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Spatio-temporal variations in selected water quality parameters and trophic status of Lake Baringo, Kenya

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Abstract

Lacustrine and riverine ecosystems provide important goods and services, including being habitats for aquatic biodiversity, local micro-climate moderation and a source of economic livelihoods for riparian communities. At the same time, however, they fact continuing anthropogenic and natural threats that can affect their water quality, ecological integrity and biodiversity. The present study focused on assessing spatio-temporal variations in water quality and trophic status of Lake Baringo, a Ramsar site in Kenya. A number of physicochemical parameters, including nutrient loads, trophic status and organic pollution indices, were evaluated for the lake from water samples collected from March 2008 to December 2020. The results of the present study indicated five parameters (turbidity, fluoride, SiO_4^{4-}, total phosphorus and DO) exceeded the permissible limits for drinking water based on WHO standards. The water quality index (WQI) values ranged between 556.04 and 693.54, being well above the WHO recommended limit (WQI = 100), indicating Lake Baringo water to be unsuitable for human consumption. The fluoride (F^-) ions and water turbidity contributed the most relative weights to the lake's WQI. The organic pollution index (OPI) for the lake varied from 4.33 to 4.67, significantly above the organic pollution scale of 1.0–3.9 and indicating the lake is not organically polluted. A positive relationship was found between turbidity and rainfall, suggesting the influence of catchment activities on the lake. The nutrient load had less effect on both the WQI and OPI of the lake, indicating low inputs from the catchment. The lake's trophic status shifted between eutrophic and mesotrophic conditions from 2008 to 2020, based on the Carlson's trophic status index (CTSI) values. Application of a holistic and integrated lake basin management (ILBM) approach is recommended for the management of Lake Baringo and its watershed in order to sustain its ecological processes and the associated riparian community economic livelihood support from the lake.

KEYWORDS
organic pollution index, physicochemical parameters, water quality and trophic status indices, watershed management

1 | INTRODUCTION

Aquatic ecosystems such as lakes and rivers provide habitats for a range of biodiversity, perform important ecological services and serve as a source of economic livelihoods for local communities. At the same time, however, lakes and rivers are facing intense human pressures and natural influences that affect their water quality and ecological integrity (Dudgeon et al., 2006). Safe water quality for human consumption is considered a human rights issue by the World Health Organization (WHO, 2008). Pollution and deterioration of water quality from heavy nutrient and chemical loads compromise the ecological and livelihood services provided by aquatic ecosystems (Wetzel, 2001). Anthropogenic activities are a major source of nutrient and trace metal loads to water bodies (Li et al., 2009; Lina, 2016). In turn, these affect ecological processes either through eutrophication, biomagnification and accumulation of metals, in addition to reducing both the aesthetic conditions and the different ecosystem services to the riparian communities (Dudgeon et al., 2006; Wetzel, 2001). Thus, water quality monitoring programmes for aquatic ecosystems are useful in determining whether or not lake and river water properties are suitable for aquatic life and various livelihood uses (Şener et al., 2013).

Lake Baringo is a shallow freshwater lake located in the eastern arm of the Great Rift Valley in Kenya and is recognized as a Ramsar Site because of its rich biodiversity (ramsar.org). It supports a significant fishery and human livelihoods in a semi-arid area (Omondi et al., 2014). Unfortunately, the lake ecosystem has become degraded over time because of the increasing pollutant loads from multiple sources, including settlements, agricultural and surface runoff from the watershed (Odada et al., 2006; Omondi et al., 2014). Deterioration of the lake's water quality has also been attributed to irrigation water abstractions, as well as turbidity and sedimentation changes attributable to excessive livestock grazing leading to erosion in the lake catchment (Bryan, 1994; Onyando et al., 2005). Impairment of the lake water quality because of the diverse pollutants (organic and non-organic) has the potential to affect lake productivity, ecological functions and species distribution and diversity.

Despite studies on the anthropogenic influences on the lake (Odada et al., 2006), the observed lake water level fluctuations (Odada et al., 2006; Okech et al., 2019; Omondi et al., 2014) and recent climatic influences on the fishery (Nyakeya et al., 2018), there has been a minimal attempt to evaluate the water quality changes in Lake Baringo using ecologically relevant indices. In addition, the effects of the changes on the ecological processes of the lake have not yet been studied. Thus, to bridge the information gap, the present study assessed the spatio-temporal changes in the water quality properties of the lake in relation to established international thresholds, and also assessed their potential effects on the lake's ecological processes. The information generated in the present study also can be applied in monitoring and managing the lake environment.

2 | METHODS

2.1 | Study area

Lake Baringo (Figure 1) is a shallow freshwater lake located in the eastern arm of the Great Rift Valley in Kenya. It is also a designated Ramsar Site (Ramsar, 2002), famous for its high bird diversity, hippopotamus and crocodile populations (Odada et al., 2006). The lake is located between latitude 0°30′N and 0°45′N and longitude 36°00′E and 36°10′E, lying approximately 60-km north of the Equator at an altitude of 975-m above sea level (Kallqvist, 1987). The lake has a surface area of approximately 130 km^2 and a catchment of 6.820 km^2 (Ondiba et al., 2018), with an average depth of 3 m, and the deepest point being about 7 m (Odada et al., 2006). However, with the heavy rains experienced in 2011 in Kenya and the eastern arm of Africa, the lake's surface area was reported to have increased to 207 km^2 in 2016 (Obando et al., 2016; Okech et al., 2019). A recent study depicts a further lake surface area increase to more than 250 km^2 in 2019, with the current deepest point being 15.8 m (Nyakeya et al., 2020). Lake Baringo's surface area and depth may vary greatly from the reported figures due to recently observed rising water levels occasioned by increased precipitation since early-2020 (Aura et al., 2020).

Although Lake Baringo is located in a semi-arid zone, its catchment covers a range of climatic zones, from semi-arid through semi-humid and subhumid, to a small portion in the humid zone. The lake environment experiences low and unsteady annual rainfall ranging between 500 and 750 mm, with a mean annual potential evaporation varying between 1650 and 2300 mm, being characteristic of semi-arid zones (Ngaira, 2006). The lake is fed by two main rivers, the perennial Perkerra River and the Molo River, which has become seasonal in recent years because of damming (Nyakeya et al., 2020, Riziki, pers. obs.), and as well as other temporary rivers, including the Endau, Makutani and Ol Arabe Rivers (Figure 1). Although Lake Baringo has no surface outflow, its water remains fresh because of underground seepage estimated to exceed 108 m^3/year (Dunkley et al., 1993; Ngaira, 2006).

2.2 | Sampling

A total of 126 previously collected water samples collected monthly from March 2008 to June 2019 by the Kenya Marine and Fisheries Research Institute (KMFRI), Baringo research team were used in the present study. These data were supplemented by an additional twelve water samples collected by University of Eldoret scientists in collaboration with KMFRI during 2020. The samples were collected in triplicates at each sampling site. The five sites were chosen because they were regularly sampled by KMFRI, and because they highlighted the availability and consistency of the data before and after the lake levels dramatically increased over time. The sites also were selected to provide representative coverage of the lake surface. The five selected sites included one station in the northern

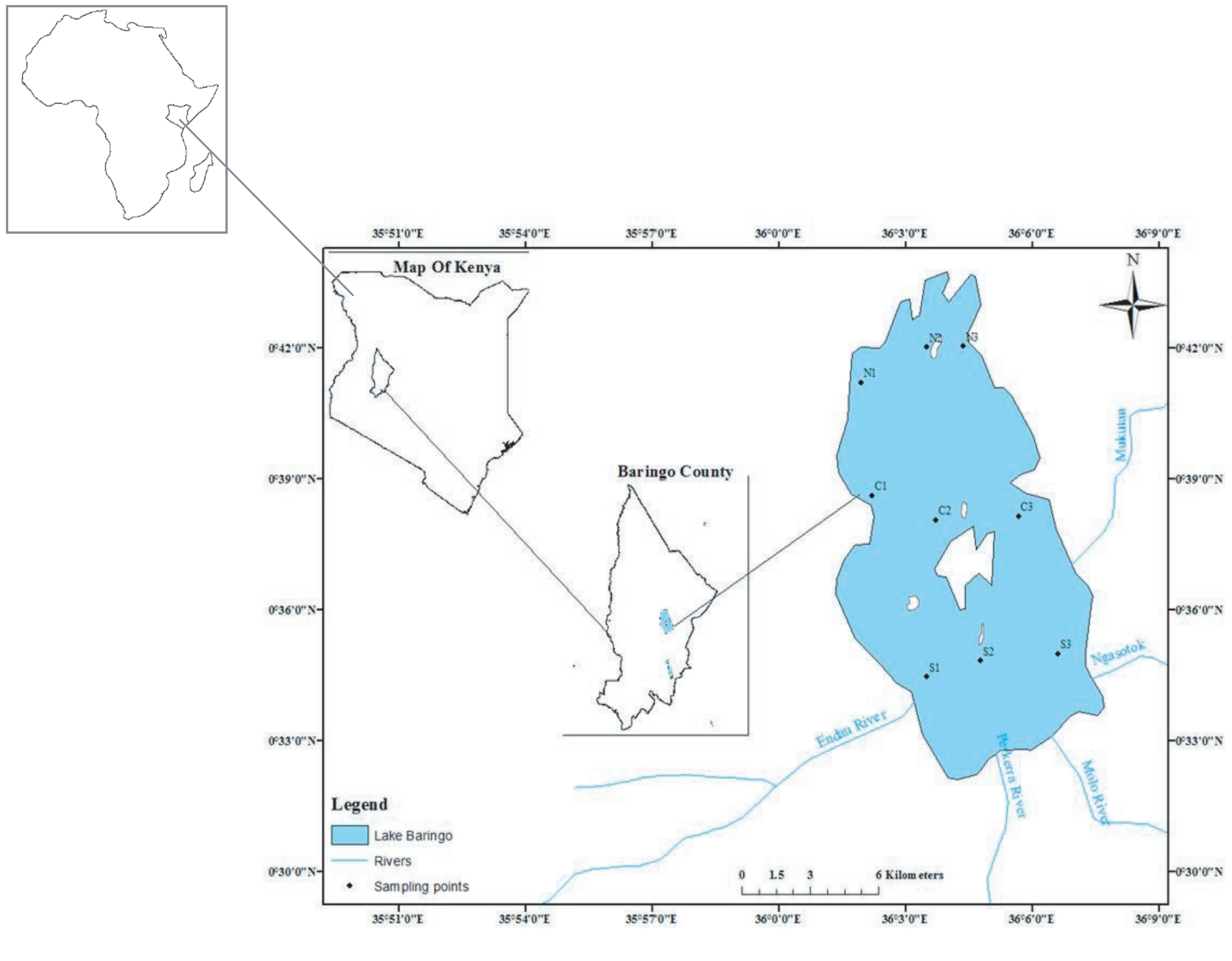

FIGURE 1 Map of Lake Baringo (Kenya) showing sampling sites (S2, southern station; C1, C2 and C3, three stations in central part of lake; N2, northern station; adapted from Nyakeya et al., 2020)

part (N2), three sampling sites in the central part (C1, C2 and C3) and one station in the southern part (S2) (Figure 1). S2 experienced daily influences of the Molo River and partly from the Perkerra River. Station C3 experienced the influence of the Molo and Mukutan rivers. Station C1 was situated on the western side adjacent to rocky shores, while N2 was located in the north without any river influence.

The geographical positions of the sampling sites were recorded with a hand-held GPS. Water samples for analysis of nutrients, total suspended solids (TSS) and chlorophyll-*a* concentrations were collected monthly directly from the lake surface with clean pre-treated 1-litre polyethylene sample bottles (APHA, 2005). The bottles were labelled, filled and the samples were carried in cooler boxes at about 4°C in transport from the lake to the laboratory. Water samples for chlorophyll-*a* analysis were filtered in the laboratory with GF5 filter papers (47 mm diameter; 0.7 μm pore size) within 24 h of collection. The vials were labelled after filtration and preserved in a refrigerator at −20°C for chlorophyll-*a* analysis. The extraction of chlorophyll-*a* was undertaken through a sonication process (APHA, 2005) and the concentrations were calculated following the Lorenzen equation (APHA, 2005) using absorbance readings obtained with the UV-spectrophotometric method.

Monthly average rainfall, humidity and air temperature data for the 2008–2020 period were obtained from an online station (https://www.worldweatheronline.com/baringo-weather-averages/rift-valley/ke.aspx).

2.3 | Analytical procedures

Measurements of pH, total dissolved solids (TDS) and dissolved oxygen (DO) concentrations, temperature (*T*) and electrical conductivity (EC) were carried out in situ with a Professional Plus multi-parameter instrument (YSI 550) calibrated with standard solutions (SMEWW, 1998). In situ measurements of turbidity (TUR) were performed with a calibrated portable turbidimeter probe (HACH 21000Q), which was calibrated using standard chemical solutions made of stabilized formazin with turbidity values of 20, 100 and 800 NTU (HACH, 2009). Samples exhibiting turbidity exceeding

800 NTU were diluted with distilled water to convert them into the turbidimeter reading capacity limits (HACH, 2009). The turbidity of the diluted samples was then estimated by multiplying the actual reading by the number of dilutions applied to the sample. Water transparency (m) was measured with a standard Secchi disk (20 cm diameter). The measured Secchi depth values were used to calculate the eutrophic zone (Zeu) of the lake at each sampling site. The euphotic zone (Zeu), the depth at which photosynthetically available radiation (PAR) is 1% of its surface value, was estimated as Zeu = 4.6/k (Bartram & Balance, 1996) and derived from estimates of the vertical light extinction coefficient from the Secchi disk transparency using a coefficient k (k = 1.5/Secchi disk depth in metres) at each sampling site.

A UV-spectrophotometer was used to determine the ammonium, phosphate, total phosphorus, nitrite, nitrate, total nitrogen and silica concentrations, following the procedures of APHA (2005) and Bartram and Balance (1996). The soluble reactive silica (SRSi) concentration was determined with the molybdate complex method, while the soluble reactive phosphorus (SRP) was determined with the molybdenum blue method (APHA, 2005). The ammonium (NH_4^+) concentration was determined with the dichloroisocyanurate–salicylate method, the nitrate (NO_3) concentration by the cadmium reduction method and the nitrite (NO_2^-) concentration by the azo–dye complex formation (APHA, 2005; Rodier et al., 2009).

The total phosphorus and total nitrogen concentrations were determined with the ascorbic acid reduction method and the diazotization method, respectively, using unfiltered water (APHA, 2005). The total alkalinity was estimated by the volumetric method, using sulphuric acid (H_2SO_4), phenolphthalein and methyl orange indicator (APHA, 2005). The fluoride ion (F^-) concentrations were determined with titrimetric methods, based on titration of a sample with aluminium chloride, while the chloride ions were determined with silver nitrate ($AgNO_3$) titration (Bartram & Balance, 1996). The total suspended solids (TSS) concentrations were determined by filtering a known volume of lake water through GF/C filters that were first dried and pre-weighed and then oven-dried after filtration. The final weights were taken to determine the difference as the TSS weight (g) per unit volume of the sample (Rodier et al., 2009). The total dissolved solids (TDS) concentrations were determined using filtration and gravimetric methods with a temperature-controlled oven. Alkaline potassium persulphate was used for total nitrogen (TN) digestion at 210 nm, while the TP was first oxidized by potassium persulphate under pressure and then analysed with the ammonium molybdenum method using UV-spectrophotometry on unfiltered water samples.

The water total hardness content was determined by the complexometric method using EDTA solution. The various analytical methods and procedures are described in detail by APHA (2005). Most of the water quality analyses were performed at the KMFRI Baringo Station water quality laboratory, with additional analysis at the KMFRI Kisumu laboratory.

2.4 | Data treatment and statistical analyses

The water quality parameter values were evaluated using the water quality index (WQI) as an indicator of the suitability of the lake water for human consumption and multipurpose uses (WHO, 2008), while organic pollution index (OPI) was used as an estimate of the organic load in the lake (Leclercq & Maquet, 1987). The WQI was calculated using the weighted arithmetic method (Brown et al., 1972). The calculated values were compared to various international standard guidelines (WHO, 2008, 2011). Two-way analysis of variance (ANOVA Two-Factor) was performed to determine the influence of both the sampling sites and years (time) on the water quality parameters in the lake. The mean values of the parameters with significant differences between the sampling sites ($p < .05$) were compared using one-way ANOVA on log-transformed data combined for the study years. Because the year effects were significant (see Table S1), the temporal variation of the variables for the years 2008–2020 were plotted and smoothed trend lines were fitted to the data series using a locally weighted-scatterplot smoother (LOWESS; Cleveland, 1979) in the MINITAB statistical package. The LOWESS is based on a weighted least-squares algorithm that attributes local weights with the most influence, while also minimizing the effects of outliers. A smoothness parameter (f) of 0.2 was found to adequately smooth the data without distorting the temporal patterns.

The co-variation among the physicochemical parameters, including the WQI, was tested using Pearson's linear correlation. The trophic status of Lake Baringo was estimated according to the Istvánovics (eutrophic status estimation based on water quality parameter values) and Carlson's (status estimation based on trophic status indices) methods (Carlson, 1977). All analyses were carried out using the PAST 32.6b statistical package.

2.5 | Calculation of water quality index

The WQI is defined as a rating reflecting the composite influence of different water quality parameters (Ramakrishnaiah et al., 2009; Sahu & Sikdar, 2008). Each chemical parameter (e.g. pH, TDS, turbidity, total alkalinity, hardness, fluoride, nitrate, nitrite, silica, phosphate) is assigned different weights (AW_i) on a scale of 1 (least effect on water quality) to 5 (highest effect on water quality), based on its perceived human health effects and its relative importance in regard to drinking water or groundwater quality (Brown et al., 1972; Şener et al., 2017). The highest weight of 5 was assigned to parameters having critical human health effects and whose presence exceeding critical concentration limits could hinder its use for domestic and drinking purposes (Bhateria & Jain, 2016; Şener et al., 2017). Nutrients and fluoride were assigned the highest weight (5) in the present study because of their health influences (Sahu & Sikdar, 2008; Yidana & Yidana, 2010) and their water quality importance, while a minimum weight of 1 was assigned to total alkalinity and electrical conductivity because of their least water quality importance (Brown et al., 1972; Katyal, 2011). The relative weight (RW_i) was then computed from the following equation (Şener et al., 2017):

$$RW_i = \frac{AW_i}{\sum_i^n AW_i} \quad (1)$$

where AW_i = assigned weight of each parameter; and n = number of parameters. A quality rating (Q_i) for each parameter (except for pH and DO concentration) was then assigned by dividing its concentration (C_i) in each water sample by its limits values/standards of the WHO (2008, 2011), with the result being multiplied by 100, as follows:

$$Q_i = \frac{C_i}{S_i} \times 100 \quad (2)$$

where Q_i = quality rating; C_i = concentration of the chemical parameter in each water sample (mg/L); and S_i = drinking water standard for the chemical parameter (mg/L), according to WHO (2008) guidelines.

The quality rating for pH or DO (QpH; DO) was calculated on the basis of the procedure of Alobaidy et al. (2010), as follows:

$$Q_{ph}, DO = \frac{[C_i - V_i]}{S_i - V_i} \times 100 \quad (3)$$

where, V_i = ideal value (considered to 7.0 for pH; 14.6 for DO; WHO, 2011).

Equations (2) and (3) ensure $Q_i = 0$ when a pollutant is absent in the water, and $Q_i = 100$ when the value of this parameter is just equal to its permissible value (Bhateria & Jain, 2016). Thus, the higher the Q_i value, the greater the pollution status of the water.

To calculate the WQI, therefore, the sub-index (SI_i) value is first determined for each water quality parameter, and then used to derive the WQI with the following equations (Bhateria & Jain, 2016; Kumar et al., 2018):

$$SI_i = RW_i \times Q \quad (4)$$

and

$$WQI = \sum_1^n SI_i \quad (5)$$

where SI_i = sub-index of an ith parameter; and Q_i = quality rating based on concentration of the ith parameter. The computed WQI values were classified into five categories ranging from 1 (excellent) to 5 (unsuitable for drinking), as summarized in Table 1 following the equation proposed by Bhateria and Jain (2016). Thus, the highest WQI reflects the poorest water quality of the lake in space and time.

The effective weights (EW_i) of each water quality parameter correspond to its influence on the water quality. The EW_i values were calculated using the derived WQI values. The effective weight for each parameter was derived by dividing its sub-index value (SI_i) by the overall WQI value, and the result multiplied by 100, as follows (Şener et al., 2017):

TABLE 1 Water quality classification based on WQI values (adopted for Lake Baringo from Bhateria & Jain, 2016)

N°	WQI values	Water quality
1	<50	Excellent water
2	50–100	Good water
3	100–200	Poor water
4	200–300	Very poor water
5	>300	Unsuitable for drinking

$$EW_i = \frac{SI_i}{WQI} \times 100 \quad (6)$$

where EW_i = effective weight of ith parameter; SI_i = sub-index value of ith parameter (Equation 4); and WQI_i = overall WQI computed with Equation (5).

2.6 | Calculation of organic pollution index

The organic pollution index, a measure of the organic load, was calculated for each sample collected at all five sites, following the procedure described by Bahroun and Bousnoubra (2011). The OPI derivation is based on calculation of the average of four parameters, including the biological oxygen demand (BOD), ammonium, nitrite and phosphate concentrations (Bartram & Balance, 1996). The concentrations were compared with the standard limits to determine the parameter class numbers (Rodier et al., 2009; Tables 2 and 3). The OPI class for the samples in the present study was evaluated using three nutrient variables (ammonium, nitrite and phosphate concentrations) of the recommended parameters. The biochemical oxygen demand (BOD) was not determined during the data collection. The OPI was then calculated as the average of the class numbers (Table 2) of the three parameters used in the present study (Bahroun & Bousnoubra, 2011). Thus, the lower the OPI value, the more organically polluted is the water body, based on categories in Table 3.

2.7 | Lake Baringo trophic status estimation

The trophic status of Lake Baringo was evaluated using information about the limiting nutrient concentration (total phosphorus), chlorophyll-*a* as an indicator of phytoplankton biomass and sediment transparency (dependent on both algal biomass and sediment resuspension; expressed as Secchi depth; Istvánovics, 2010). The nutrient availability was assessed considering the concentrations of readily bioavailable inorganic nutrients, the total nitrogen: total phosphorus ratio (TN:TP ratio) and the SRP and DIN ratio (the latter comprising nitrate plus nitrite) and ammonium (OECD, 1982; Reynolds, 1999). The N limitation was considered probable when the molar TN:TP ratio was <10, and P limitation when the TN:TP ratio

TABLE 2 Parameter classes and limits for OPI index calculation for Lake Baringo (adopted from Leclercq & Maquet, 1987)

Parameter classes	Ammonium concentration (mg N/L)	Nitrite concentration (μg N/L)	Phosphate concentration (μg P/L)
5	<0.1	5	15
4	0.1–0.9	6–10	16–75
3	–2.4	11–50	76–250
2	2.5–6.0	51–150	251–900
1	>6	>150	>900

TABLE 3 Categories of water pollution based on OPI index and colour of water (adopted from Leclercq & Maquet, 1987)

Category of pollution	OPI	Colours allocated to index
Null pollution	5.0–4.6	Blue
Weak pollution	4.5–4.0	Green
Moderated pollution	3.9–3.0	Yellow
Strong pollution	2.9–2.0	Orange
Very strong pollution	1.9–1.0	Red

was >20 (Stephen et al., 2020). The Carlson's trophic state index (CTSI; Carlson & Simpson, 1996) was also used to evaluate the lake's trophic status. The accepted standard limits for evaluating the lake trophic status were adopted from the Organization for Economic Cooperation and Development (OECD) for the individual parameters (total phosphorus; chlorophyll-*a*; Secchi depth) and Carlson and Simpson (1996).

The trophic status of a lake or reservoir ecosystem (TSI), based on the individual parameters with a scale of 0–100, was used in this analysis. The calculated TSI value facilitates a qualitative description of a lake's trophic status.

The TSI is split into five groups (0–20; 20–40; 40–60; 60–80;80–100) corresponding to five lake trophic states (hyper oligotrophic; oligotrophic; mesotrophic; eutrophic; hypereutrophic respectively; Likens et al., 1977).

The CTSI (Al-Haidarey et al., 2016) was calculated on the basis of the individual parameter values, using the following formulae:

$$\text{TSI for chlorophyll - } a\, \text{TSI (chl - } a) = 9.89 * \ln\left[\text{chl - } a\left(\frac{\mu g}{L}\right)\right] + 30.6 \quad (7)$$

$$\text{TSI for Secchi depth TSI (SD)} = 60 - 14.41\,\%\,(\text{SD})(\text{m}) \quad (8)$$

$$\text{TSI for Total phosphorus TSI (TP)} = (14.42 * \text{TP}(\frac{\mu g}{l})) + 4.15 \quad (9)$$

The CTSI was then obtained by calculating the average of Equations (7–9) as follows (Al-Haidarey et al., 2016):

$$(\text{CTSI}) = \frac{[\text{TSI(TP)} + \text{TSI(CA)} + \text{TSI(SD)}]}{3} \quad (10)$$

Based on the TSI parameter values obtained with Equations (7–9) the trophic state of Lake Baringo was determined according to Table 4 (Carlson & Simpson, 1996).

3 | RESULTS

3.1 | Physicochemical water quality parameters and quality standards

The variations of the physicochemical parameters and nutrient loads of the lake between years (n = 13) and sampling sites, tested using two-way ANOVA, are presented in Table S1. There were significant influences of sampling site and year of sampling for all the physicochemical and nutrient variables in the lake except for turbidity (Table S1). The interactions between years and sampling sites were significant for all the measured variables, except for turbidity, Secchi depth and chlorophyll-*a* and TN concentration. The lake water quality parameters and their international standard limits for both human consumption and aquatic life requirements are summarized in Table 5. The values for five parameters (DO, turbidity, fluoride, total phosphorus, and silicate) exceeded the recommended threshold values for both human consumption and aquatic life (APHA, 2005; Rodier et al., 2009; WHO, 2008, 2011). The other parameters (temperature, conductivity, hardness, alkalinity, TN, TDS, TP, , , , and TSS) were within the recommended standard limits for human consumption and maintenance of ecological processes (Table 5). The mean values (±SD) of the DO and concentrations and temperature exhibited significant variations (p < .05) between the five samplings in the lake (Table 5). The dissolved oxygen (DO) concentration was marginally high at the northern Station N2 (6.48 ± 0.86 mg/L) and lower in the southern Station S2 (5.73 ± 0.92 mg/L), while the temperature exhibited higher mean values for the central Station C1 (26.67 ± 2.99°C) and lowest values in the southern Station S2 (24.94 ± 1.42°C). The concentration was significantly different between the sampling sites, with higher values at the central lake Station C1 (9.71 ± 9.57 μg/L) and lowest in the near-shoreline Station C3 (3.90 ± 2.12 μg/L). The values did not exceed the recommended WHO levels (3000 μg/L) for aquatic metabolism. Although all the other parameters did not exhibit significant variations between the sampling sites (p > .05), some exhibited values were above the recommended WHO thresholds for human consumption and ecological

TABLE 4 Trophic state indices and Carlson's trophic state index (CTSI) values for trophic classification of Lake Baringo

Secchi depth (m)	Total phosphorus concentration (μg/L)	Chlorophyll-*a* concentration (μg/L)	Carlson's trophic status index	Lake trophic state	Attributes
>8	<6	<0.95	<30	Oligotrophic	Clear water; oxygen in hypolimnion throughout the annual cycle
8–4	6–12	0.95–2.6	30–40	Oligotrophic	Oligotrophy, but some shallower lakes may become anoxic during dry season
3.9–2	12.1–24	2.6–7.2	40–50	Mesotrophic	Water moderately clear, but the increasing occurrence of anoxia during dry season
1.9–1	24.1–48	7.2–25	50–70	Eutrophic	Decreased transparency, warm water fisheries only
0.9–0.5	48.1–98	25–55	70–80	Eutrophic	Possibility of heavy algal blooms during dry season with tendency to become hypereutrophic
<0.5	>98	>55	>80	Eutrophic (hypereutrophic)	Reduction in macrophyte species; occurrence of algal scum; loss of fish stocks in dry season

integrity. The fluoride (F^-) concentrations in the lake waters, for example varied from 6.62 ± 5.20 to 7.59 ± 5.75 mg/L, well above the WHO permissible level of 1.5 mg/L. Similarly, the turbidity levels varied from 49.75 ± 42.96 NTU at the northern Station N2 to 64.43 ± 111.40 NTU at the central Station C2, both values exceeding the WHO recommended maximum values of 5 NTU for human use.

The total nitrogen (TN) concentrations varied from 291.28 ± 179.14 μg/L at the southern Station S2 to 422.78 ± 213.66 μg/L at the central Station C3, both exceeding the APHA recommended threshold of 100 μg/L suitable for aquatic life sustenance. The lake's productivity, as measured by the chlorophyll-*a* concentrations, ranged from 4.13 ± 2.03 μg/L at northern station N2 to 8.10 ± 13.52 μg/L at central station C1 and did not vary significantly (p = .341) between the sampling sites, suggesting uniform productivity within the lake.

Three physicochemical parameters (fluoride, turbidity and chlorophyll-*a*) exhibited significant temporal fluctuations, while other parameters fluctuated only slightly over the years (Figure 2). The Secchi depth (SD), a measure of a lake's water transparency, exhibited an increasing trend between 2012 and 2016, subsequently declining to 2020, while the Chl-a concentration, a measure of a lake's productivity, was low and uniform between 2008 and 2018, subsequently increasing from 2018 to 2020 (Figure 2). The fluoride concentrations have important health implications, with the values peaking in 2009 and 2013, and subsequently declining to low levels from 2016 to 2020. The dissolved oxygen concentrations fluctuated over the years, peaking in 2010 (~8.6 mg/L) and subsequently declining a low level of ~5.4 mg/L in 2020. The electrical conductivity (a measure of water quality deterioration) peaked at 769.5 μs/cm in 2012, declining to a low value of 409.4 μs/cm in 2018, while the total suspended solids concentrations (TSS) exhibited a pattern of increasing values from 2016 onward (Figure 2).

The nutrient loads (TN, TP, PO_4^{3-}, SiO_4^{4-}, NO_2^-, NO_3^- and NH_4^+) exhibited variable trends between parameters from 2008 to 2020 (Figure 3). The nitrite (NO_2^-) concentration increased in the lake by 94.66% between 2008 (68.2 μg/L) to 2014 (603.0 μg/L), then decreased continuously to ~24.3 μg/L in 2020. The mean nitrate (NO_3^-) concentrations have fluctuated from 5.3 in 2008 to 14.7 μg/L in 2013, while the NH_4^+ concentrations ranged between 23.62 μg/L in 2008 to a peak of 42.0 μg/L in 2016. The phosphate (PO_4^{3-}) concentrations, reflecting leaching from the riparian zone, peaked in 2011 (34 μg/L), remaining relatively stable at approximately 5.6 μg/L between 2013 and 2020. This contrasts with the silicate (SiO_4^{4-}) concentrations, which exhibited a general decline in the lake from their high values in 2008. The total phosphorus (TP) concentration has exhibited a steady decline from peak values in 2011 (180.9 μg/L), being similar to total nitrogen (TN) trends in the lake.

3.2 | Relationships between limnological parameters in lake

Generation of the Pearson's linear correlation matrix used 21 parameters to determine the functional relationships between the limnological parameters (Table 6). The WQI only exhibited a positive significant correlation with turbidity (r = .999, p < .001; Table 6). There was a positive significant correlation between alkalinity and temperature (p = .004, r = .978) and between NO_3^- and NO_2^- (p = .005, r = .973). Positive significant relationships were also observed between the DO and Secchi depth (p = .026, r = .922) and between the DO and alkalinity (p = .024, r = .926). A strong significant correlation was observed between SiO_4^{4-} and alkalinity (p = .02, r = .933) and between chlorophyll-*a* and NO_3^- (p = .039, r = .898). Negative relationships were observed between SiO_4^{4-} and total hardness (p = .033, r = −.908) and between total suspended solid (TSS) and total nitrogen (TN; p = .013, r = −.950).

Linear models indicated a moderate negative relationship between chlorophyll-a as a measure of productivity and total

TABLE 5 Statistical summary of selected physicochemical parameters for Lake Baringo from March 2008 to 2020 (bold figures indicate significant differences between sampling sites or exceedance of WHO/APHA thresholds (ANOVA results are significant at $p < .05$)

	Sampling sites					ANOVA		Values criteria	
	S2	C1	C2	C3	N2				
Parameters	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	*F*	*p*	WHO (2008)	**
DO (mg/L)	**5.73 ± 0.92**	**6.42 ± 0.94**	**6.43 ± 0.95**	**6.14 ± 0.84**	**6.48 ± 0.86**	8.84	**.001**	5	6[a,b,c,d]
Temp (°C)	**24.94 ± 1.42**	**26.67 ± 2.99**	**26.43 ± 1.63**	**25.61 ± 1.53**	**26.33 ± 1.47**	**21.23**	**.001**	<30	–
EC (µS/cm)	509.87 ± 128.99	513.57 ± 132.98	526.01 ± 138.50	518.34 ± 143.18	524.40 ± 137.51	0.13	.97	1000	1500[c]
pH	8.356 ± 0.48	8.41 ± 0.50	8.45 ± 0.52	8.42 ± 0.50	8.43 ± 0.48	0.36	.836	6.5–8.5	6.5–9[a,b,c]
TUR (NTU)	**56.08 ± 56.36**	**51.46 ± 43.79**	**64.43 ± 111.40**	**59.40 ± 56.46**	**49.75 ± 42.96**	0.47	.755	<5	5[a]
Secchi depth (cm)	60.74 ± 41.75	65.84 ± 42.66	66.72 ± 43.71	62.90 ± 42.75	69.52 ± 45.49	1.12	.348	–	–
HD (mg/L)	60.64 ± 18.87	59.31 ± 18.75	59.68 ± 20.50	61.01 ± 19.35	59.95 ± 17.86	0.09	.985	100–300	500[a]
Alk (mg/L)	175.21 ± 41.25	179.97 ± 46.04	179.29 ± 44.59	176.19 ± 44.59	178.89 ± 45.83	0.19	.944	500	≥20[d]
TDS (mg/L)	235.49 ± 91.36	224.10 ± 103.26	229.88 ± 102.64	226.05 ± 104.48	230.07 ± 102.95	0.11	.981	<500	500[a]
F^- (mg/L)	**6.62 ± 5.20**	**6.91 ± 5.12**	**6.94 ± 5.04**	**7.59 ± 5.75**	**6.82 ± 5.18**	0.17	.953	1.5	5[a]
PO_4^{3-} (µg/L)	24.10 ± 13.11	22.20 ± 16.76	23.03 ± 16.76	20.85 ± 9.98	18.42 ± 12.78	0.31	.869	<30	<100[a,d]
TP (µg/L)	**122.75 ± 87.51**	**121.41 ± 75.13**	**129.34 ± 84.68**	**125.47 ± 84.98**	**134.28 ± 87.15**	0.08	.987	70	50[d,e,f]
NO_2^- (µg/L)	**5.14 ± 2.09**	**9.71 ± 9.57**	**7.01 ± 3.77**	**3.90 ± 2.12**	**4.51 ± 3.33**	**2.86**	**.031**	300	<100[a,d]
NO_3^- (µg/L)	9.62 ± 2.91	13.10 ± 9.45	10.59 ± 5.09	9.28 ± 3.40	8.77 ± 4.09	1.28	.286	1000	<1000[a,d]
TN (µg/L)	291.28 ± 179.14	375.34 ± 243.33	360.90 ± 166.56	422.78 ± 213.66	379.68 ± 207.38	0.37	.827	5000	4000[e,f]
SiO_4^{4-} (mg/L)	**18.70 ± 2.53**	**21.21 ± 5.30**	**21.57 ± 4.49**	**18.35 ± 3.31**	**21.56 ± 4.44**	**2.34**	**.064**	5	–
NH_4^+ (µg/L)	31.43 ± 15.45	20.94 ± 13.14	32.47 ± 16.64	25.46 ± 4.41	30.34 ± 7.96	2.25	.074	<1500	<1000[a,d]
Chl *a* (µg/L)	4.33 ± 2.54	8.10 ± 13.52	5.72 ± 4.17	5.94 ± 7.60	4.13 ± 2.03	1.15	.341	–	12[b,c]
TSS (mg/L)	14.94 ± 5.05	12.94 ± 5.58	12.07 ± 4.63	10.92 ± 4.39	12.18 ± 4.45	1.23	.307	–	<30[a,b,c,d]
Zeu (m)	1.97 ± 1.27	2.07 ± 1.32	2.08 ± 1.34	1.87 ± 1.30	2.17 ± 1.40			–	–

Note: Explanation: **standard limits for aquatic fauna.

Abbreviations: Alk, alkalinity; Chl.*a*, chlorophyll-*a* concentration; DO, dissolved oxygen concentration; EC, electrical conductivity; HD, hardness; TDS, total dissolved solids concentration; TN, total nitrogen concentration; TP, total phosphorus concentration; TSS, total suspended solids concentration; TUR, turbidity; Zeu, euphotic zone.

[a]CCME (1999).

[b]APHA (2005).

[c]Rodier et al. (2009).

[d]ANZECC (2000).

[e]Phillips et al. (2018).

[f]Poikane et al. (2019).

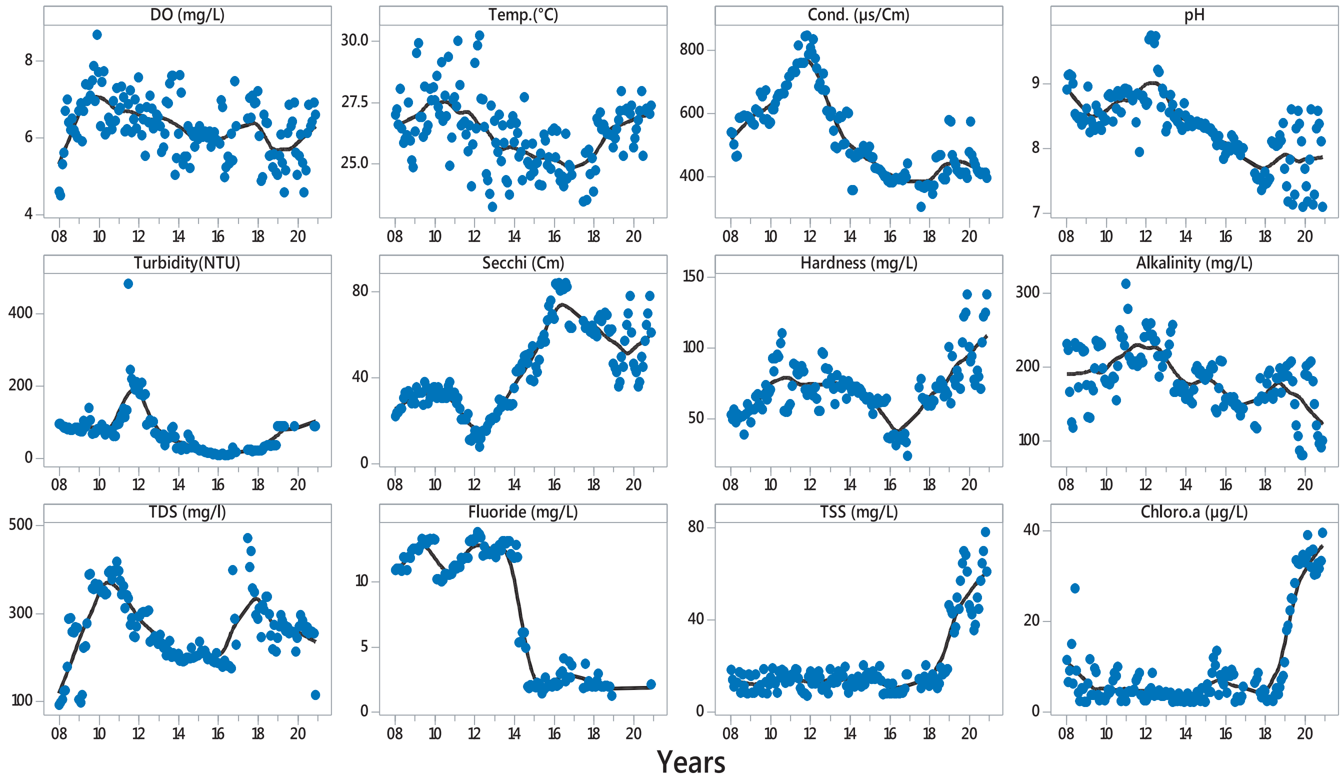

FIGURE 2 Temporal variation of physico-chemical water quality parameters in Lake Baringo, Kenya, for the period 2008–2020 (circles are mean values of all samples collected monthly; smoothing trendline was estimated with LOWESS smoother)

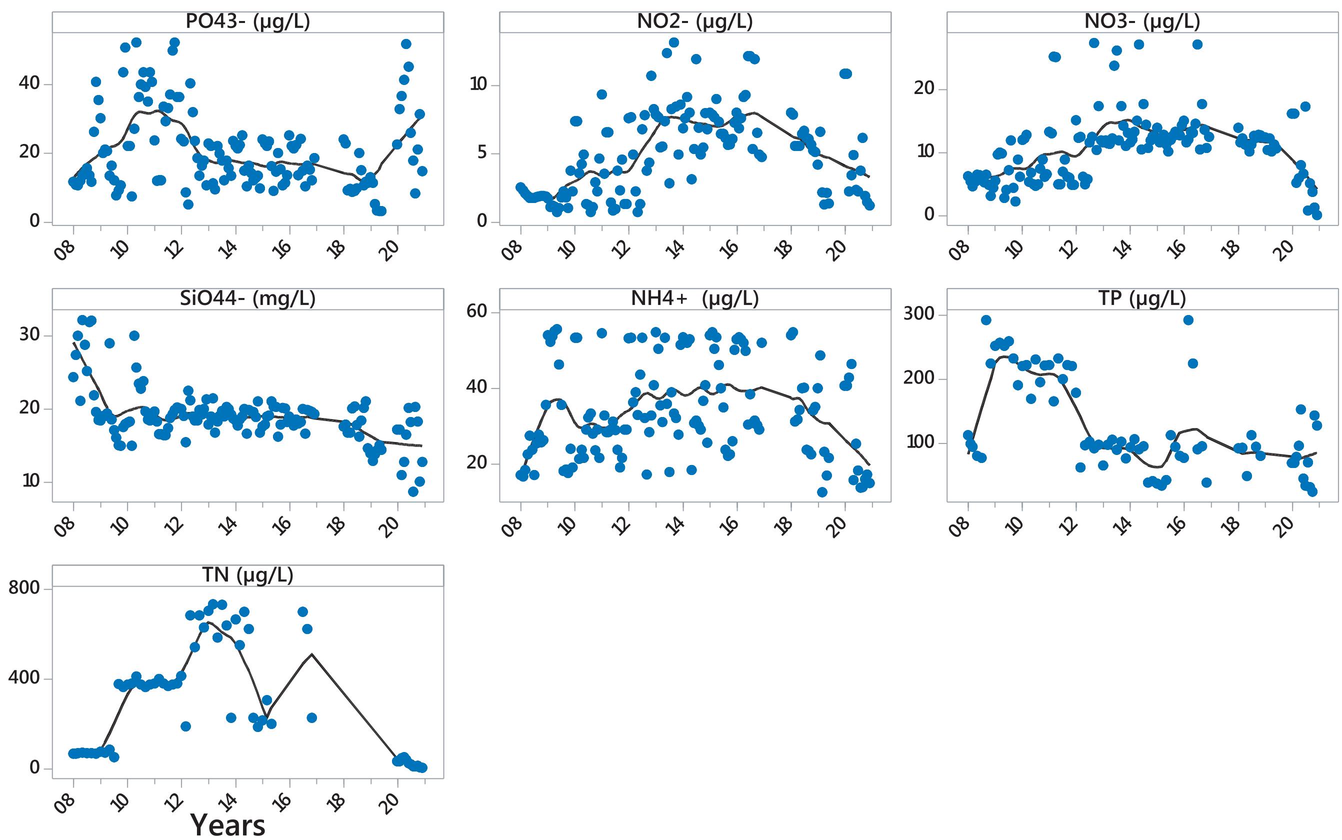

FIGURE 3 Time-series of nutrient loads in Lake Baringo, Kenya (circles are mean values of all samples collected monthly from 2008 to 2020; solid line within time-series plot is trendline of monthly mean values calculated with LOWESS smoother)

TABLE 6 Pearson's linear correlation matrix of physicochemical parameters derived for Lake Baringo from March 2008 to June 2019 (parameter abbreviations given in Table 5)

	DO	Temp	EC	pH	TUR	Secchi	HD	Alk.	Depth	TDS	F^-	PO_4^{3-}	TP	NO_2^-	NO_3^-	TN	SiO_4^{4-}	NH_4^+	Chl.a	TSS	WQI
DO	1.000																				
Temp	0.919*	1.000																			
EC	0.733	0.435	1.000																		
pH	0.819	0.741	0.772	1.000																	
TUR	−0.150	−0.228	0.290	0.435	1.000																
Secchi	0.922*	0.767	0.772	0.629	−0.310	1.000															
HD	−0.720	−0.876	−0.258	−0.565	0.247	−0.662	1.000														
Alk.	0.926*	0.978**	0.514	0.755	−0.201	0.832	−0.926*	1.000													
Depth	0.618	0.447	0.689	0.404	−0.205	0.843	−0.584	0.607	1.000												
TDS	−0.622	−0.712	−0.152	−0.529	0.128	−0.323	0.340	−0.556	0.220	1.000											
F^-	0.126	0.009	0.209	0.295	0.348	−0.119	0.449	−0.142	−0.530	−0.624	1.000										
PO_4^{3-}	−0.569	−0.318	−0.536	−0.156	0.511	−0.687	0.010	−0.295	−0.413	0.345	−0.295	1.000									
TP	0.533	0.182	0.866	0.372	−0.044	0.754	−0.090	0.297	0.802	0.158	−0.036	−0.706	1.000								
NO_2^-	0.395	0.713	−0.180	0.388	−0.112	0.192	−0.841	0.689	0.068	−0.445	−0.300	0.378	−0.452	1.000							
NO_3^-	0.301	0.647	−0.309	0.314	−0.103	0.042	−0.711	0.578	−0.153	−0.550	−0.136	0.401	−0.605	0.973**	1.000						
TN	0.595	0.454	0.480	0.526	0.014	0.399	0.030	0.327	−0.106	−0.823	0.845	−0.656	0.266	−0.102	−0.010	1.000					
SiO_4^{4-}	0.854	0.841	0.599	0.665	−0.209	0.890*	−0.908*	0.933*	0.841	−0.234	−0.395	−0.295	0.498	0.545	0.367	0.091	1.000				
NH_4^+	−0.218	−0.456	0.398	−0.029	0.405	0.045	0.214	−0.274	0.504	0.836	−0.402	0.121	0.558	−0.502	−0.657	−0.496	0.054	1.000			
Chl.a	0.364	0.643	−0.209	0.414	−0.004	0.015	−0.492	0.507	−0.370	−0.825	0.310	0.207	−0.583	0.798	0.898*	0.384	0.190	−0.838	1.000		
TSS	−0.611	−0.395	−0.683	−0.660	−0.251	−0.442	−0.060	−0.312	−0.026	0.672	−0.828	0.603	−0.435	0.204	0.153	−0.950*	−0.142	0.227	−0.226	1.000	
WQI	−0.113	−0.197	0.318	0.468	0.999***	−0.282	0.238	−0.176	−0.202	0.086	0.384	0.478	−0.028	−0.109	−0.097	0.062	−0.194	0.381	0.018	−0.297	1.000

***$p < .001$.; **$p < .01$.; *$p < .05$.

suspended solids (R^2 = .59; Figure 4a), while a strong positive correlation was observed between turbidity and rainfall in the lake catchment (R^2 = .71; Figure 4b).

3.3 | Water quality index and organic pollution index

The WQI values of Lake Baringo water samples ranged from 540.85 at Station N2 on the north to the lowest value of 631.89 at central Station C3 (Figure 5). There was no significant difference in the WQI between the sampling sites (F = 0.6816; p = .6077). The mean monthly WQI exhibited patterns of variation similar to those of the mean monthly turbidity for the period from January 2008 to June 2018 (Figure 5), indicating the influence of turbidity on the lake's WQI. The highest WQI peaks above the threshold of 100 were observed during the rainy season (May 2011), while the lowest WQI values were observed during the dry month of September 2016 at ~120, indicating a relatively good water quality during these months.

The relative weight (RW) and effective weight (EW) values of each water quality parameter are summarized in Table 7. The turbidity exhibited the highest mean effective weight of 84.82%, followed by fluoride (8.82%), indicating these parameters have the main influence on the Lake Baringo WQI. The other parameters (mostly nutrients) exhibited a low effective influence on the lake's WQI. Nevertheless, the reactive soluble silica (SiO_4^{4-}) and pH had a moderate mean effective weight of 3.09% and 1.50% respectively. The OPI values ranged between 4.5 at Station C2 to 4.9 at Station C3, with a significant difference noted among the sampling sites (F = 3.59, p = .013; Table 8). These results indicate the OPI of Lake Baringo water is within the interval limits of water exhibiting null organic pollution (5.0–4.6; Table 3), except for one central Station C2 characterized by weak organic pollution manifesting in greenish watercolour.

3.4 | Trophic status of the lake

The TN:TP and DIN:SRP ratios and the results of the trophic status index (TSI) analyses, based on evaluation of the total phosphorus, Secchi depth and chlorophyll-a values during the period from 2008 to 2020, and the temporal mean Carlson's trophic status index (CTSI) values for Lake Baringo are summarized in Table 9. The TN:TP stoichiometric ratio varied from the highest value of 6.91 ± 2.66 in 2013, to the lowest value of 0.38 ± 0.21 in 2020. The seston mass DIN:SRP ratio fluctuated over time between 4.42 ± 1.37 in 2018 and 1.45 ± 0.84 in 2020. These ratios indicate the lake is eutrophic and that the nitrogen component (NO_2^-) is the limiting nutrient for primary production in the lake. The TSI and mean CTSI values were then used to determine the lake's annual trophic status for the period from 2008 to 2020. The mean (±SD) TSI calculated on the basis of the total phosphorus (TP) concentration varied from a high value of 84.24 ± 0.52 in 2009 to its lowest value of 21.92 ± 4.90 in 2014. The TSI based on the Secchi depth also varied from a high level of 88.00 ± 2.99 in 2012 to the lowest level of 55.63 ± 0.59 in 2019. The TSI based on the lake productivity, expressed in the Chl-a values, varied from a high value of 83.50 ± 0.78 in 2009 to its lowest value of 42.69 ± 3.33 in 2014. The CTSI varied from the highest value of 82.68 ± 2.10 in 2011, indicating a hypereutrophic state of the lake, to its lowest value of 42.61 ± 2.49 indicating a mesotrophic state in 2015. All the CSTI values indicated the Lake Baringo trophic status has been fluctuating from a hypereutrophic to mesotrophic condition and from water of bad quality to water of moderate quality for domestic water supply. Lake Baringo is currently (2020) considered to be eutrophic. These results indicated the CTSI is mostly affected by the suspended solids (SD) concentrations in Lake Baringo.

4 | DISCUSSION

The results of the present study provided a first time, long-term evaluation of the water quality and trophic status of Lake Baringo, Kenya, using water quality indices. There were spatio-temporal differences observed in the physicochemical properties of the lake. It is likely the differential influences of shoreline inputs and locations of the influent rivers resulted in differences in the lake's water properties at the various sampling sites in the lake. Some water quality parameters (turbidity, fluoride, total phosphorus, SiO_4^{4-}, DO) were found to exceed the WHO and APHA recommended thresholds for livelihoods and ecological processes. The dissolved oxygen (DO) values, for example at all the sampling sites exceeded the WHO recommended threshold of 5 mg/L for human use of the lake water. The fluoride concentrations exceeded the WHO recommended threshold values of 1.50 mg/L for human consumption, indicating Lake

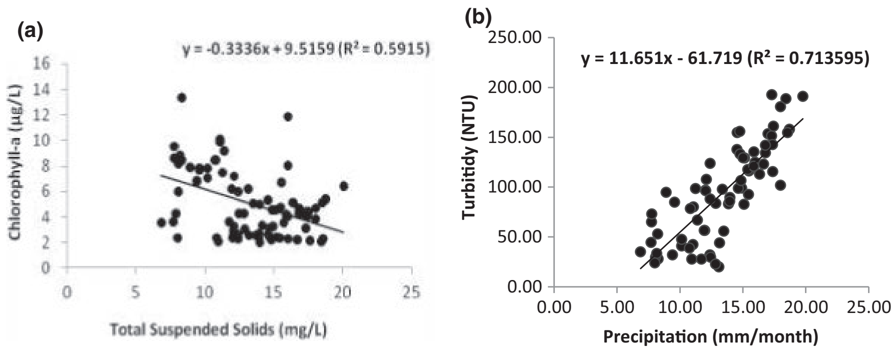

FIGURE 4 Relationship between (a) chlorophyll-a and total suspended solids concentration; (b) turbidity of lake water and rainfall in Lake Baringo catchment for the period 2008–2020

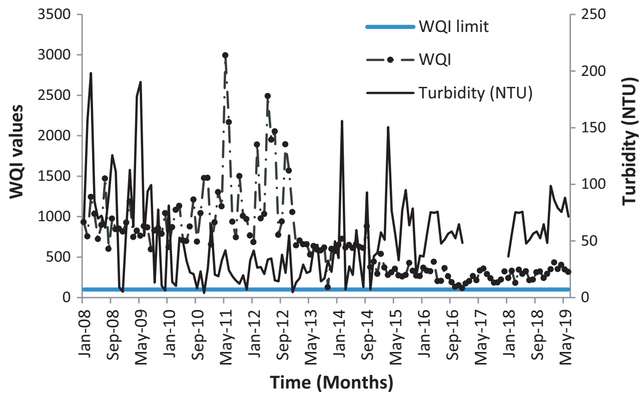

FIGURE 5 Changes in monthly water quality index (WQI) in relation to turbidity in Lake Baringo for the period 2008–2020

TABLE 8 Organic pollution index (OPI) values and organic pollution types of Lake Baringo at sampling sites from 2008 to 2020 (different letters indicate significant difference between sampling sites)

Sampling site ID	OPI (mean ± SD)	Organic pollution	Colours of index
S2	4.6 ± 0.19[ab]	Null	Blue
C1	4.6 ± 0.29[ab]	Null	Blue
C2	4.5 ± 0.34[b]	Weak	Green
C3	4.7 ± 0.29[ab]	Null	Blue
N2	4.9 ± 0.14[a]	Null	Blue
ANOVA F = 3.59 p = .013			

TABLE 7 Effective weight contribution of physicochemical parameters to water quality index (WQI) for Lake Baringo from 2008 to 2020 in relation to WHO standards

Parameters	WHO (2005, 2008)	Weight (w_i)	Relative weight (RW)	Effective weight (%)			
				Min	Max	Mean	SD
DO (mg/L)	5.00	4.00	4.65	0.86	1.08	0.95	0.11
EC (μS/cm)	1000.00	1.00	2.33	0.18	0.22	0.20	0.02
Ph	8.50	4.00	9.30	1.33	1.66	1.50	0.13
TUR (NTU)	5.00	4.00	9.30	83.24	86.42	84.82	1.33
HD (mg/L)	500.00	2.00	4.65	0.08	0.10	0.09	0.01
Alk (mg/L)	500.00	1.00	2.33	0.12	0.15	0.14	0.01
TDS (mg/L)	500.00	2.00	4.65	0.31	0.38	0.35	0.03
F^- (mg/L)	1.50	5.00	11.63	7.76	9.51	8.82	0.73
PO_4^{3-} (mg/L)	0.03	5.00	11.63	0.00	0.00	0.00	0.00
NO_2^- (mg/L)	0.30	5.00	11.63	0.00	0.01	0.00	0.00
NO_3^- (mg/L)	1.00	5.00	11.63	0.00	0.00	0.00	0.00
SiO_4^{4-} (mg/L)	5.00	2.00	4.65	2.63	3.61	3.09	0.42
NH_4^+ (mg/L)	1.50	5.00	11.63	0.03	0.04	0.04	0.01

Abbreviations: NH_4^+, ammonium concentration; NO_2^-, nitrite concentration; NO_3^-, nitrate concentration;PO_4^{3-}, phosphate concentration; SiO_4^{4-}, silica concentration; Alk, alkalinity; DO, dissolved oxygen concentration; EC, electrical conductivity; F^-, fluoride ion concentration; HD, hardness; TDS, total dissolved solids concentration; TUR, turbidity.

Baringo water is unsuitable as drinking water, requiring pretreatment before its consumption by the riparian communities. The high fluoride concentrations (2.0–13.0 mg/L) in Lake Baringo might have originated from natural processes, with the lake being one of the African Rift Valley Lakes which are reported to exhibit high fluoride levels (Ayenew, 2008). The effects of high fluoride concentrations in natural water are the main cause of the development of dental fluorosis responsible for brownish teeth (Edmunds & Smedley, 2013), a prevalent condition among the Lake Baringo riparian communities. High fluoride concentrations also expose the riparian communities to cancer in extreme cases of exposition (>7.5 mg/L; Marshall, 1990).

Compared to international standard limits, the DO, turbidity, fluoride, SiO_4^{4-} and TN levels in Lake Baringo were above the threshold values recommended for human consumption by the WHO (2008, 2011) and aquatic life processes by APHA (2005) and Rodier et al. (2009), reflecting the poor conditions of Lake Baringo waters over the years. Soluble silica (SiO_4^{4-}) and total nitrogen (TN) concentrations in the lake were also above those recommended by APHA and WHO (5 mg/L and 100 μg/L respectively), while the other nutrients (nitrates, phosphates, TP and ammonium) loads in the lake exhibited variations that were within both the WHO and APHA recommended levels for ecological processes (APHA, 2005; WHO, 2008). The turbidity level in the lake was above the WHO permissible levels (5 NTU) for drinking (WHO, 2008) and for support of some species of aquatic life (Bartram & Balance, 1996; PNRM, 2009; Rodier et al., 2009). High turbidity and total dissolved solids (TDS) have been reported to be the main physical indicators of water quality degradation in lakes (Wetzel, 2001) and may affect fisheries production and biodiversity (Odada et al., 2006). The high turbidity in Lake Baringo has been reported to be a responsible factor for restricting

TABLE 9 Temporal variation of TN:TP and DIN:SRP ratios as phytoplankton nutrient limitation indicators in Lake Baringo and trophic indices and lake water status from 2008 to 2020

				Trophic state index (TSI) values				
Years	*n*	TN:TP	DIN:SRP	TSI (TP)	TSI (SD)	TSI (Chl-*a*)	CTSI	Lake status
2008	11	0.62 ± 0.27	2.04 ± 0.69	31.51 ± 9.36	78.50 ± 2.30	49.22 ± 6.37	53.07 ± 5.31	Mesotrophic
2009	12	0.77 ± 0.78	2.75 ± 1.21	84.24 ± 0.52	76.47 ± 1.60	83.50 ± 0.78	81.30 ± 0.79	Hypereutrophic
2010	11	1.84 ± 0.30	1.65 ± 1.42	83.02 ± 4.60	76.09 ± 1.10	81.2 ± 1.18	80.14 ± 0.78	Hypereutrophic
2011	11	1.84 ± 0.29	2.08 ± 1.74	83.13 ± 0.58	83.57 ± 5.02	81.37 ± 0.84	82.68 ± 2.10	Hypereutrophic
2012	12	5.27 ± 2.15	3.82 ± 2.29	76.17 ± 2.93	88.00 ± 2.99	71.13 ± 3.52	78.43 ± 2.01	Eutrophic
2013	12	6.91 ± 2.66	3.68 ± 0.78	74.64 ± 1.07	79.34 ± 1.28	68.88 ± 1.56	74.29 ± 0.73	Eutrophic
2014	12	6.19 ± 1.19	3.78 ± 0.57	21.92 ± 4.90	71.16 ± 2.05	42.69 ± 3.33	45.27 ± 3.10	Mesotrophic
2015	11	3.3 ± 3.90	3.73 ± 1.13	25.98 ± 5.54	56.40 ± 1.91	45.45 ± 3.77	42.61 ± 3.62	Mesotrophic
2016	11	3.37 ± 3.74	3.76 ± 0.88	28.38 ± 6.71	61.34 ± 1.93	47.08 ± 4.56	45.60 ± 3.69	Mesotrophic
2017	6	3.34 ± 3.82	4.09 ± 1.13	26.80 ± 6.11	62.86 ± 3.10	46.01 ± 4.16	45.22 ± 3.98	Mesotrophic
2018	11	3.36 ± 3.78	4.42 ± 1.37	25.22 ± 5.51	64.37 ± 4.27	44.94 ± 3.75	44.84 ± 4.08	Mesotrophic
2019	6	1.87 ± 2.01	2.94 ± 1.12	27.42 ± 4.18	55.63 ± 0.59	46.13 ± 2.85	43.17 ± 2.49	Mesotrophic
2020	12	0.38 ± 0.21	1.45 ± 0.84	55.10 ± 10.49	70.90 ± 1.16	65.26 ± 7.44	63.76 ± 6.14	Eutrophic

Abbreviations: Chl-*a*, chlorophyll-*a*; CTSI, Carlson's trophic state index; DIN, dissolved inorganic nitrogen; *n*, number of samples; N, total nitrogen; SD, Secchi depth; SRP, soluble reactive phosphorus; TP, total phosphorus.

the zooplankton abundance and diversity which, in turn, affects the feeding habits of some fish species in the lake (Omondi et al., 2014; Tarras-Wahlberg et al., 2003).

Strong positive correlations were found between lake turbidity and rainfall in the watershed, and between lake water turbidity and WQI, highlighting the influence of watershed erosion on lake water quality. Baok (2007) reported the correlation between turbidity and total suspended solids is very high in lakes and determines light reflectance and diffraction, and therefore the ecological processes. The negative relationship between Chl-a and turbidity observed in the present study indicated the direct effect of turbidity on light penetration into the lake's water column. A high turbidity level reduces the lake's productivity, therefore being the likely cause of the low plankton diversity and reduced fisheries production in the lake (Nyakeya et al., 2020; Tarras-Wahlberg et al., 2003). The lake's high turbidity can be attributed mostly to watershed erosion, the resuspension of the bottom sediments into the water column by wind action, and partly from algal blooms (Oduor et al., 2003; Omondi et al., 2014; Tarras-Wahlberg et al., 2003). Recent attempts at watershed management (Nyakeya et al., 2020) have seen progressive temporal positive changes in some parameters, as also reported in the present study. Nevertheless, there is a need for more aggressive integrated watershed management interventions such as afforestation and land-use policy changes to attempt to reduce sediment inputs to the lake (Grobbelaar, 1984; Schagerl & Oduor, 2003). Thus holistic watershed management is required to sustain the water quality of the lake and its fisheries productivity for riparian community livelihoods.

The WQI values for Lake Baringo in the present study greatly exceeded the WHO (2008) permissible limits (WQI = 100) for drinking water, indicating the lake's water is currently "unsuitable for human consumption" (WHO, 2008), despite its continued use by the local communities. The OPI values (4.5–4.9), however, were below the recommended limits for lakes (Leclercq & Maquet, 1987), indicating the lake water is still organically unpolluted. Low organic nutrient loads are likely leached into the lake, possibly attributable to a low level of agricultural activities in the lake's mostly semi-arid watershed. The nutrient availability assessment was well below a value of 10, with the OECD (1982) N:P ratio for the study period suggesting that N is the limiting nutrient for the lake's primary production. This result indicates management of the lake's nutrient enrichment should be focused on reducing the phosphorus levels, rather than nitrogen, because N-fixation by certain cyanobacteria allows a reprieve from N limitation of the algal biomass (Schindler, 1977).

As measured by the TSI (TP) and the Carlson scale (Carlson, 1977), the lake's trophic status has been variable, ranging from mesotrophic, hypereutrophic to eutrophic over the period from 2008 to 2020. Consequently, Lake Baringo's trophic status has been fluctuating over time, indicating an instability of the lake's ecological processes probably attributable to climate variability and human activities in the watershed. Similar variability in the trophic status of lentic water systems has been reported elsewhere, being attributed to anthropogenic influences (Al-Haidarey et al., 2016). These results indicate the classification of Lake Baringo's trophic status will depend on the methods used and the overriding factors within the watershed at a given time.

5 | CONCLUSIONS

The present study evaluated the water quality and trophic status of Lake Baringo, a Rift Valley Lake in Kenya that was designated as a Ramsar Site because of its high biodiversity. Monthly WQI values exceeded 100, the upper limit for drinking water, indicating the lake's water is unsuitable for human consumption. The high value of WQI for the lake was attributed to the higher turbidity levels caused by rainfall-mediated erosion in its catchment. Accordingly, there is a need for a comprehensive and integrated lake catchment management plan to combat the soil erosion in the lake's watershed. The OPI results indicated the lake water is not organically polluted. The spatial variations in the TN and TP concentrations, however, suggest the possibility of localized eutrophication. Nutrients with the highest relative weights exhibited less effects on the water quality indices (WQI and OPI), indicating minimal effects of agricultural runoff on the lake. The lake's trophic status has been changing over time, from hypereutrophic to mesotrophic, indicating temporal variability in anthropogenic influences on the lake. Implementation of land-use management policies at the watershed scale is needed for the lake water to support economic livelihoods of riparian communities and to sustain ecological processes.

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CONFLICT OF INTEREST

None.

DATA AVAILABILITY STATEMENT

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

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