinko-Profiler ASTD102	0 to 20 mg L ⁻¹
4	pH	Water quality checker	Lutron WA-2017SD	
5	Electrical Conductivity (EC)	Logger CTD profiler	Rinko-Profiler ASTD102	0 to 2,000 µS cm ⁻¹
6	Turbidity	Logger CTD profiler	Rinko-Profiler ASTD102	0 to 1,000 NTU
7	Total Suspended Solid (TSS)	Gravimetry	APHA (Baird & Bridgewater, 2017)	0.5 mg/L
8	Total Nitrogen (TN)	Spectrophotometry	(USEPA, 1971)	0.1 mg NO ₃ ⁻ -N/L
9	Total Phosphorus (TP)	Spectrophotometry	APHA (Baird & Bridgewater, 2017)	0.01 mg P/L
10	Chlorophyll-a (Chlor-a)	Logger CTD profiler	Rinko-Profiler ASTD102	0 to 400 µg L ⁻¹

Data Analysis

Visual data representations, including bar and line graphs, were applied to depict vertical distributions, temporal fluctuations, and possible pollution sources. Multivariate statistical techniques were applied to recognise prevailing patterns and possible sources of variability. The Principal Component Analysis (PCA) approach was employed to interpret interrelationships among water quality indicators and to determine the principal factors governing spatial and temporal fluctuations across varying depth layers. Cluster Analysis (CA) was applied using Ward's linkage algorithm in conjunction with Euclidean distance metrics to group sampling locations according to similarities in their water quality profiles under both wet and dry seasonal conditions.

Furthermore, spatial interpolation was performed through the Inverse Distance Weighting (IDW) technique in QGIS version 3.22.10 as a qualitative visualisation tool to illustrate broad, first-order horizontal concentration patterns and to identify prospective zones of sediment deposition and material export within the reservoir system. Given the limited number of sampling sites ($n = 5$), the interpolation is not intended to resolve fine-scale spatial variability and may introduce artifacts (e.g., bullseye effects); therefore, interpretations are restricted to zonal-scale trends.

All statistical computations were conducted with RStudio version 4.5.0. Moreover, the Carlson Trophic State Index (TSI) was applied to evaluate the eutrophication level of the Cileunca Reservoir. We used the Carlson's TSI formula based on the method developed by Carlson and Simpson (1996). The Carlson TSI was determined according to the following mathematical expressions:

$$TSI(Chl) = 9.81 \ln(Chl) + 30.6 \quad (1)$$

$$TSI(SD) = 60 - 14.41 \ln(SD) \quad (2)$$

$$TSI(TP) = 14.42 \ln(TP) + 4.15 \quad (3)$$

$$Carson's\ TSI = \frac{[TSI(Chl) + TSI(SD) + TSI(TP)]}{3} \quad (4)$$

where *TSI* denotes the Carlson Trophic State Index, *Chl* represents the concentration of chlorophyll-a ($\mu\text{g/L}$), *SD* refers to Secchi disk transparency (m), *TP* indicates total phosphorus content ($\mu\text{g/L}$), and $\ln$ denotes the natural logarithmic function.

Nutrient load calculations were not performed in this study because discharge or runoff volume data were not available. Consequently, interpretations regarding the influence of catchment land use on nutrient enrichment are based on inflow concentration patterns rather than mass-balance estimates.

Results

Throughout the monitoring period, the depth of sampling varied seasonally, extending between four metres and nine metres in the wet season and between three metres and eight metres in the dry period (Figure 3). Similarly, water clarity demonstrated a recurring seasonal trend, with Secchi disk readings generally higher in the wet season (65–77 cm) than in the dry season (45–75 cm) (Figure 3), indicating greater water transparency during the wet season and relatively lower transparency during the dry season. The reduced water transparency during the dry season may be associated with increased suspended materials, potentially resulting from sediment resuspension and more intensive anthropogenic activities along the reservoir margins.

Vertical and Seasonal Variations in Water Quality Parameters

Water temperature profiles displayed a gradual decline with water depth, warmer surface waters and cooler bottom layers indicating thermal stratification. This stratification was stronger during the dry season, while the wet season showed weaker gradients (Figure 4). In the wet period, thermal variation between surface waters (24°C – 25°C) and bottom layers (21°C – 22°C) remained minimal. Conversely, during the dry season, temperatures decreased more sharply

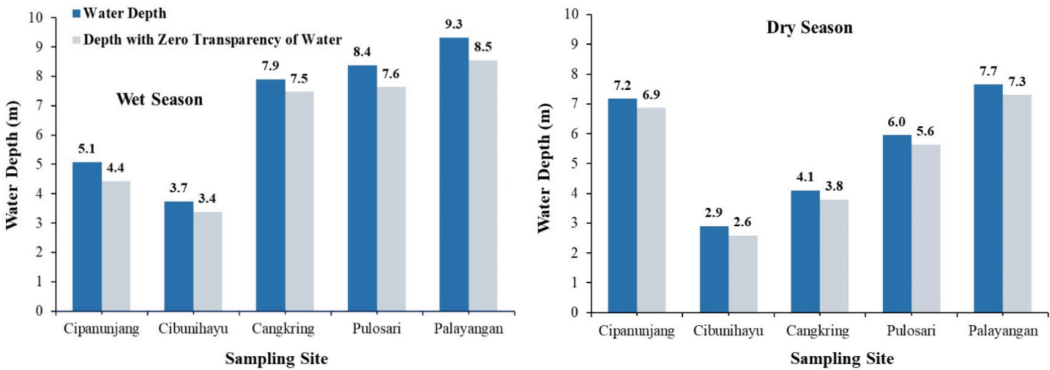


Figure 3: Water depth and zero transparency areas in Cileunca Reservoir during the wet (left) and dry (right) seasons

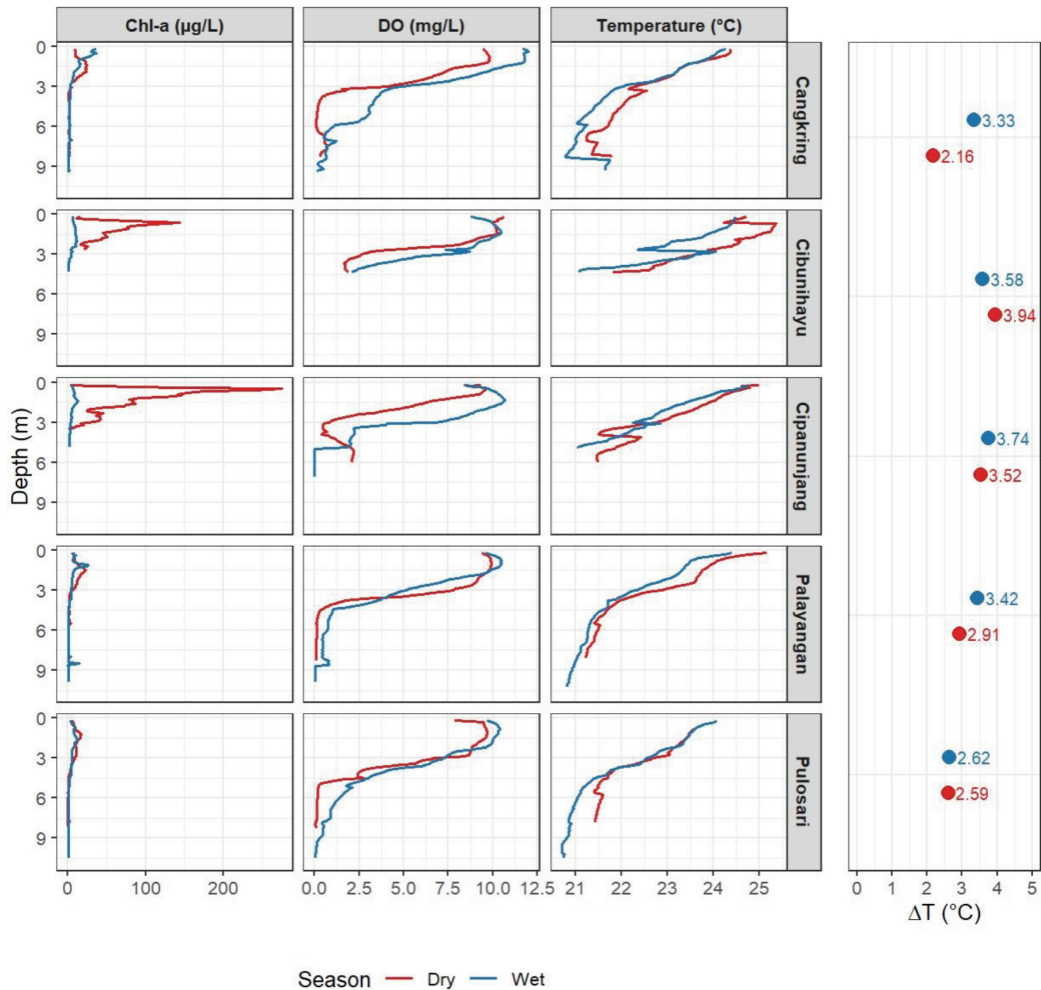


Figure 4: Vertical chlorophyll-a profiles, dissolved oxygen (DO), and temperature across sampling stations with the ΔT surface-bottom during wet and dry seasons

between 2 m–6 m depths. Surface waters warm to 25°C–26°C.

Dissolved Oxygen exhibited clear depth-related stratification in both seasons. In the wet period, DO levels within the epilimnetic layer (0–3 m) remained fairly consistent, with concentrations varying from 8 mg/L to 10 mg/L at all sampling locations. Below 4 m depth, DO gradually declined, reaching hypoxic conditions (< 5 mg/L) at between 8 m and 10 m, particularly in the outlet site (Pulosari) and centre site (Cangkring) of Cileunca reservoir (Figure 4). In contrast, the dry season showed stronger surface oxygen supersaturation, with DO exceeding 11 mg/L–12 mg/L at several stations (e.g., Cipanunjang and Palayangan).

Vertical chlorophyll-a profiles showed strong spatial and seasonal patterns, particularly at the inflow locations (Cibunihayu and Cipanunjang). During the dry season, chlorophyll-a concentrations at these two stations were significantly higher than at the middle (Cangkring) and outlet area (Pulosari and Palayangan). Higher chlorophyll concentrations were distributed in the surface column down to a depth of three meters, with the highest concentration reaching 280 µg/L.

pH generally increased with depth in both seasons (Figure 5), with slightly higher alkalinity during the wet period, whereas dry-season profiles were more neutral and weakly stratified. Electrical conductivity was consistently higher in surface waters across seasons. Turbidity and TSS showed broadly similar spatial patterns, although site-specific discrepancies indicate differences in particle sources. For example, during the wet season, Cangkring exhibited high turbidity but moderate TSS, whereas Pulosari showed the opposite pattern. In the dry season, TSS decreased and became more uniform, while turbidity remained elevated at Cibunihayu and Palayangan.

Both Total Nitrogen (TN) and Total Phosphorus (TP) exhibit vertical stratification with distinct seasonal patterns. TN increases in surface waters during the rainy season, while TP remains relatively high at the surface in both

seasons, with moderate enrichment near the bottom during dry periods.

Spatial and Seasonal Variability of Water Quality

The cluster analysis revealed a clear spatial differentiation of water quality across the reservoir, largely structured by hydrological zones and seasonal conditions (Figure 6). In both seasons, Cibunihayu and Cipanunjang consistently formed a separate group representing the inlet zone, where water quality is strongly influenced by catchment runoff and external nutrient loading. Conversely, Pulosari and Palayangan, located near the outlet, clustered together during the dry season, reflecting their relatively stable physicochemical conditions under limited inflow and longer residence time. During the wet season, these two outlet sites grouped with Cangkring, the transition zone.

The PCA further supports the spatial patterns identified in the dendrograms and clarifies the underlying variables controlling them (Figure 7). The first principal component (Dim1) explained 59.9% of the total variance during the dry season and was positively associated with DO, WT, TSS, and TP. Meanwhile, during the wet season, Dim1 accounted for 51.9% of the variance, dominated by TSS, EC, WT, DO, and TP with pH, TDS, and Secchi depth loaded negatively.

The spatial interpolation maps (Figure 8) provide a qualitative visualisation of the distribution of key water quality parameters (DO, TP, TN, TSS, and WT) across the reservoir and are interpreted in conjunction with the multivariate analyses. During the dry season, the interpolated maps indicate generally higher DO, TP, and TSS values in the inflow zone, whereas the dam (outlet) zone exhibited relatively more uniform conditions. During the wet season, the inflow and central basin generally showed higher TSS, EC, and TP than the dam zone, suggesting a stronger influence of catchment runoff and increased hydrological connectivity. In contrast, TN did not exhibit a consistent inflow-to-dam gradient, consistent with the PCA results indicating that nitrogen dynamics are influenced

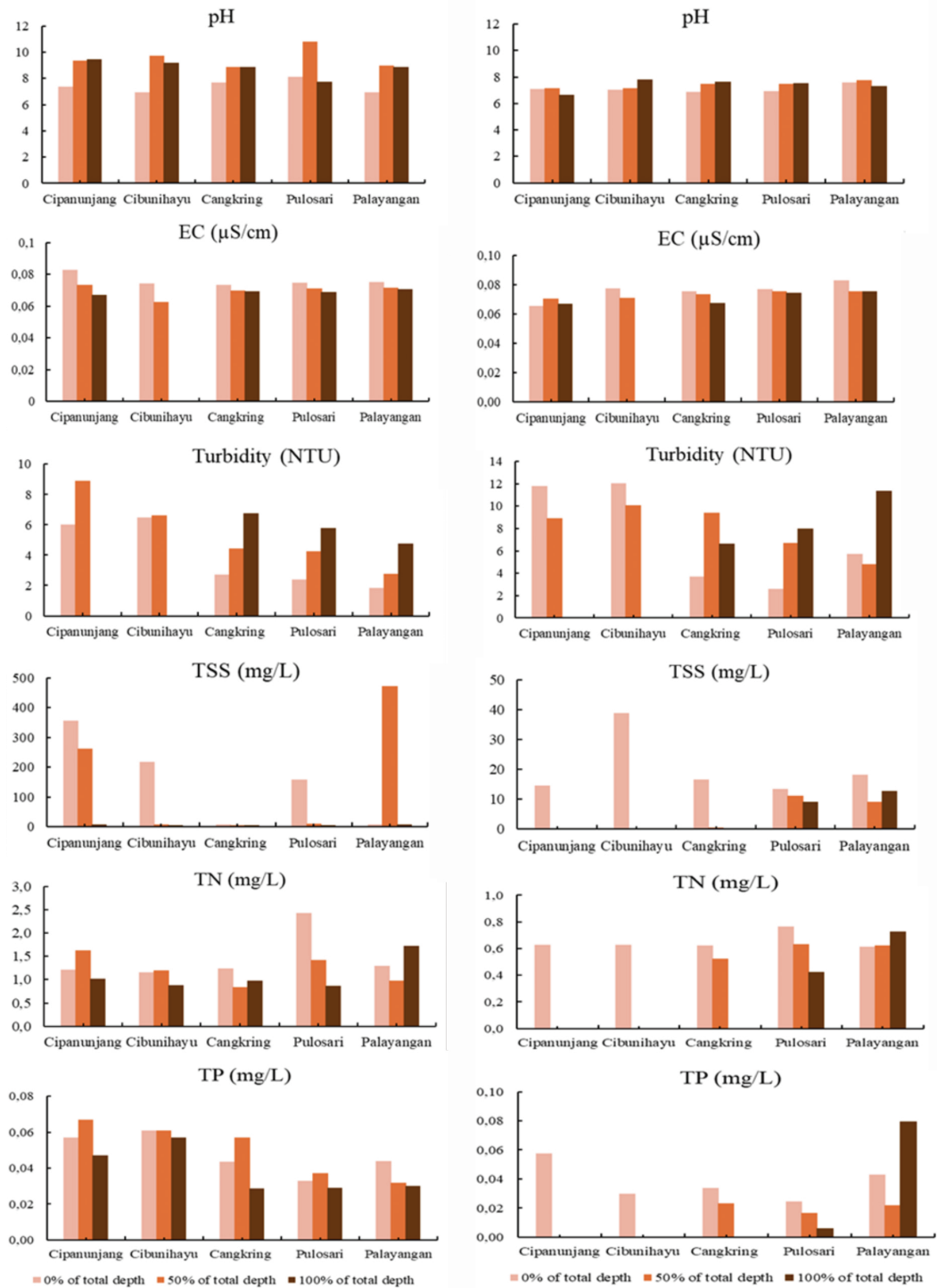


Figure 5: Vertical distributions of key water quality parameters across sampling stations during wet (left) and dry (right) seasons

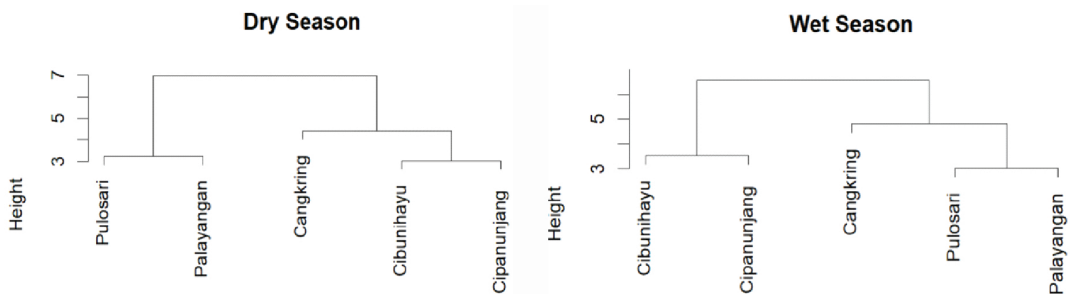


Figure 6: Cluster analysis dendrograms of water quality profiles across wet and dry seasons

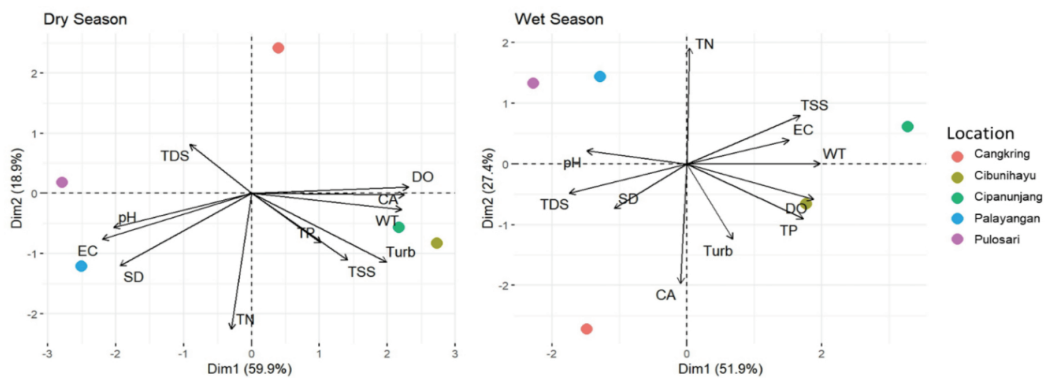


Figure 7: The spatial patterns identified in the dendrograms

by local biogeochemical processes rather than external loading alone. Given the limited number of sampling stations ($n = 5$), these interpolation maps are intended to illustrate broad zonal patterns rather than fine-scale spatial variability. Overall, the combined statistical and spatial analyses suggest that external inflows are the primary driver of spatial heterogeneity, while seasonal runoff influences the extent of this zonal differentiation, supporting management strategies focused on inflow control and seasonal water quality monitoring.

Trophic Status

According to the Carlson Trophic State Index (Carlson & Simpson, 1996), the Cileunca Reservoir falls within the eutrophic category, exhibiting TSI scores of 57.8 during the rainy period and 60.4 in the dry phase (Figure 9).

Discussions

Water quality dynamics in Cileunca Reservoir are jointly controlled by seasonal hydrological forcing and spatial heterogeneity across inlet–outlet zones. These drivers regulate vertical stratification, biogeochemical processes, and the distribution of nutrients and phytoplankton. Thermal structure exhibits clear seasonal contrasts. During the wet season, increased inflow and wind-induced turbulence likely promote vertical mixing, resulting in weak stratification and relatively homogeneous temperature profiles (Istvánovics *et al.*, 2014; Tundisi & Matsumura-Tundisi, 2021). In contrast, the dry season is characterised by stronger thermal stratification driven by increased solar radiation and reduced inflow, as reported in other tropical reservoirs (Pérez-Fuentetaja *et al.*, 1996; Naselli-Flores & Barone, 2003). The persistence of a cooler hypolimnion during this period indicates limited vertical circulation, creating conditions conducive to

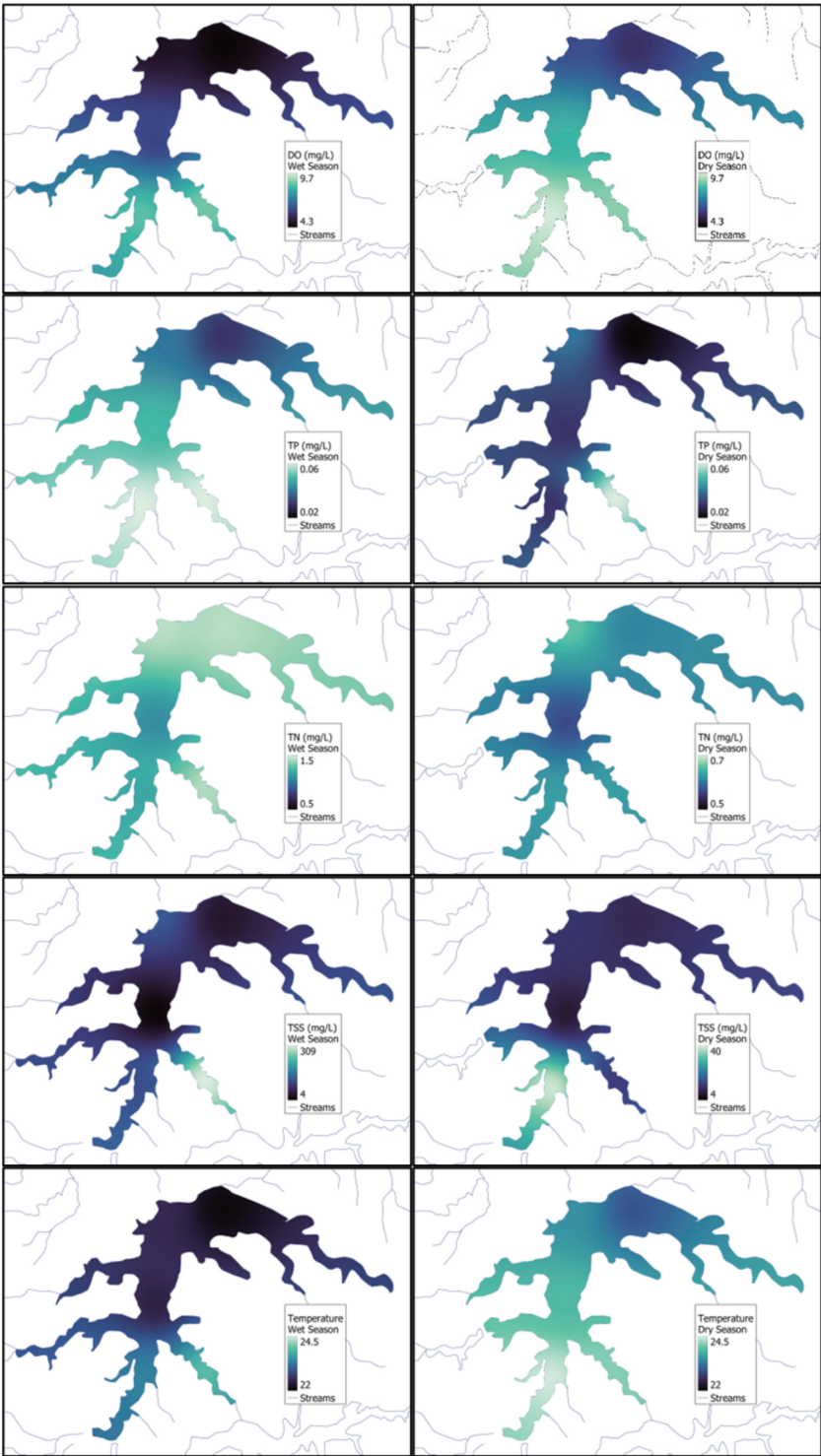


Figure 8: Spatial interpolation of selected water quality parameters (average values) at the surface layer during wet and dry seasons

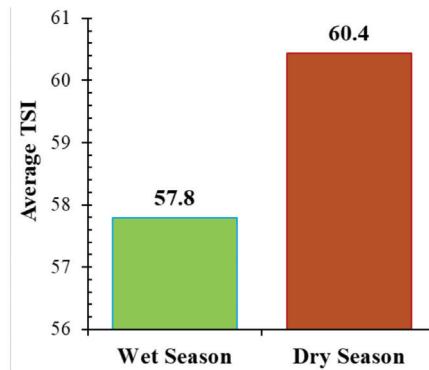


Figure 9: Trophic State Index average during wet and dry seasons

oxygen depletion and internal nutrient loading (Wetzel, 2001; Calijuri *et al.*, 2020).

Spatial variations in temperature profiles across the reservoir show relatively consistent patterns of surface warming and decreasing temperature with depth at all sites, indicating a broadly similar thermal structure. However, subtle differences among locations reflect the influence of hydrodynamic conditions and inflow inputs. Inflow-associated sites such as Cibunihayu and Cipanunjang exhibit slightly more variable temperature gradients, particularly in the upper to bottom layers, suggesting localised mixing and the influence of incoming water masses. In contrast, sites located further from direct inflow influence such as Palayangan and Pulosari, display smoother and more gradual temperature profiles, indicating more stable thermal conditions and reduced disturbance. The tendency toward more uniform temperature gradients across depths at several locations reflects enhanced vertical mixing driven by increased inflow and hydrological activity.

Consistent with this pattern, Dissolved Oxygen (DO) shows pronounced vertical gradients. Lower DO concentrations at depth reflect oxygen consumption through microbial decomposition of organic matter and sediment oxygen demand, particularly under stratified conditions. Meanwhile, elevated surface DO during the dry season is closely linked to intensified phytoplankton photosynthesis under

enhanced light availability and water column stability (Padisák *et al.*, 2000; Sarmiento *et al.*, 2013).

Locations associated with inflow, particularly Cibunihayu and Cipanunjang, consistently show higher surface Chlorophyll-*a* concentrations compared to other locations, indicating greater phytoplankton biomass, likely driven by increased nutrient input from the upstream watershed. These locations also exhibit relatively high surface DO levels, indicating increased photosynthetic oxygen production. In contrast, locations further from the influence of direct inflow such as Palayangan and Pulosari, show lower Chlorophyll-*a* concentrations and more gradual vertical gradients, reflecting more stable and less nutrient-rich conditions.

Variations in vertical chlorophyll maxima among stations are likely influenced by phytoplankton composition, where motile species such as *Ceratium hirundinella* (dominant in Cibunihayu, Cipanunjang, and Cangkring—unpublished) can maintain position in the upper water column, while *Synedra ulna* (dominant in Palayangan and Pulosari—unpublished) tend to settle more rapidly (Reynolds, 1984; Carty, 2003; Bellinger & Sigeo, 2010). This may explain why the maximum concentration of chlorophyll-*a* is found at the upper water column in Cibunihayu, Cangkring, and Cipanunjang, compared to Palayangan and Pulosari, especially in the dry season.

Seasonal forcing also shapes broader biogeochemical conditions, including pH dynamics. A tendency for increasing pH with depth during the wet season suggests active mineralisation and decomposition of organic matter in bottom sediments, releasing bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions into the overlying water (Wetzel, 2001). In addition, surface runoff may introduce alkaline materials from the surrounding catchment, further influencing pH levels (Effendi, 2003). It is estimated that the influx of nutrients from agriculture will result in high $\text{NH}_3\text{-N}$ concentrations which will contribute to an increase in pH through photosynthesis (Alkhadher *et al.*, 2025). Conversely, slightly lower pH during the dry season can be associated with enhanced CO_2 accumulation from microbial respiration and organic matter degradation under more stable, stratified conditions (Boyd & Tucker, 1998). These patterns indicate that pH variability reflects the balance between sediment-driven biogeochemical processes and physical mixing across seasons.

Other physicochemical parameters reinforce this seasonal signal. Lower Electrical Conductivity (EC) and higher turbidity during the wet season indicate dilution and increased inputs of fine suspended particles from catchment runoff (Singh & Sharma, 2018). Conversely, higher EC and clearer conditions in the dry season suggest evaporative concentration and enhanced conditions for phytoplankton growth (Nguyen *et al.*, 2020).

The relationship between turbidity and Total Suspended Solids (TSS) varies with particle characteristics (Bilotta & Brazier, 2008; Su *et al.*, 2022). Finer particles that strongly scatter light dominate during high-flow conditions resulting in higher turbidity relative to TSS. Conversely, high TSS values but relatively lower turbidity likely reflect coarser mineral sediments with lower optical scattering efficiency.

Declining TSS values while turbidity remains relatively high at locations such as Cibunihayu and Palayangan indicate a shift from hydrologically driven sediment input

toward finer particles, potentially derived from phytoplankton, that remain suspended under stratified and low-flow conditions (Gao *et al.*, 2021). These patterns suggest that while turbidity can serve as an indirect indicator of TSS under certain conditions, the relationship between the two can weaken when particle size distribution or composition changes seasonally. Turbidity can be used to quickly estimate TSS trends, but it must be calibrated for each situation to ensure accurate estimates. Real-time turbidity sensors offer significant advantages in dynamic water quality monitoring and rapid response, while reducing reliance on manual sampling and laboratory analysis.

Nutrient dynamics reflect the interplay between external loading and internal processes. Surface phosphorus concentrations remain relatively high in both seasons, indicating strong association with suspended particles and catchment-derived inputs. However, increased phosphorus near the bottom during the dry season suggests the onset of sediment release under low-oxygen conditions (Anderson *et al.*, 2021; Yang *et al.*, 2021), a process commonly reported in stratified tropical reservoirs (Li *et al.*, 2023; Zhang *et al.*, 2025). Despite this internal loading, phytoplankton biomass remains concentrated near the surface, implying that light limitation and possibly grazing restrict nutrient utilisation at depth.

At the system scale, these nutrient and productivity patterns are reflected in the trophic status of the reservoir. The Carlson Trophic State Index (TSI) classifies Cileunca Reservoir as eutrophic, consistent with previous assessments describing it as eutrophic to hypertrophic (Tjahjo & Purnamaningtyas, 2017). The slightly higher TSI observed during the dry season is consistent with enhanced water column stability, increased phytoplankton productivity, and reduced dilution effects, all of which favour higher algal biomass accumulation. Comparable TSI ranges reported for other tropical reservoirs such as Sempor Reservoir (53.55–66.74), indicate that Cileunca falls within the upper range of productive inland waters (Shaleh *et al.*, 2014).

The consistency between TSI values and observed patterns of chlorophyll-a, dissolved oxygen supersaturation, and nutrient availability further indicates that reservoir productivity is primarily driven by external nutrient inputs during the wet season and sustained by internal recycling during the dry season. This reinforces the interpretation that seasonal hydrological forcing not only structures spatial variability but also regulates the trophic state of the system.

This seasonal control is further expressed in the spatial organisation of water quality across the reservoir. Cluster and PCA results demonstrate a clear separation between inlet, transition, and outlet zones, particularly during the wet season when catchment runoff intensifies the delivery of suspended solids and nutrients. This leads to strong spatial gradients, with the inlet zone exhibiting distinct water quality characteristics. During the dry season, reduced inflow and longer residence time promote more homogeneous conditions, especially in the outlet zone.

The dominance of agricultural land use in the surrounding catchment provides important context for these patterns, as fertiliser and livestock-derived inputs likely enhance nutrient loading during runoff events. Nevertheless, not all parameters follow the same spatial gradients. Total nitrogen, for instance, shows localised variability, suggesting that internal processes such as mineralisation, sediment–water interactions, and biological uptake play an important role in regulating site-specific conditions.

Overall, the interaction between seasonal forcing and spatial heterogeneity governs water quality dynamics in Cileunca Reservoir. External inputs dominate during the wet season, strengthening spatial contrasts, whereas internal processes become more influential during the dry season under stratified conditions. This interplay highlights the potential for increased eutrophication risk under prolonged dry periods, particularly if stratification intensifies and sediment nutrient release becomes more pronounced.

Taken together, these findings demonstrate that eutrophication in Cileunca Reservoir is not only a function of nutrient enrichment, but also of how seasonal hydrological forcing and spatial heterogeneity regulate the transport, transformation, and retention of those nutrients. This has important implications for the design of effective reservoir management strategies.

The findings of this study have direct implications for the development of seasonally adaptive and spatially targeted reservoir management strategies. In tropical reservoirs, sedimentation frequently occurs as a consequence of extreme precipitation and accelerated soil erosion (Khan *et al.*, 2025). The amplification of spatial gradients during the wet season indicates that management efforts should prioritise catchment-based interventions, particularly in upstream areas where runoff-driven inputs are most pronounced.

To maintain reservoir water quality, effective management of agricultural runoff within the catchment area is crucial. Potential strategies include the implementation of vegetative buffers, structural control measures, and improved fertiliser management practices. Alkhadher *et al.* (2025) reported, both in the catchment and at the inlet of the reservoir, vegetation development is recommended. Riparian buffer strips, for example, can remove over 50% of nitrogen and phosphorus from surface runoff before it reaches aquatic systems (Zhou *et al.*, 2021). Conservation practices such as contour farming and terracing help reduce soil erosion on sloped agricultural land (Farahani *et al.*, 2016). Effects of contour farming on runoff and soil erosion reduction: A review study. Elixir Agriculture, while sedimentation ponds and constructed wetlands positioned between farmland and reservoirs effectively trap suspended solids and absorb dissolved nutrients (Lu *et al.*, 2009; Tang *et al.*, 2021).

Collectively, these integrated management practices offer a scientifically sound and practical approach to reducing contaminant loads while supporting sustainable agricultural productivity and protecting aquatic ecosystems.

In addition to catchment-based measures, reservoir operational decisions for hydropower generation such as outflow regulation and water level fluctuations, should also consider their influence on water residence time and nutrient retention. While these operational strategies may improve energy production efficiency, they can also affect nutrient dynamics, algal growth, and overall water quality, highlighting the need to balance hydropower generation with ecological sustainability in reservoir management.

This study provides insight into the seasonal and spatial dynamics of physicochemical parameters in a tropical, agriculture-influenced reservoir. However, several limitations should be acknowledged. The analysis is based on a limited temporal dataset and a constrained set of variables, which may not fully capture interannual variability or complex ecological interactions.

Future research should incorporate long-term monitoring, higher temporal resolution, and expanded parameters (e.g., biological indicators, sediment fluxes, and continuous profiling) to better resolve the mechanisms governing stratification and nutrient cycling. Under increasing climate variability and anthropogenic pressure, such efforts are essential to develop a more comprehensive understanding of water quality dynamics in Cileunca Reservoir and comparable tropical systems.

Conclusion

Water quality in Cileunca Reservoir is strongly influenced by seasonal hydrological forcing, which regulates the balance between external inputs and internal processes. During the wet season, elevated TSS, total phosphorus, and turbidity near inlet zones reflect substantial sediment and nutrient loading from the surrounding agricultural catchment. In contrast, the dry season is characterised by reduced surface turbidity but persistent hypolimnetic oxygen depletion, indicating enhanced water column stability and internal nutrient recycling. The reservoir consistently exhibits eutrophic

conditions (TSI: 57.8 in the wet season; 60.4 in the dry season), supported by strong coupling between nutrients, chlorophyll-a, and dissolved oxygen. Frequent vertical mixing can redistribute oxygen and nutrients, prevent severe hypoxia while maintaining nutrient availability for phytoplankton growth.

These findings indicate that eutrophication in Cileunca Reservoir is driven by both catchment-derived inputs and internal recycling processes. Effective management should therefore integrate catchment-based measures—such as reducing agricultural runoff—with adaptive in-reservoir strategies that consider seasonal variability. Overall, the interaction between seasonal forcing and spatial heterogeneity is a key determinant of water quality and trophic status and must be explicitly addressed to achieve sustainable reservoir management. To protect water quality and ensure the sustainability of reservoir ecosystems, an optimal operational framework is needed to improve the current reservoir operation scheme, which is primarily based on quantitative water availability, toward a more balanced approach that integrates water quantity and water quality objectives.

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Author Contributions Statement

SA carried out the research, wrote and revised the article; HAR wrote and revised the article; AA conceptualised the central research idea, carried out the research, wrote and revised the

article; DV carried out the research and prepared the manuscript layout; FAS carried out the research and revised the article; LS supervised research progress; ESB wrote and revised the article; FS wrote and revised the article; SS wrote and revised the article.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethical Conduct

Ethical approval and informed consent were not required because the study did not involve human participants or animals.

Declaration of AI-usage

During the preparation of this work, the authors used artificial intelligence (AI) for grammatical improvements and clarity. In using the AI-tools, the authors reviewed and edited the content as needed and bear full responsibility for the content of this manuscript.

Data Availability Statement

The data that support the findings of this study are available upon reasonable request.

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