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Elucidating Differences in Limnological Parameters of Three Ghanaian Reservoirs (Tono, Bontanga and Golinga)

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Abstract

Reservoirs play a crucial role in sustaining fisheries and local livelihoods; however, their ecological dynamics in dryland environments remain understudied. This study examines the spatial and seasonal variations in key physicochemical parameters, including chlorophyll a, temperature, electrical conductivity, dissolved oxygen, pH, and turbidity, across three reservoirs (Tono, Bontanga, and Golinga) in Ghana. Understanding these variations is essential for sustainable reservoir management, particularly in the context of increasing anthropogenic pressures. Water quality parameters were monitored in situ using an OTT Hydrolab DS5X multi-parameter water quality probe, while nutrient concentrations were analysed using a TECAN-plate reader and a combustion analyzer (TOC-V, Shimadzu). Data were collected over one year, covering dry, pre-wet, wet, and post-wet seasons. Linear models with Gaussian error terms were used to assess variability, with degrees of freedom and sample sizes explicitly stated for statistical robustness. Results revealed significant spatial variation in o-SiO_4^{4-} concentrations ($F_{2,29}$ = 7.252, p = 0.0028), with the largest and deepest reservoir, Tono, exhibiting the highest concentration (0.762 mg L^{-1}), likely due to geological inputs or hydrodynamic factors. Dissolved organic carbon (DOC) concentrations also varied significantly among reservoirs ($F_{2,27}$ = 6.798, p = 0.0041), with the smallest and shallowest reservoir, Golinga, recording the highest levels (533.63 µM), significantly exceeding Tono (350.02 µM, p = 0.0098) and Bontanga (359.40 µM, p = 0.0108). Similarly, Golinga had significantly higher total dissolved nitrogen (TDNb) concentrations ($F_{2,27}$ = 6.798, p = 0.0041), reaching 80.22 µM compared to Tono (31.98 µM, p = 0.0011) and Bontanga (44.40 µM, p = 0.0269). These findings suggest that Golinga is more impacted by anthropogenic activities, such as agricultural runoff and organic matter input, leading to greater nutrient accumulation and water turbidity. Despite seasonal variations, dissolved oxygen concentrations in all reservoirs remained within optimal ranges for sustaining aquatic life. The high nitrate-nitrogen levels stimulated photosynthetic activity, as evidenced by occasional algal blooms. Anthropogenic activities, such as agricultural runoff and domestic waste disposal, disproportionately impacted the Golinga reservoir, contributing to increased DOC, TDNb, NO2-N, and turbidity. These findings underscore the urgent need for improved regulatory enforcement to mitigate human-induced degradation. Future research should focus on long-term ecological monitoring to assess the resilience of reservoir ecosystems in dryland regions.

Keywords: Anthropogenic activities, eutrophication, nutrients, photosynthetic activity, temporal-spatial variations.

Introduction

Understanding spatial and seasonal variations in environmental variables is crucial for evaluating, assessing, and managing inland fisheries. However, most existing studies focus on marine ecosystems or riverine systems, with limited attention given to man-made reservoirs. While research has explored the relationships between fisheries metrics (e.g., catch per unit effort, biomass, or abundance), socioeconomic drivers of fishing, and environmental conditions (Cardinale and Arrhenius 2000, de Mérona and Gascuel 1993, Mangi et al. 2007, Petry et al. 2003, Schaefer 1957, Skud 1982, Whitfield and Elliott 2002). These studies are predominantly marine-focused. This leaves a significant gap in understanding the complex interactions between limnological factors and fish productivity in the unique ecosystems of man-made reservoirs.

Unlike marine systems, which are open and influenced by tidal dynamics, reservoirs are enclosed, with water level fluctuations controlled by human activities. Unlike riverine systems, which experience continuous flow, reservoirs exhibit standing water conditions with distinct thermal and chemical stratification. These factors make reservoirs unique in their response to environmental changes, necessitating specific research tailored to their limnological dynamics.

Reservoirs such as Tono, Bontanga, and Golinga are crucial for supporting fisheries and local livelihoods in Northern Ghana. These reservoirs were selected due to their differing sizes, depths, and catchment characteristics, which provide a representative spectrum of reservoir conditions in Northern Ghana. Their varying hydrodynamics and anthropogenic pressures allow for a comparative assessment of limnological factors affecting fisheries and water quality. Additionally, these reservoirs are critical for local fisheries, irrigation, and domestic water supply, making their ecological management essential. However, there has been no comprehensive study analyzing their spatial and seasonal physicochemical characteristics. Limited studies have focused on the limnological characteristics of Tono, Bontanga, and Golinga reservoirs. While previous research in Ghana has examined fisheries dynamics in the Volta Reservoir (Van Zwieten et al. 2011, Alhassan et al. 2016), there remains a gap in understanding smaller reservoirs in dryland environments. This study provides the first comprehensive assessment of these reservoirs, filling a critical knowledge gap in limnological research." However, there has been no comprehensive study analyzing their spatial and seasonal physicochemical characteristics. This study is the first to evaluate these parameters across multiple reservoirs in the region, providing critical insights into their ecological dynamics and fisheries potential.

Several physical and chemical factors influence fish production in freshwater systems. For instance, in tropical freshwaters, water level fluctuations have been shown to significantly influence fish abundance (Abobi et al. 2013, Alhassan et al. 2016, Amarasinghe 1987, Amarasinghe and Pitcher 1986, Blay and Asabere-Ameyaw 1993, Braimah 1995, Quarcoopome et al. 2008). Climatic and hydrological characteristics of drylands further influence fish production (Kolding et al. 2016b). Evidence suggests that year-to-year variations in fish stock abundance are linked to fluctuations in hydrological regimes (Welcomme 1985). Stable systems like rivers or flood-controlled reservoirs show little variation in standing stock, whereas flood-dependent systems exhibit catch fluctuations tied to the flood cycle. Reservoirs, however, experience unique interannual variations. For example, Wishard (1978) found that weighted average monthly fish landings were inversely related to mean water levels in riverine ecosystems. Similarly, FAO (2016a) noted a relationship between chlorophyll concentrations—an indicator of freshwater primary production—and fishery yield and used remotely sensed chlorophyll data globally to predict lake yields. A study on the Black Volta in Ghana established a link between catch per unit effort (CPUE), chlorophyll concentration, and water level, suggesting that fish production is influenced by nutrient flux (Alhassan et al. 2016). Additionally, Van Zwieten et al. (2011) attributed the high productivity of the Volta Reservoir to the annual flooding of extensive land areas, despite relatively low nutrient concentrations in the water. However, the significant annual variations in flooding, including years without recessions, suggest that fish production can vary accordingly.

In addition to hydrological factors, other physicochemical variables such as temperature, dissolved oxygen, pH, and nutrient concentrations (nitrogen and phosphorus) play critical roles in shaping the ecological balance and productivity of reservoir ecosystems (Carr et al. 2020, Hamid et al. 2020). For example, higher temperatures can accelerate fish metabolism but increase the risk of hypoxia, particularly under low dissolved oxygen conditions (Gamperl et al. 2020). Elevated nutrient concentrations can enhance primary production, but, if unmanaged, may lead to eutrophication and harmful algal blooms (Hwang et al. 2024, Igwaran et al. 2024).

Man-made reservoirs also face anthropogenic pressures from agriculture, urbanization, and industrial activities. These activities can introduce pollutants and alter natural hydrological regimes, leading to sedimentation, nutrient loading, and chemical contamination, which degrade water quality and fish habitats (Newton et al. 2020, Winton et al. 2021). Effective monitoring and control of these pressures are necessary to maintain ecological integrity and ensure sustainable fisheries production. Climate change presents additional challenges for reservoir management. Shifts in precipitation patterns, rising temperatures, and increased frequency of extreme weather events exacerbate the variability of hydrological regimes and water quality parameters (Whitehead et al. 2009). Studies that incorporate climatic variables are therefore essential to understanding their impact on reservoir dynamics and fisheries productivity.

This research therefore aims to uncover how key physicochemical variables change seasonally and spatially in dryland environments by integrating environmental data and assessing their dynamics across reservoirs. Unlike previous works, this study explicitly addresses the implications of anthropogenic pressures and climate variability on reservoir systems in dryland areas, offering valuable recommendations for sustainable reservoir resource management. This study tests the hypothesis that significant spatial and seasonal variations exist in key physicochemical parameters across the three reservoirs, influenced by differences in reservoir size, depth, and anthropogenic pressures. Specifically, this study aims to (i) assess the spatial and seasonal variations in physicochemical characteristics of the Tono, Bontanga, and Golinga reservoirs, and (ii) evaluate their environmental conditions to inform fisheries management practices.

Materials and methods

Reservoir systems

The study was carried out at three reservoirs: Tono (10° 52' 48" N; 1° 9' 36" W), Bontanga (9° 33' 0" N; 1° 1' 12" W) and Golinga (9° 21' 36" N; 0° 57' 14.4" W) (Figure 1). Tono is the largest reservoir in the Upper East region of Ghana with a surface area of 1,860 ha. Bontanga and Golinga are the two largest reservoirs in the Northern region of Ghana. Bontanga has a surface area of 670 ha, while Golinga is the smallest with an area of 62 ha. Bontanga and Golinga are 20 km apart, while Tono is approximately 210 km away from Bontanga and Golinga. Golinga has one landing site, Bontanga has two main landing sites, namely Voggu and Bontanga, and Tono has five landing sites (locally called “bays”). The Tono Lake has a length of 3471 m and a catchment area of 650 km^2. The mean depth of the lake is 6.6 m, and it has a volume of 93×10^6 m^3. Bontanga, on the other hand, has a length of 1900 m and a catchment area of 165 km^2, a mean depth of 5.9 m and a water volume capacity of 25×10^6 m^3. The mean depth of the Golinga reservoir is 2.7 m. The reservoirs are within the Guinea

Savanna belt, where the most prominent rainy season is from June to October.

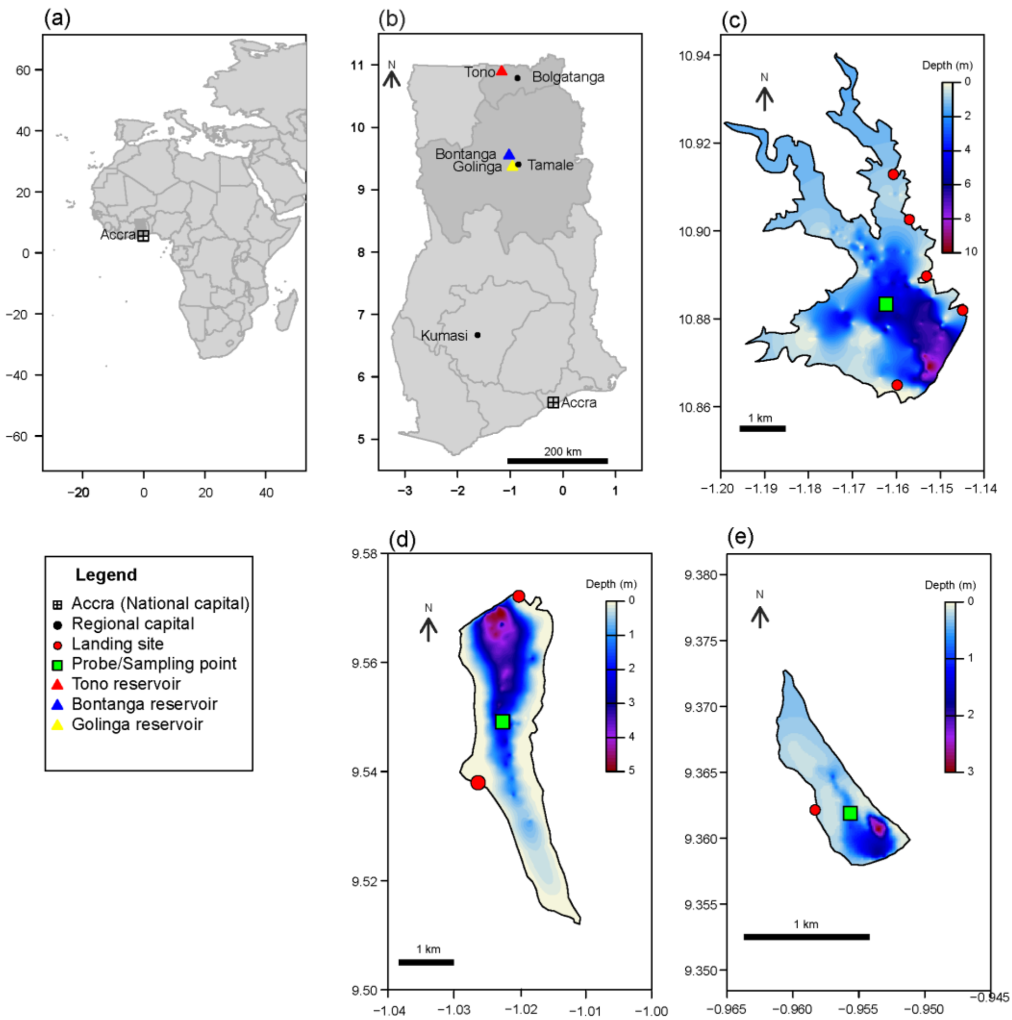

Figure 1: Overview maps of the African continent (a) and Ghana (b), indicating the location of national and regional capital cities, as well as the three reservoirs studied in this work. The bathymetric maps of Tono (c), Bontanga (d) and Golinga (e) reservoirs in Ghana, showing landing sites and points (green boxes) where physicochemical characteristics of the reservoirs were monitored. The bathymetric data were obtained during the dry season (March-April 2017).

Study and sampling approach

Data on chlorophyll *a* (Chl-*a*), dissolved oxygen (DO), temperature, turbidity, Secchi disk depth (SDD), conductivity, pH, water level and nutrients were collected monthly from July 2016 to June 2017 to assess the seasonal variations in the environmental variables of Tono, Bontanga and Golinga reservoirs. A two-level sampling approach was adopted for the study. The first level is defined by four hydrological seasons in northern Ghana: the dry season (January-March), pre-wet season (April-June), wet season (July-September) and post-wet season

(October-December) (Abban et al. 2000). The second factor was based on lake size (Large reservoir (Tono), medium-sized reservoir (Bontanga) and small reservoir (Golinga)).

Measurement of physicochemical parameters

The physicochemical parameters: chlorophyll *a*, temperature, electrical conductivity, dissolved oxygen, pH and turbidity were monitored in situ using an OTT Hydrolab DS5X multi-parameter water quality probe. The water quality of reservoirs was monitored for 24 hours each month, and the data were logged every 30 minutes. The probe was suspended at a depth of 2m in all three reservoirs with the aid of solid rectangular foam and a measured length of static rope. The probe was deployed either between 8:00 and 9:00 GMT or between 16:00 and 17:00 GMT and retrieved the next day within the same period of deployment. A Secchi disc was used to measure water transparency. The water level was measured monthly from fixed graduated poles positioned at the dam walls of the reservoirs. Using GARMIN GPSMAP 78s and SPEEDTECH SM5 Depthmate Portable Depth Sounder, XYZ data were collected between March and April 2017 (lowest water level) to generate bathymetric maps for the reservoirs. Water samples were collected using the Hydrobios Niskin-Type general-purpose water sampler at the same depth as the multi-parameter water quality probe. The water was filtered using 0.45 µm Sartorius Minisart NML syringe filters. Nutrient samples were filtered into clear 50ml polyethylene bottles and were immediately preserved with Mercury (II) Chloride (HgCl2). Dissolved organic carbon samples were stored after filtration in 24mL glass vials with seals and lids without holes and preserved with 32% HCl. The nutrients: o-PO4 3-, NO3-N, NO2-N, NH4-N, o-SiO4 4-, DOC and TDNb were analysed using a TECAN-plate reader, while dissolved organic carbon samples were analysed using a combustion analyzer (TOC-V, Shimadzu).

Instrument Calibration and Quality Control

Instrument calibration was performed before each field deployment according to the manufacturer's recommendations. The OTT Hydrolab DS5X probe was calibrated using standard solutions for each parameter (e.g., pH, dissolved oxygen, conductivity). Additionally, regular maintenance and cleaning of the probe were conducted to minimize measurement errors. Quality control measures included periodic cross-checks of the in situ data with other independent measurement techniques, such as Secchi disk readings for water transparency and depth soundings for bathymetric data. Calibration checks were conducted at the beginning of each sampling campaign, and post-deployment checks were performed to ensure consistency in data accuracy. These measures were incorporated to ensure high data reliability and minimize potential measurement biases.

Data analysis

We employed statistical modeling to analyze the effects of ‘Lake’ (Tono, Bontanga, and Golinga), ‘Season’ (dry, pre-wet, wet, post-wet), and their interaction on abiotic parameters. Linear models with Gaussian error terms were fitted using the lm function in R (R Core Team 2024). The model-fitting process involved optimization of the residual sum of squares to obtain parameter estimates, ensuring that the derived model best explains the observed data.

Model assumptions of normality and homoscedasticity were validated through visual inspection of Q-Q plots and scatterplots of fitted values versus residuals. Where necessary, data were log-transformed to meet these assumptions. Diagnostic checks, including Cook's distance and DFFITS (Cohen and Cohen 2008), were used to identify and exclude potential outliers. Leverage analysis (Quinn and Keough 2002) revealed some deviations, likely due to unbalanced sample sizes across factors, which were acknowledged in the interpretation of results. Despite these deviations, the models were deemed robust for assessing abiotic parameter variability.

Seasonal variations in parameters monitored with the OTT Hydrolab DS5X (chlorophyll a, dissolved oxygen, electrical conductivity, temperature, turbidity, and pH) and Secchi depth transparency were analyzed due to their high sample sizes. For parameters analyzed in the laboratory (o-PO4 3-, NO3-N, NO2-N, NH4-N, o-SiO4 4-, DOC, TDNb), statistical tests focused on spatial variation among the lakes.

Results

Chlorophyll a (Chl-a)

The seasonal average Chl-a concentrations ranged from 2.35 ± 0.05 to 45.9 ± 5.35 mg m^{-3} (Table 1). Concentrations were significantly higher during the post-wet and dry seasons compared to the wet and pre-wet seasons (Figure 2a). During the dry season, Golinga reservoir recorded the highest Chl-a concentrations, followed by Bontanga and Tono. Significant differences were also observed during the pre-wet season, with Golinga exceeding Tono, while Bontanga showed intermediate concentrations. These patterns suggest that Chl-a levels are influenced by seasonal hydrological and ecological dynamics.

Dissolved oxygen

DO concentrations varied seasonally from 5.45 ± 0.06 to 9.11 ± 0.13 mg L^{-1}, with lower values during the dry season and higher values during the pre-wet season (Table 1, Figure 2b). Significant differences were observed across reservoirs, with Bontanga showing consistently higher concentrations than Tono during the wet and post-wet seasons. In contrast, Tono had higher concentrations during the pre-wet season, suggesting localized factors affecting oxygen dynamics in each reservoir.

Temperature

The seasonal variation in reservoir water temperatures ranged from 25.8 ± 0.33 °C to 31.27 ± 0.10 °C (Table 1, Figure 2c). Distinct patterns were observed in the temperature dynamics across the reservoirs. Tono and Bontanga reservoirs exhibited their highest temperatures during the pre-wet season, indicating a strong influence of pre-monsoon climatic conditions. Golinga, which is the smallest and shallowest reservoir, recorded its peak temperatures during the dry season, likely due to its reduced water volume and higher exposure to direct solar radiation.

The lowest temperatures were recorded during different seasons: the post-wet season in Tono, the dry season in Bontanga, and the wet season in Golinga (Figure 2c). This variability may be attributed to the interplay of reservoir size, depth, and seasonal atmospheric changes. In terms of seasonal comparisons across reservoirs, during the wet season, Bontanga exhibited significantly higher temperatures than both Tono and Golinga. Golinga's temperature was also significantly higher than Tono's, highlighting spatial thermal stratification. In the post-wet season, temperatures in Bontanga and Golinga were similar, while Tono remained significantly cooler than both. During the dry season, Golinga showed the highest temperatures, followed by Bontanga and Tono. This trend reversed during the pre-wet season, with Tono exhibiting the highest temperatures, Bontanga intermediate, and Golinga the lowest.

These findings suggest that reservoir-specific factors such as size, depth, and exposure to seasonal atmospheric variations significantly influence temperature dynamics. This knowledge is critical for understanding how thermal regimes might impact aquatic ecosystems and their management under different seasonal and climatic conditions.

Table 1: Seasonal variation in physicochemical characteristics among the reservoirs. Figures on the same row with different superscript letters within a season column are significantly different. α at a 5% significance level.

Parameters	Wet season			Post-wet season			Dry season			Pre-wet		
	Tono	Bontanga	Golinga	Tono	Bontanga	Golinga	Tono	Bontanga	Golinga	Tono	Bontanga	Golinga
Chlorophyll a (mg m^{-3})	2.35^{a} ± 0.05	3.58^{a} ± 0.11	5.24^{a} ± 0.15	22.15^{a} ± 1.88	17.74^{a} ± 2.49	16.62^{a} ± 0.54	27.77^{a} ± 2.07	38.72^{b} ±3.14	45.90^{c} ± 5.35	3.51^{a} ± 0.07	6.83^{ac} ± 0.21	9.73^{c} ± 0.87
DO (mg L^{-1})	6.23^{a} ± 0.10	8.35^{b} ± 0.07	7.75^{c} ± 0.06	5.92^{a} ± 0.15	8.16^{b} ± 0.25	7.42^{c} ± 0.01	5.45^{a} ± 0.06	6.10^{b} ± 0.06	6.13^{b} ± 0.03	9.11^{a} ± 0.13	8.21^{b} ± 0.14	7.53^{c} ± 0.19
Temperature (°C)	26.71^{a} ± 0.11	28.34^{b} ± 0.02	27.69^{c} ± 0.05	25.8^{a} ± 0.33	29.00^{b} ± 0.18	28.80^{b} ± 0.02	26.26^{a} ± 0.33	26.95^{b} ± 0.30	29.77^{c} ± 0.26	31.27^{a} ± 0.10	29.92^{b} ± 0.15	29.18^{c} ± 0.05
Turbidity (NTU)	222.6^{a} ± 11.85	111.5^{b} ± 1.52	180^{c} ± 8.22	67.0^{a} ±4.05	56.3^{a} ± 0.77	42^{a} ± 0.22	42.9^{ab} ± 0.69	41.5^{b} ± 0.43	73.3^{a} ± 1.68	49.7^{a} ± 0.29	57.5^{a} ± 0.50	544^{b} ± 32.03
Transparency (cm)	44.93^{a} ± 2.14	25.42^{b} ± 1.42	37.75^{c} ± 1.85	83.03^{a} ± 2.46	59.10^{b} ± 1.98	83.80^{a} ± 2.24	91.95^{a} ± 1.50	85.64^{a} ± 1.15	74.67^{b} ± 7.41	65.36^{a} ± 3.26	26.64^{b} ± 1.80	5.77^{c} ± 0.95
Conductivity (µS cm^{-1})	47.63^{a} ± 1.00	59.11^{b} ± 0.55	74.39^{c} ± 0.58	84.09^{a} ± 1.39	61.76^{b} ± 0.96	112.08^{c} ± 1.14	95.71^{a} ± 0.74	75.07^{b} ± 0.62	129.53^{c} ± 0.16	92.240^{a} ± 0.45	62.94^{b} ± 0.64	87.65^{c} ± 3.47
pH (pH units)	7.04^{a} ± 0.09	6.90^{a} ± 0.07	6.98^{a} ± 0.08	7.39^{a} ± 0.06	7.18^{b} ± 0.03	7.11^{b} ± 0.06	7.53^{a} ± 0.04	7.42^{a} ± 0.04	7.36^{a} ± 0.06	7.70^{a} ± 0.05	7.91^{b} ± 0.10	6.96^{c} ± 0.10

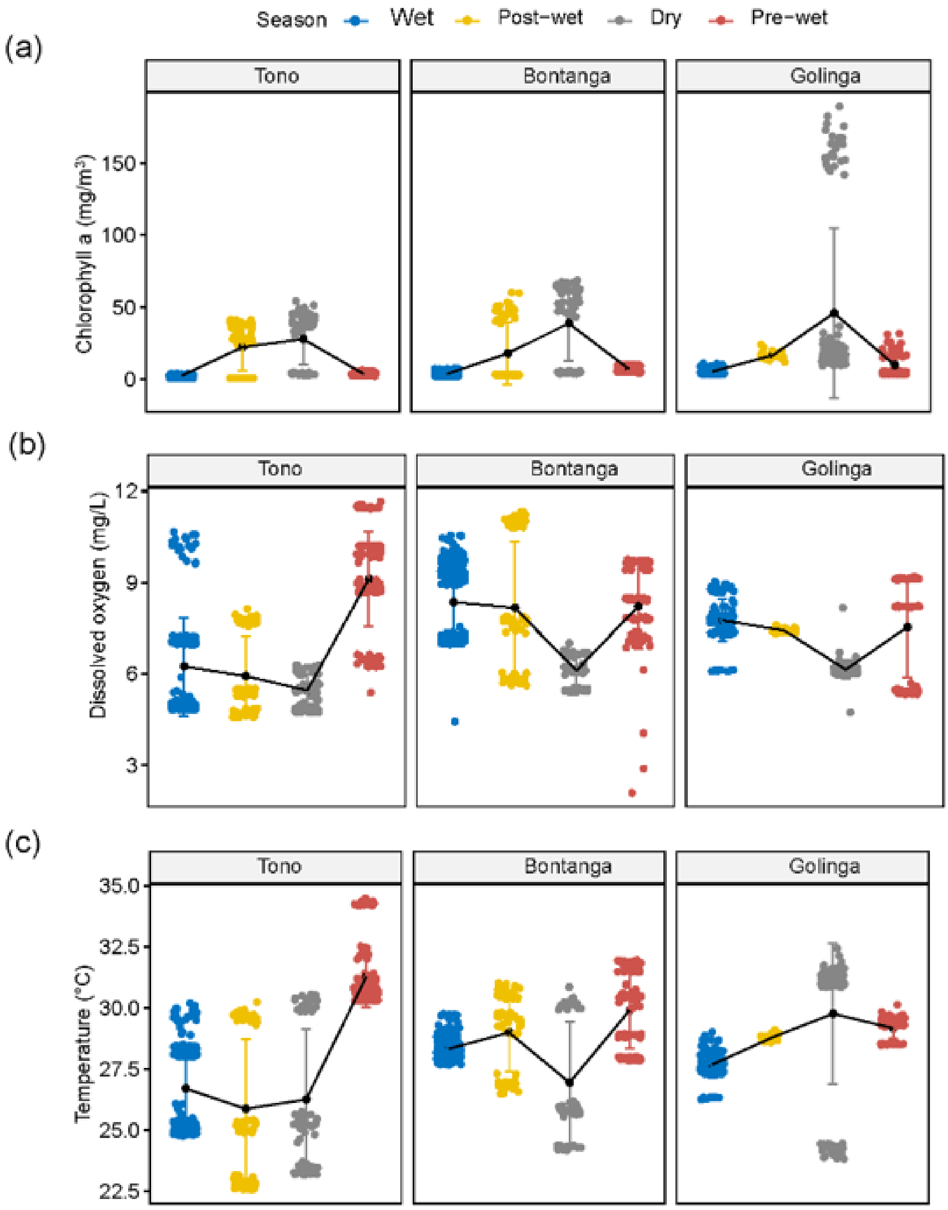

Figure 2: Seasonal variation in Chlorophyll *a* (a), dissolved oxygen (b) and temperature (c) in Tono, Bontanga and Golinga reservoirs. Wet season-July 216-September 2016; Post-wet season-October 2016-December 2016; Dry season-January 2017-March 2017; and Pre-wet season-April 2017-June 2017. The black dots and the coloured vertical lines represent the sample mean and standard deviation, respectively.

Turbidity

The average seasonal turbidity across the reservoirs ranged from 42 ± 0.22 to 544 ± 32.03 NTU, reflecting substantial variability influenced by seasonal changes and reservoir characteristics (Table 1, Figure 3a). The trends in turbidity varied both seasonally and among the three reservoirs. Both Tono and

Bontanga reservoirs exhibited similar seasonal turbidity patterns, with the highest turbidity levels recorded during the wet season. This peak is likely due to heavy rainfall, increased runoff, and sediment input into the reservoirs. Following the wet season, turbidity declined progressively through the post-wet and dry seasons, reflecting sediment settling and reduced runoff. A minor increase in turbidity was observed during the pre-wet season, possibly due to the resuspension of bottom sediments as water levels dropped and wind activity increased. Golinga reservoir, on the other hand, exhibited a distinct turbidity pattern. Like Tono and Bontanga, it showed high turbidity during the wet season due to increased runoff. Turbidity decreased significantly during the post-wet and dry seasons, likely because of sediment deposition. However, unlike the other two reservoirs, Golinga experienced a sharp and dramatic increase in turbidity during the pre-wet season, reaching the highest recorded values among all reservoirs and seasons. This could be attributed to its shallow nature, which makes it more prone to wind-driven resuspension of sediments and anthropogenic disturbances during this period. In the wet season, turbidity in Tono was significantly higher than in Golinga and Bontanga, likely due to its larger catchment area and increased sediment inflow. Golinga's turbidity was also significantly higher than Bontanga's, reflecting differences in sediment dynamics and reservoir morphology. Turbidity levels stabilized across all reservoirs during the post-wet season, with no significant differences observed. This indicates a phase of sediment settling and reduced external disturbances. In the dry season, turbidity in Golinga was significantly higher than in Bontanga, likely due to resuspension from wind and other physical disturbances. However, Golinga's turbidity was not significantly different from Tono, which showed intermediate turbidity levels. Bontanga had the lowest turbidity during this period. In the pre-wet season, turbidity in Golinga increased dramatically, becoming significantly higher than in both Tono and Bontanga. Tono and Bontanga showed similar turbidity levels, with no significant differences between them (Table 1 and Figure 3a).

Secchi disk depth (transparency)

The Secchi disk depths (SDD) of the reservoirs, indicative of water transparency, ranged from 5.77 ± 0.95 to 91.95 ± 1.50 cm across the seasons (Table 1 and Figure 3b). The seasonal trends were consistent across all three reservoirs, showing the influence of environmental conditions on water transparency. Across all three reservoirs, water transparency increased steadily from the wet season to reach its maximum during the dry season, coinciding with reduced rainfall and sediment input. This was followed by a decline in transparency during the pre-wet season, likely due to the resuspension of sediments and other disturbances as water levels dropped. In the wet season, Tono exhibited the highest Secchi disk depth (indicating the clearest water) compared to Golinga and Bontanga. Golinga's transparency was significantly higher than Bontanga, likely due to differences in sedimentation and catchment characteristics. During the post-wet season, transparency in Bontanga was significantly lower than in Tono and Golinga, which had similar Secchi depths with no significant difference. This suggests more suspended particles or higher turbidity in Bontanga during this period compared to the other two reservoirs. During the dry season, Tono and Bontanga showed no significant differences in transparency. However, Golinga exhibited significantly lower Secchi depth values, likely due to sediment resuspension in this shallow reservoir. During the pre-wet season, transparency decreased significantly across all reservoirs, with Tono recording the highest Secchi depth, followed by Bontanga (intermediate transparency), and Golinga, which had the lowest transparency. These differences highlight the greater sensitivity of Golinga to seasonal sediment dynamics compared to the other reservoirs.

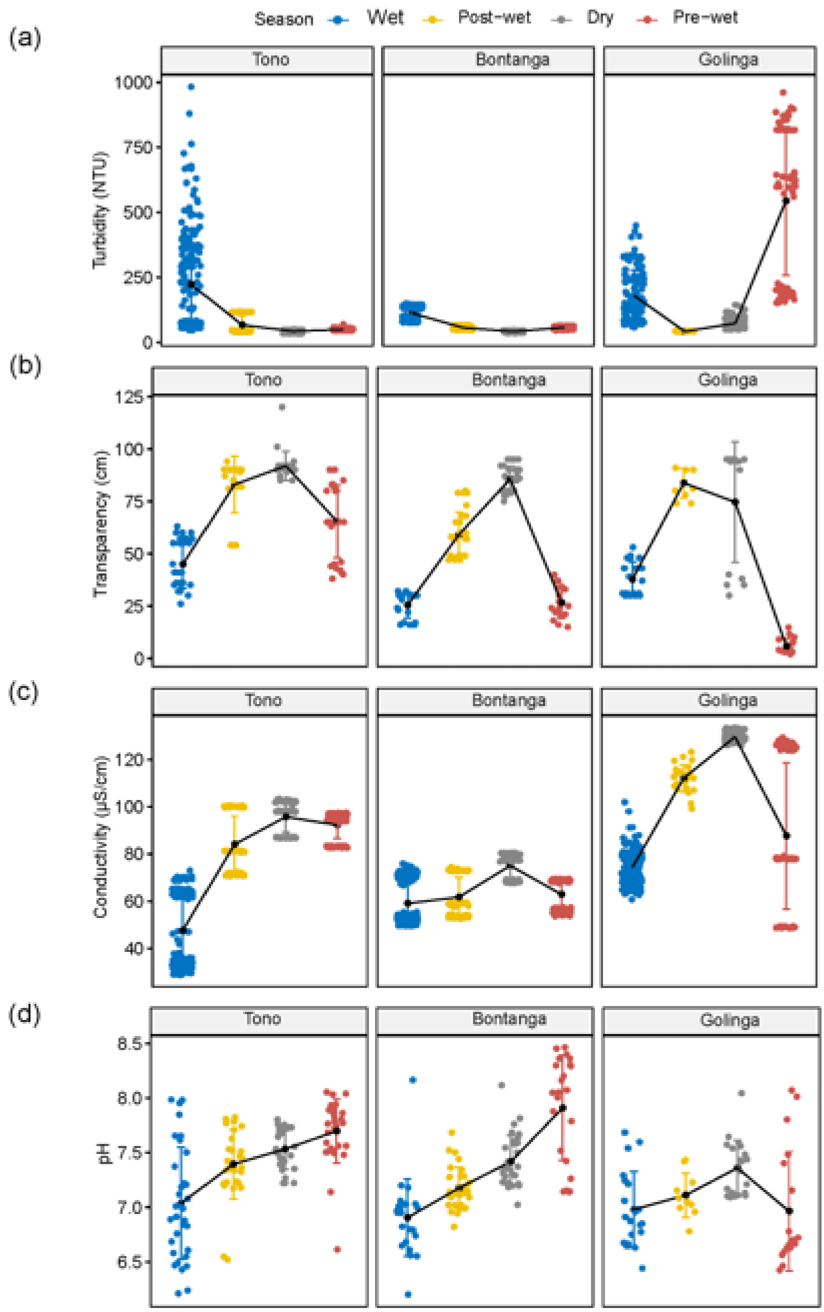

Figure 3: Seasonal variation in turbidity(a), transparency (b), conductivity (c) and pH (d) in Tono, Bontanga and Golinga reservoirs. Wet season-July 216-September 2016; Post-wet season-October 2016-December 2016; Dry season-January 2017-March 2017; and Pre-wet season-April 2017-June 2017. The black dots and the coloured vertical lines represent the sample mean and standard deviation, respectively.

Electrical conductivity.

The electrical conductivity of the reservoirs varied seasonally, ranging from 47.63 ± 1.00 to 129.53 ± 0.16 µS cm^{-1}. A consistent seasonal pattern was observed across the reservoirs, with conductivity levels increasing from the wet season to peak during the dry season, followed by a decrease during the pre-wet season. Notably, the pre-wet season's decline in conductivity was more pronounced in the Golinga and Bontanga reservoirs compared to Tono (Figure 3c). Across all seasons, significant differences in conductivity levels were recorded among the reservoirs. During the wet season, Golinga exhibited the highest conductivity, followed by Bontanga and Tono, which had the lowest values. In both the dry and pre-wet seasons, the conductivity ranking shifted slightly, with Golinga maintaining the highest levels, followed by Tono with intermediate values and Bontanga with the lowest.

Interestingly, during the pre-wet season, Tono exhibited the highest conductivity, while Golinga and Bontanga ranked second and third, respectively (Table 1 and Figure 3c). These patterns reflect seasonal variations in hydrological processes, water volume, and ion concentration dynamics, highlighting the unique responses of each reservoir to seasonal environmental changes.

Hydrogen ion concentration (pH)

The hydrogen ion concentration (pH) of the reservoirs ranged from 6.90 ± 0.07 to 7.91 ± 0.10, showing distinct seasonal variations. In the Tono and Bontanga reservoirs, pH levels exhibited an increasing trend from the wet season, peaking during the pre-wet season. However, in Golinga, the pH peaked during the dry season and then decreased during the pre-wet season (Figure 3d). No significant differences in pH were observed among the reservoirs during the wet and dry seasons. In the post-wet season, the pH in the Tono reservoir was significantly higher compared to Bontanga and Golinga, with no significant difference between the latter two. By the pre-wet season, the reservoirs displayed significant pH variations, with Bontanga recording the highest values, Tono intermediate, and Golinga the lowest (Table 1 and Figure 3d).

These seasonal and spatial pH differences underline the distinct physicochemical dynamics in the reservoirs. Further details on the seasonal variations of physicochemical characteristics within each reservoir are provided in Table 2.

Orthophosphate, nitrate-nitrogen, nitrite-nitrogen, ammonium-nitrogen, orthosilicate, dissolved organic carbon and total dissolved nitrogen bonded

The concentrations of ortho-phosphate (o-PO_4^{3-}), nitrate-nitrogen (NO_3^--N), nitrite-nitrogen (NO_2^--N), ammonium-nitrogen (NH_4^+-N), ortho-silicate (o-SiO_4^{4-}), dissolved organic carbon (DOC), and total dissolved nitrogen bonded (TDNb) across the reservoirs revealed distinct spatial patterns (Table 3).

The analysis of variance (ANOVA) indicated no significant differences in concentrations of o-PO_4^{3-}, NO_3^--N, and NH_4^+-N among the three reservoirs (o-PO_4^{3-}: F_2,29 = 1.494, p = 0.2403; NO_3^--N: F_2,12 = 0.4459, p = 0.6505; NH_4^+-N: F_2,29 = 1.267, p = 0.2969). These results suggest that the reservoirs share similar biogeochemical processes for these nutrients, potentially reflecting comparable nutrient inputs or cycling rates. Significant differences in NO_2^--N concentrations were observed across the reservoirs. Golinga had the highest NO_2^--N concentration (0.033 mg L^{-1}), significantly higher than Tono (0.0064 mg L^{-1}, p = 0.0176), while Bontanga (0.012 mg L^{-1}) exhibited intermediate values, differing significantly from neither Golinga (p = 0.2122) nor Tono (p = 0.199). These variations may indicate differences in microbial nitrification or denitrification rates among the reservoirs.

The ANOVA revealed significant spatial variation in o-SiO_4^{4-} concentrations (F_2,29 = 7.252, p = 0.0028). Tono exhibited the highest concentration (0.762 mg L^{-1}), significantly exceeding Bontanga (0.304 mg L^{-1}, p = 0.0028) and Golinga (0.329 mg L^{-1}, p = 0.0024). However, no significant difference was found between Bontanga and Golinga (p = 0.7510). The elevated o-SiO_4^{4-} in Tono may be attributed to geological inputs or hydrodynamic differences influencing silicon mobilization. DOC concentrations varied significantly across the reservoirs ($F_{2,27}$ = 6.798, p = 0.0041). Golinga recorded the highest DOC concentration (533.63 μM), significantly surpassing Tono (350.02 μM, p = 0.0098) and Bontanga (359.40 μM, p = 0.0108). Tono and Bontanga did not differ significantly (p = 0.9142). This pattern suggests differences in organic matter input, decomposition, or hydrological flushing among the reservoirs.

TDNb concentrations also differed significantly ($F_{2,27}$ = 6.798, p = 0.0041), with Golinga exhibiting the highest levels (80.22 μM), significantly higher than Tono (31.98 μM, p = 0.0011) and Bontanga (44.40 μM, p = 0.0269). No significant difference was observed between Tono and Bontanga (p = 0.1610). The elevated TDNb in Golinga may indicate higher nitrogen inputs or slower nitrogen processing relative to the other reservoirs.

Table 2: Seasonal variation in physicochemical characteristics within the reservoirs. (Mean ± standard error). Figures on the same row with different superscript letters within a lake column are significantly different. α at a 5% significance level.

Parameters	Tono				Bontanga				Golinga			
	Wet	Post-wet	Dry	Pre-wet	Wet	Post-wet	Dry	Pre-wet	Wet	Post-wet	Dry	Pre-wet
Chlorophyll *a* (mg m^{-3})	2.35^{a} ± 0.05	22.15^{b} ± 1.88	27.77^{b} ± 2.07	3.51^{a} ± 0.07	3.58^{a} ± 0.11	17.74^{b} ± 2.49	38.72^{c} ±3.14	6.83^{a} ± 0.21	5.24^{a} ± 0.15	16.62^{b} ± 0.54	45.90^{c} ± 5.35	9.73^{b} ± 0.87
DO (mg L^{-1})	6.23^{a} ± 0.10	5.92^{a} ± 0.15	5.45^{b} ± 0.06	9.11^{c} ± 0.13	8.35^{a} ± 0.07	8.16^{a} ± 0.25	6.10^{b} ± 0.06	8.21^{a} ± 0.14	7.75^{a} ± 0.06	7.42^{a} ± 0.01	6.13^{b} ± 0.03	7.53^{a} ± 0.19
Temperature (°C)	26.71^{a} ± 0.11	25.8^{a} ± 0.33	26.26^{b} ± 0.33	31.27^{c} ± 0.10	28.34^{a} ± 0.02	29.00^{b} ± 0.18	26.95^{c} ± 0.30	29.92^{d} ± 0.15	27.69^{a} ± 0.05	28.80^{b} ± 0.02	29.77^{c} ± 0.26	29.18^{b} ± 0.05
Turbidity (NTU)	222.6^{a} ± 11.85	67.0^{b} ±4.05	42.9^{b} ± 0.69	49.7^{b} ± 0.29	111.5^{a} ± 1.52	56.3^{b} ± 0.77	41.5^{b} ± 0.43	57.5^{b} ± 0.50	180^{a} ± 8.22	42^{b} ± 0.22	73.3^{b} ± 1.68	544^{c} ± 32.03
Transparency (cm)	44.93^{a} ± 2.14	83.03^{b} ± 2.46	91.95^{c} ± 1.50	65.36^{d} ± 3.26	25.42^{a} ± 1.42	59.10^{b} ± 1.98	85.64^{c} ± 1.15	26.64^{a} ± 1.80	37.75^{a} ± 1.85	83.80^{b} ± 2.24	74.67^{b} ± 7.41	5.77^{c} ± 0.95
Conductivity (µS *cm^{-1}*)	47.63^{a} ± 1.00	84.09^{b} ± 1.39	95.71^{c} ± 0.74	92.240^{d} ± 0.45	59.11^{a} ± 0.55	61.76^{ab} ± 0.96	75.07^{c} ± 0.62	62.94^{b} ± 0.64	74.39^{a} ± 0.58	112.1^{b} ± 1.14	129.5^{c} ± 0.16	87.65^{d} ± 3.47
pH (pH units)	7.04^{a} ± 0.09	7.39^{b} ± 0.06	7.53^{bc} ± 0.04	7.70^{c} ± 0.05	6.90^{a} ± 0.07	7.18^{b} ± 0.03	7.42^{c} ± 0.04	7.91^{d} ± 0.10	6.98^{a} ± 0.08	7.11^{ab} ± 0.06	7.36^{b} ± 0.06	6.96^{a} ± 0.10

Table 3: Variation in o-PO_4^{3-}, NO3-N, NO2-N, NH4-N, o-SiO_4^{4-}, DOC and TDNb in Tono, Bontanga and Golinga reservoirs based on sampling conducted between July 2016 and June 2017 (Mean ± Confidence interval).

Parameter/Reservoir	Tono	Bontanga	Golinga
o-PO_4^{3-} (mg L^{-1})	0.371^{a} ± 0.036	0.491^{a} ± 0.033	0.293^{a} ± 0.035
NO3-N (mg L^{-1})	2.402^{a} ± 0.144	2.477^{a} ± 0.192	1.618^{a} ± 0.119
NO2-N (mg L^{-1})	0.0064^{a} ± 0.0034	0.012^{ab} ± 0.0034	0.033^{b} ± 0.0035
NH4-N (mg L^{-1})	0.101^{a} ± 0.0081	0.202^{a} ± 0.0084	0.208^{a} ± 0.0086
o-SiO_4^{4-} (mg L^{-1})	0.762^{a} ± 0.020	0.304^{b} ± 0.0195	0.329^{b} ± 0.021
DOC (µM)	350.02^{a} ± 19.54	359.40^{a} ± 19.14	533.63^{b} ± 18.79
TDNb (µM)	31.99^{a} ± 2.50	44.44^{a} ± 2.45	80.22^{b} ± 2.41

Figures on the same row with different superscript letters are significantly different. α at a 5% significance level

Discussion

In the past decades, monitoring of aquatic ecosystems depended solely on collecting samples for laboratory analysis to assess ecological and management-relevant parameters. However, advances in technology now allow for the automatic monitoring of numerous parameters using in-situ sensors, with data accessible remotely via the web. Unlike traditional monitoring, which typically occurs at weekly, bi-weekly, or monthly intervals, this approach provides data at much higher frequencies–often every few minutes–enabling the detection of both short-term fluctuations and long-term trends when used over multiple years (Jennings et al. 2022). Jennings et al. (2022) used the OTT Hydrolab DS5X multi-parameter water quality probe, the same device used for this study, to monitor Irish aquatic systems and underscored its importance in conducting high-frequency in-situ monitoring of aquatic systems. The OTT Hydrolab DS5X probe has also been used to monitor Lake Untersee, Antarctica (Brady et al. 2023); global (lake, Africa, Eurasia, North America, Oceania, reservoir, South America (Sharma 2015)). In this study, we used both the high-frequency monitoring (HFM) approach, that is, the use of Hydrolab DS5 multisonde (OTT Hydromet GmbH, Germany) and the conventional laboratory approach to assess and compare the limnological parameters of the three reservoirs across the seasons. The multisonde was used to automatically and continuously monitor chlorophyll *a*, temperature, electrical conductivity, dissolved oxygen, pH and turbidity in real-time high-frequency data collection. The laboratory analyses of nutrients (o-PO4 3-, NO3-N, NO2-N, NH4-N, o-SiO4 4-, DOC and TDNb) complimented the limnological assessment of the reservoirs. Combining both approaches helps determine whether either method, in the absence of the other, can provide adequate information to categorise and/or determine the ecological condition of an aquatic environment. While HFM enables real-time tracking of short-term fluctuations, laboratory analyses provide a more detailed assessment of nutrient composition and long-term ecological health, ensuring a comprehensive evaluation of reservoir conditions. Secondly, it provides confirmative information about the state of an aquatic ecosystem.

The studied reservoirs can be considered eutrophic during the post-wet and dry seasons as indicated by the high levels of Chl-*a.* The Chl-*a* concentrations during the post-wet and dry seasons were above the desirable limit of 7-10 mg m^{-3} for tropical reservoirs (Araújo et al. 2011, Fondriest 2019). Chl-a concentrations were similar across the wet, post-wet, and pre-wet seasons, but significantly different in the dry season with Golinga recording the highest concentration of Chl-*a*, followed by Bontanga, and then Tono (the lowest concentration). The variation in Chl-*a* concentrations could be attributed to differences in organic matter inputs into the reservoirs. Additionally, seasonal shifts in light availability and temperature can influence phytoplankton growth, further contributing to observed fluctuations in Chl-a levels. The high Chl-*a* contents of Golinga during the dry season are reflected in the extreme and significantly higher turbidity levels recorded in the reservoirs in the proceeding pre-wet (Apr-Jun). The dissolved oxygen concentrations in the reservoirs were within the acceptable limits that support many aquatic animals, which indicates healthy ecosystems. The high DO levels of the reservoirs suggest that 'fish kill' in the reservoirs is unlikely if the levels are maintained. While elevated nutrient levels are observed, the reservoirs maintained dissolved oxygen concentrations above critical thresholds for aquatic life during the study period. However, prolonged eutrophication could lead to episodic hypoxic events, particularly in deeper or stratified areas. Continued monitoring is essential to assess long-term risks. Behar et al. (1997) indicated that a dissolved oxygen concentration of 0-2 mg L^{-1} is not enough oxygen to support life. While 2-4 mg L^{-1} can sustain only a few fish and aquatic insects, 4-7 mg L^{-1} is suitable for many aquatic animals, but low for cold water fish. The concentration range of 7-11 mg L^{-1} is perfect for most stream fish. The reservoir temperatures were within the typical range for man-made reservoirs in Ghana. Quarcoopome et al. (2008) reported mean annual temperatures of 29.7 °C and 30.2 °C in the Bontanga and Libga reservoirs, respectively, which are within the temperature range of this study. Webb (1960) indicated that in the tropics, rainfall is more important than temperature in determining environmental quality. According to Behar et al. (1997), the widest variety of freshwater aquatic organisms prefer a pH range from 6.5 to 8.0. pH levels of Tono, Bontanga and Golinga reservoirs were within this range across all four seasons. The transparency trend of the studied reservoirs, with higher transparency during the dry season (Jan–Mar) compared to the wet season (Jul–Sep) is similar to the pattern observed in a tropical reservoir (Funil) in Brazil (Araújo et al. 2011). The conductivity levels of the reservoirs (average seasonal concentration of conductivity ranged from 47.63 ± 1.00 to 129.53 ± 0.16 $\mu S\ cm^{-1}$) were low. Kotut et al. (1999) found that conductivity levels in Turkwell Gorge Reservoir (Kenya) ranged from 160 to 200 $\mu S\ cm^{-1}$. The nitrate levels found in the reservoirs were not above the limit of 10 mg L^{-1}. According to Behar et al. (1997), concentrations over 10 mg L^{-1} may affect the freshwater aquatic environment. The average phosphate contents of the reservoirs (Table 3) were above the range of 0.02-0.29 mg L^{-1} recorded in the Bui dam area of the Black Volta in Ghana (Alhassan et al. 2015). However, low phosphate content in the range of 0.5-0.75 mg L^{-1} was recorded in the Asejire reservoir in Nigeria (Egborge 1979).

The significantly higher values of turbidity recorded during the rainy season are attributed to surface runoff. During the rainy season, runoff from agriculture fields and other urban sources introduces high loads of suspended matter into reservoirs and the occurrence of algae and aquatic weeds contributes to high turbid waters (Asante et al. 2008). The variability in turbidity reflects the interplay of seasonal rainfall, runoff, sedimentation, and resuspension dynamics specific to each reservoir. While Tono and Bontanga exhibited similar seasonal patterns, Golinga's unique turbidity peaks during the pre-wet season highlight its sensitivity to environmental and anthropogenic disturbances. These findings emphasize the importance of considering individual reservoir characteristics when developing management strategies for water quality and sediment control. To mitigate the impact of anthropogenic activities, we recommend implementing buffer zones around reservoirs to reduce agricultural runoff, establishing sediment control structures to manage turbidity, and enforcing sustainable farming practices such as reduced fertilizer application and agroforestry. Additionally, community-based watershed management programs should be promoted to engage local stakeholders in conservation efforts. Land-use activities in the reservoir catchments, particularly agricultural expansion and deforestation, contribute to increased nutrient and sediment loads. Previous studies in Ghanaian wetlands (Nsor and Obodai 2016) and reservoirs (Abobi et al. 2023) have shown that land use significantly influences turbidity and nutrient concentrations. Future studies should incorporate spatial analyses of land-use changes to provide a more comprehensive understanding of watershed impacts on reservoir conditions. Considering the high levels of DOC, TDNb, NO2-N, and turbidity, it is evident that the smallest shallow (Golinga) reservoir is significantly more impacted than the other two reservoirs. Studies on changes in these limnological parameters are important in understanding variability in fish distribution patterns. Particularly, nitrate-nitrogen, phosphate, conductivity, temperature and turbidity have been noted to influence fish community structure in wetlands in the Northern Region of Ghana (Nsor and Obodai, 2016). Olds et al. (2011) reported changes in chlorophyll a, turbidity, temperature, and dissolved oxygen over 7 months (April–October) during 2003–2006 (drought conditions) and 2007–2009 (normal conditions) at 15 locations of a Nebraska reservoir. Chlorophyll *a* and turbidity were both significantly greater during drought conditions in most months.

Dissolved oxygen predominately decreased during drought conditions, while water temperature did not change. Except for turbidity, our findings on seasonal changes in chlorophyll *a*, dissolved oxygen, and temperature align with those of Olds et al. (2011). In all three reservoirs, Chlorophyll *a* was significantly high during the dry season, while dissolved oxygen was significantly low during the same season (Table 2). There is increasing evidence that inland fish production in Africa is more dependent on external climatic drivers, such as seasonal variability of water levels (Gownaris et al. 2017, Jul-Larsen et al. 2003, Kolding et al. 2016b, Kolding and Van Zwieten 2011, Kolding and Van Zwieten 2012). Fluctuations in the water levels of the three reservoirs have been previously studied. A study by Abobi and Wolff (2020) observed a significant reduction in water levels of Tono, Bontanga and Golinga reservoirs from the flood (wet) season to the dry season. Trends in rainfall, evaporation and siltation are crucial to the resilience and productivity of reservoirs in West Africa (Abobi and Wolff 2020). Subsequently, the need to include precipitation and inflow patterns when examining water quality parameters of reservoirs cannot be overemphasized.

Farming activities lead to an increase in turbidity in lakes, reservoirs, and wetlands (Abobi 2020, Abobi et al. 2023, Cooper et al. 2016, Nsor and Obodai 2016). Furthermore, siltation has been noted as the most important factor that affects reservoir shape, size, and turbidity. It results from the excessive transport of sediments and silts from reservoir catchment areas (Abobi 2020). Based on the high turbidity levels observed, controlling runoff from agricultural fields is crucial in maintaining healthy reservoir ecosystems. Farming practices such as ploughing land, slashing and burning, and animal grazing in the catchment areas of the reservoirs are sources of phosphate. Moreover, these practices contribute to high turbidity and eutrophication in the reservoirs, which may adversely impact the aquatic organisms.

The observed seasonal changes in chlorophyll-a, dissolved oxygen, and turbidity in the Ghanaian reservoirs align with findings from other tropical systems, such as the Tapacurá Reservoir in Brazil (Bouvy et al. 2003) and Amazonian floodplain lakes (Kraus et al. 2019). In comparison to other African reservoirs, our findings align with studies in Nigeria's Asejire Reservoir (Egborge 1979) and Kenya's Turkwell Gorge Reservoir (Kotut et al. 1999), where seasonal variations in turbidity, dissolved oxygen, and nutrient levels were observed. These similarities highlight the broader applicability of our results across tropical reservoirs in Africa, further emphasizing the influence of seasonal hydrological cycles on water quality. However, the influence of anthropogenic activities appears more pronounced in the Golinga reservoir, reflecting trends seen in reservoirs subjected to intensive agricultural runoff, such as Turkwell Gorge Reservoir in Kenya (Kotut et al. 1999). The combination of high-frequency monitoring and laboratory analysis used in this study offers insights similar to those reported by Jennings et al. (2022) in Irish aquatic systems, underscoring the global utility of these methods for assessing ecological conditions.

The study highlights unique spatial and seasonal variations in nutrient and carbon concentrations across reservoirs in the region. The significant differences in NO_2^--N, o-SiO_4^{4-}, DOC, and TDNb concentrations underline the influence of reservoir-specific factors such as hydrodynamics, organic matter decomposition, and nutrient inputs. The findings on o-SiO_4^{4-} and DOC provide valuable insights into the silicon and carbon dynamics, which are often underrepresented in similar studies. Elevated silicon levels in Tono suggest geological contributions, while high DOC and TDNb in Golinga emphasize organic and nitrogenous material inputs. The variations in DOC and nitrogen species highlight potential implications for water quality and reservoir management, particularly concerning eutrophication risks and organic matter decomposition.

Although this study evaluated seasonal changes over one year, it is important to note that the seasonal changes as reported in this study might not be consistent all over the years. Reservoirs may experience interannual variability in the parameters studied. The variations could be driven by yearly changes in precipitation patterns. Interannual variability in limnological characteristics has been observed in both African and Asian reservoirs (Kolding and Van Zwieten 2012), with similar findings in Amazonian floodplain lakes (Kraus et al. 2019) and the Tapacurá Reservoir in Brazil (Bouvy et al. 2003). Also, results show significant variations in some parameters between the reservoirs. Differences in organic input from terrestrial sources, mean depth, water level fluctuation, and reservoir size (Abobi and Wolff 2020) impact the result, thereby making it challenging to generalise the findings across different reservoirs. To understand the long-term trends and the impacts of various factors on the reservoir's limnological conditions, an extended longer-term study is required to strengthen the temporal analysis and implications of the study. Future research should incorporate multi-year datasets, integrating climatic and hydrological variables to assess the resilience of reservoirs to interannual variability. While the study provides valuable and crucial information on the limnological parameters of the reservoirs, the above limitations imply that further research with extended temporal and spatial scope is needed to fully understand and manage the reservoir systems effectively. As checks on the models' leverage (Quinn and Keough 2002) showed some influential deviations which are due to the unbalanced sample sizes, the models' results should be interpreted cautiously. A follow-up study with balanced data across the parameters, the three reservoirs and the four seasons is needed to apply these results to similar projects.

Conclusion

In this study, we assessed differences in the limnological features of three Ghanaian reservoirs, namely Tono, Bontanga and Golinga reservoirs. The monitored parameters exhibited significant temporal and spatial variations across the three reservoirs. The Golinga reservoir, being the smallest and shallowest, showed higher concentrations of DOC and TDNb compared to Tono and Bontanga reservoirs. Conversely, the Tono reservoir, which is large and deep, had significantly higher concentrations of o-SiO4 4- compared to the other two reservoirs. There were no significant differences among lakes in the concentrations of o-PO4 3-, NO3-N and NH4-N. Dissolved oxygen (DO) levels in all reservoirs were within the optimal range necessary to sustain aquatic life, indicating healthy oxygenation. The high concentrations of nitrate-nitrogen promote photosynthetic activity, driving primary production in the reservoirs.

While this study provides valuable insights into the limnological features of these reservoirs, it is important to acknowledge the limitations of the monitoring period (one year) and the lack of hydrological data. The short monitoring duration limits the ability to detect interannual variability and long-term trends in water quality. Moreover, the absence of hydrological data on inflows, outflows, and precipitation restricts our understanding of the full range of factors influencing water quality dynamics. Future studies should aim to extend the monitoring period and include hydrological data to offer a more comprehensive understanding of the environmental processes affecting water quality in these reservoirs.

The study found that smaller reservoirs, though highly productive, are more susceptible to pollution from anthropogenic activities, such as agricultural runoff, which negatively impacts water quality. However, it is important to note that this conclusion is drawn from only three reservoirs. While the observed trend suggests that smaller, shallow reservoirs may be more vulnerable to pollution, this finding should not be generalized to all smaller reservoirs, as the impacts may vary depending on other factors such as land-use practices and management strategies. Further research, involving a broader range of reservoirs, is needed to better understand how anthropogenic activities affect smaller reservoirs across different environmental contexts.

In addition to summarizing the findings, this study highlights the significant role of reservoir size, depth, and hydrological characteristics in shaping water quality. These insights offer a basis for future research that can explore the interplay between catchment characteristics, human activities, and water quality in diverse reservoir settings.

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Declaration of interest

The authors declare no conflicts of interest.

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