Received: 30 November 2020 | Revised: 31 December 2021 | Accepted: 7 March 2022

DOI: 10.1111/lre.12401

ORIGINAL ARTICLE

Lakes & Reservoirs Science, Policy and Management for Sustainable Use | WILEY

Water quality and ecology of Lake Kanyaboli, Kenya: Current status and historical changes

Benjamin N. Kondowe[1,2] | Frank O. Masese[1] | Philip O. Raburu[1] | Wales Singini[2] | Riziki Jacques Walumona[1,3]

[1]Department of Fisheries and Aquatic Sciences, University of Eldoret, Eldoret, Kenya

[2]Department of Fisheries and Aquatic Sciences, Mzuzu University, Mzuzu, Malawi

[3]Unité d'Enseignement et de Recherche en Hydrobiologie Appliquée (UERHA), Département de Biologie-Chimie et de Chimie-Physique, Institut Supérieur Pédagogique de Bukavu (ISP), Bukavu, D. R. Congo

Correspondence

Benjamin N. Kondowe, Department of Fisheries and Aquatic Sciences, University of Eldoret, P.O. Box 1125-30100, Eldoret, Kenya.
Email: benjy85@gmail.com

Funding information

Intra-Africa Academic Mobility Project 'Collaborative Training in Fisheries and Aquaculture in East, Central and Southern Africa (COTRA)', which is funded by the European Union (EU)

Abstract

Small waterbodies are the most threatened freshwater habitats because of the large ratio between their size and the catchment they drain. The present study assessed the current and historical changes in the physical, chemical and biological variables of Lake Kanyaboli, a satellite lake on the northern shores of Lake Victoria in western Kenya. Primary and secondary data on pH, electrical conductivity (EC), dissolved oxygen (DO) concentration, temperature, Secchi depth (SD), and nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), soluble reactive phosphorus (SRP), total nitrogen (TN), and total phosphorus (TP) and chlorophyll-*a* (Chl-*a*) concentrations were utilized in the present study. The results indicated Secchi depth and chlorophyll-*a* were the most erratic of all the analyzed environmental variables studied, exhibiting a range of 0.69 ± 0.29–0.87 ± 0.34 m and 9.03 ± 0.81–34.97 ± 3.36 µg/L respectively. Two-way ANOVA yielded no significant interactions between sampling sites and seasons for all the variables. Except chlorophyll-*a*, there also were no significant differences among the sampling sites for the studied variables. Seasonality yielded significant differences for Secchi depth, dissolved oxygen and chlorophyll-*a*. The Carlson Trophic Index for Chl-*a* and SD indicated Lake Kanyaboli is currently eutrophic, while the TP concentration indicated hypereutrophic conditions. The lake, however, has fluctuated between eutrophic and hypereutrophic conditions over the past years. Although historical water quality data for the lake is scanty and infrequent, most physical and chemical variables reflected anthropogenic effects on a temporal scale. Interestingly, despite its eutrophic status, the general lake condition is still relatively good, attributable to the buffering effect from the extensive macrophytes fringing it. The present study identified nutrient loading, wetland reclamation and connectivity with the Yala River through a feeder canal as the management issues of critical concern. Accordingly continuous monitoring of the lake's water quality to detect anthropogenic effects is recommended for management intervention purposes.

KEYWORDS

lake ecology, physical and chemical variables, trophic status, water quality, wetland, Yala Swamp

1 | INTRODUCTION

Lakes, reservoirs and rivers are essential sources of water for many rural and urban communities. Human wellbeing depends fundamentally on ecosystem goods and services from these ecosystems, such as useable water for domestic use, irrigation and fishery resources (Low et al., 2016; Merga et al., 2020). At the same time, however, these ecosystems, particularly in developing countries, are experiencing water quality problems threatening their ecological integrity and the associated ecosystem goods and services. Human activities such as nutrient enrichment, especially phosphorus and nitrogen, can lead to a degraded water quality. These nutrients originate from uplands and catchment areas as a result of anthropogenic activities, including unsustainable land use, untreated municipal and industrial waste discharges and intensive use of agrochemicals (Nirmala et al., 1991; Sheela et al., 2011). Massive algal blooms can occur as a result, causing a shift from clear water to turbid state in shallow lakes and reservoirs (Ndungu et al., 2015). Significant changes in the biological structure of lakes, reservoirs and rivers will eventually occur, affecting ecosystem services upon which riparian communities depend. Exposed to external impacts from the climate, their watersheds and groundwater fluxes, the trophic state of lakes can readily change over time (Garn et al., 2003). If the causes of the degrading changes are known, however, human intervention in lake management practices can help reduce their adverse effects. At the same time, understanding how aquatic systems function is complex because of the interdependencies among chemicals and other substances in the water and sediments, the aquatic organism populations, the water temperature, the shape and topography of the water body and the nature of the surrounding landscape (Melack, 1997).

Water quality variations in lakes can result from spatial and temporal characteristics, in addition to internal and external factors such as water inflows and outflows, meteorological conditions, and physical and biogeochemical processes (Ellah, 2020). Water inflows and outflows carry materials (dissolved and particulate) from drainage basins into lakes and also export materials and heat out of the lake respectively (Kalff, 2002). On the other hand, precipitation can either introduce solutes or dilute the water body, while evaporation concentrates solutes and modifies thermal conditions in the water column (Lesack & Melack, 1991; Talling, 2001). The impacts of these processes can vary from one lake to another depending on their sizes, catchment area, morphometry and latitude (Wetzel, 2001). These factors directly influence physical, chemical and biological variables affecting water, including temperature, pH, turbidity, electrical conductivity, dissolved oxygen concentration, biological oxygen demand, suspended solids, nutrients and chlorophyll-*a* concentrations and plankton populations. Previous studies have documented the effects of such physical, chemical and biological variables on the structure and functioning of aquatic ecosystems (Chapman & Kimstach, 1996; Doyle & Smart, 2001; Lam & Schertzer, 1999; Ngatia et al., 2019; O'Gorman et al., 2016; Oladipo & Williams, 2003; Svobodová et al., 1993; Walker et al., 2007). Of these variables, the Secchi depth, nutrient concentrations (phosphorus and nitrogen) and chlorophyll-*a* concentrations can affect a lake's productivity, subsequently dictating its trophic status. Thus, these variables essentially define the trophic status of a lake or reservoir, which can range from oligotrophic (poorly nourished), mesotrophic (moderately nourished) and eutrophic (well-nourished) to hypereutrophic (over nourished). A lake's trophic state, however, is not determined by directly measuring its algae biomass; rather, it is assessed indirectly by measuring the concentrations of nutrients and chlorophyll-*a* and the water transparency (measured as the Secchi depth; Carlson, 1977).

Nonetheless, utilization and transformation of wetlands such as Yala Swamp because of human population growth, poverty and development efforts are increasing (Owiyo et al., 2014) despite documented adverse anthropogenic effects resulting from such factors. Having been studied for its agricultural potential, Yala Swamp, for example, has undergone reclamation efforts since 1954 (Kinaro, 2008). The swamp has since experienced dramatic changes, ranging from extensive communal uses for natural resource extraction such as fishing, subsistence farming and wood for fuel, to large-scale agricultural development by the Dominion Group of Companies in 2004 (Kinaro, 2008).

1.1 | Chronology of development activities in Lake Kanyaboli catchment area

Yala Swamp houses Lake Kanyaboli, a satellite lake on the northern shores of Lake Victoria in Western Kenya. Because of its expanse and rich diversity of plants and animals, developers have targeted the wetland since the 1950s, to the chagrin of conservationists (Muoria et al., 2015). Several events have affected Yala Swamp and the surrounding water bodies, such as Lake Kanyaboli (Figure 1). The swamp originally covered an estimated 17,500 ha until the early 1960s when a major reclamation project was undertaken.

Yala Swamp was investigated for its agricultural potential in 1954 by Sir Alexander Gibbs and partners (Anyona, 1997). That study recognized the high potential of the swamp and 2300 ha of land were subsequently reclaimed between 1965 and 1970 (Owiyo et al., 2014). Lake Kanyaboli was cut off from its catchment during the reclamation by a retention dyke erected across the lake's margins. The event led to construction of a feeder canal and an outlet in 1969 to facilitate inflow from the Yala River and an outflow from the lake.

Regional government authorities granted a 25-year lease in 2003 for rice cultivation to Dominion Farms Ltd., a Dominion Group of Companies subsidiary in Edmond, Oklahoma, USA (Muoria et al., 2015). However, instead of the initially intended rice cultivation in the 2300 ha, Dominion embarked on other additional activities in the swamp beyond rice cultivation, including dams and weirs, an airstrip and aquaculture (Owiyo et al., 2014). Expansion of Dominion Farms Ltd. activities resulted in reclamation of more swamp areas initially occupied by local communities, resulting in a mixed reaction from stakeholders on conserving the swamp and community needs. Continuous conflicts between

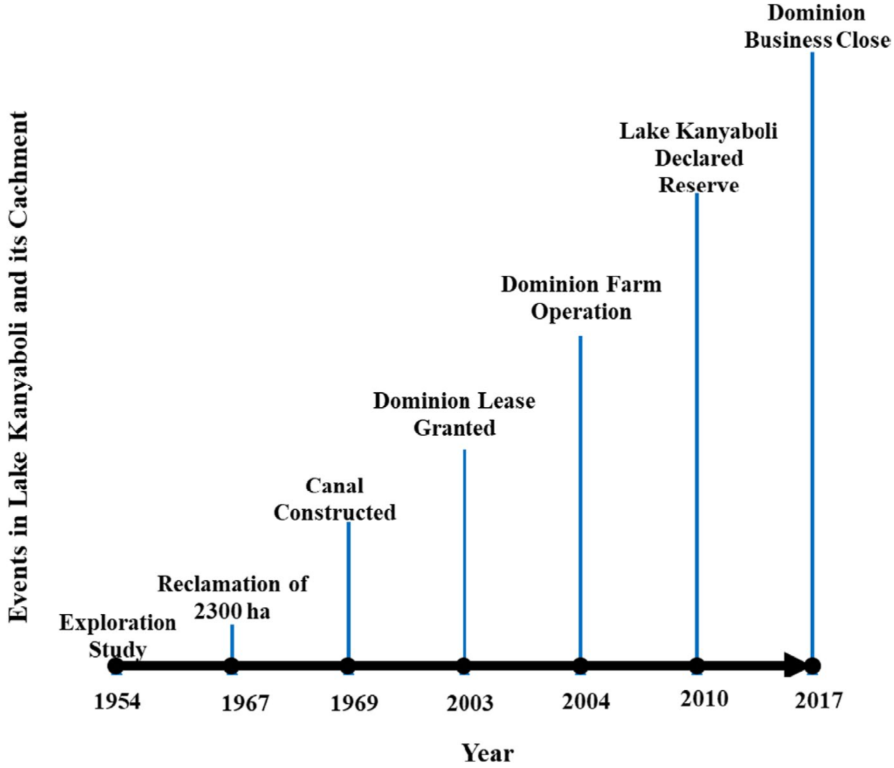


FIGURE 1 Chronology of events in Lake Kanyaboli and its catchment area in the Yala Swamp

the company and stakeholders resulted in subsequent closure of Dominion Farms Ltd. in 2017.

Lake Kanyaboli is a gazetted National Reserve through Legal Notice No 158 of 2010 (USAID, 2016). The total area of the reservoir is 41.42 km^2, being legally under the management of the Siaya County Government, with technical and policy support from the Kenya Wildlife Service. Environmentalists and the Kenya Wildlife Service also have initiated the listing of the wetland as a Wetland of International Importance under the Ramsar Convention because of its biodiversity and provision of ecosystem services (Muoria et al., 2015).

The continued controversies surrounding Yala Swamp are attributable to consideration of the essential ecosystem services, including agriculture potential, food, water, papyrus products, thatching material and water quality and quantity regulation, among others provided by the wetland. Agricultural activities and handicraft industry in Yala Swamp negatively influence the ecology, biodiversity and health of Lake Kanyaboli. Poor farming practices and industrialized agriculture have resulted in sedimentation and water pollution from pesticides and herbicides (Aloo, 2003). Moreover, removing vegetation cover (i.e. harvesting bamboos, logs and papyrus) has led to increased surface erosion, sediment loads and eutrophication in the lake. These factors affect ecosystem health, thereby adversely affecting ecosystem services and fish production from the lake. Intensive agricultural activities and nutrient losses from agricultural areas are considered significant lake pollution sources through nutrient enrichment (Jarosiewicz & Witek, 2014).

Further, nutrients such as phosphorus (P) and nitrogen (N) (referred to as limiting factors) can also enter lakes through dry deposition from the atmosphere, in addition to runoff from surrounding catchment areas, both sources contributing to lake eutrophication (Scott & McCarthy, 2010). According to Sterner et al. (1997), the concentration of potentially limiting nutrients (P and N) within the biomass at the base of the aquatic food web is a vital variable regulating ecosystem processes and functioning. Thus, it is crucial to maintain a nutrient balance between nutrient inflows and outflows. Lake Kanyaboli, however, has experienced a lack of water inflows over time because of the construction of the retention dike originally constructed to reclaim part of the Yala Swamp and Yala River blockage, negatively affecting the water quality (Aloo, 2003). Changes in Lake Kanyaboli physical and chemical variables attributable to agricultural activities and reclamation efforts in the Yala Swamp, despite construction of the feeder canal from the Yala River to the lake, have previously been reported (Aloo, 2003; Anyona, 1997; Kinaro, 2008; Okemwa, 1981; Wilfred et al., 2005). Lake Kanyaboli's ecology is also affected by the economic activities of its riparian communities.

Accordingly, it is essential to monitor physical, chemical and ecological changes in Lake Kanyaboli in order to better understand the influence of multiple anthropogenic stressors. The present study, therefore, reviewed the temporal variations in physical, chemical and biological variables in Lake Kanyaboli in order to propose possible interventions to circumvent adverse anthropogenic effects on the lake, focussing specifically on changes in water quality, trophic status, fish species and chronology of events in the lake and its catchment area from 1981 to 2020. Also included in the present study is additional data collected through an ongoing study on the lake's ecology, noting these data are essential for developing policies on the management and conservation of the lake and its linked ecosystems.

2 | MATERIALS AND METHODS

2.1 | Description of study area

The present study focussed on Lake Kanyaboli, an oxbow satellite lake of Lake Victoria located in the Yala Swamp between latitudes 0°05S′N and 0°02′N and longitudes 34°09′E and 34°ll′E, at 1156 m above sea level (Opiyo & Dadzie, 1994). The lake has an average depth of 3 m and covers an area of 10.5 km^2 (Abila et al., 2008). In addition to Lake Kanyaboli, Lake Namboyo and Lake Sare are also found in the Yala Swamp, although Lake Kanyaboli is the largest and farthest from Lake Victoria of the three lakes (Abila, 2005) (Figure 2). Yala Swamp is Kenya's largest freshwater wetland, covering 175 km^2 along the northern shores of Lake Victoria (Abila et al., 2008). It is a complex of wetlands in the delta of the Yala River on the northeast shore of Lake Victoria (Muoria et al., 2015), with Lake Kanyaboli located on the northeast extremity of the swamp (Figure 2).

Lake Kanyaboli received water from the Yala Swamp before the 1970s through water drained from the Yala River and backflow from Lake Victoria (Wilfred et al., 2005). The lake is currently replenished by direct precipitation and backwash waters from Lake Victoria through the Goye Causeway and the Yala River feeder canal. According to Burgess (2008), the surface gravity-fed feeder canal is about 9 km long with an estimated discharge of 5 m^3/s, ensuring the water flow is gentle and erosion minimized. This is an improvement from the initial design of an estimated flow capacity of 1.145 m^3/s before the maintenance by Dominion farm Ltd.

The region experiences a bimodal rainfall pattern from March to June and October to December. The latter is a short rainy period, while the former is the peak and more extended rainfall period throughout the area. Movements of the intertropical zone and the proximity of Lake Victoria influence the area's climate. The lake is within the lakeshore belt, which annually receives <1300 mm (Anyona, 1997).

The Yala Swamp lakes are ecologically and evolutionary important for preservation of the rich cichlid fish fauna of Lake Victoria (Gichuki et al., 2005), some having since gone extinct in Lake Victoria. Lake Kanyaboli and Sare support semicommercial fishing activities, while very little fishing occurs in Lake Namboyo because of its thick mats of *Cyperus papyrus* and *Phragmites australis* rendering the lake inaccessible (Abila & Othina, 2006; Wilfred et al., 2005). Algal species richness in Lakes Kanyaboli, Sare and Namboyo varies from 12 to 43, with blue-green algae being the dominant group (Wilfred et al., 2005).

Human activities in Lake Kanyaboli and Yala Swamp have implications for Lake Victoria, and Lake Victoria reciprocally influences the three satellite lakes (Kanyaboli, Sare and Namboyo) through backflow (Wilfred et al., 2005). Thus, Yala Swamp has a critical role in filtering and buffering the waters draining from the Yala River and the three lakes into Lake Victoria and vice versa (CGS, 2015). Muoria et al. (2015) noted, for example, that nitrate concentrations in the water entering Lake Victoria from Lake Sare were 3.61 mg/L, despite other parts of the swamp receiving concentrations as high as 9.84 mg/L because of the buffering effect of the swamp. In addition, the massive papyrus separating Lake Kanyaboli and Lake Victoria inhibits faunal exchanges between the two lakes.

Lake Kanyaboli is crucial because it contains cichlid populations that have either been depleted or become extinct in Lake Victoria. Although viable populations of the native *Oreochromis esculentus* and *O. variabilis* species, for example, are available in Lake Kanyaboli, they have disappeared from Lake Victoria because of predation by Nile Perch and other ecological changes (Abila, 2005). Further, Lake Kanyaboli acts as refugia for six haplochromine species (*Lipochromis maxilaris*, *Astatotilapia nubila*,

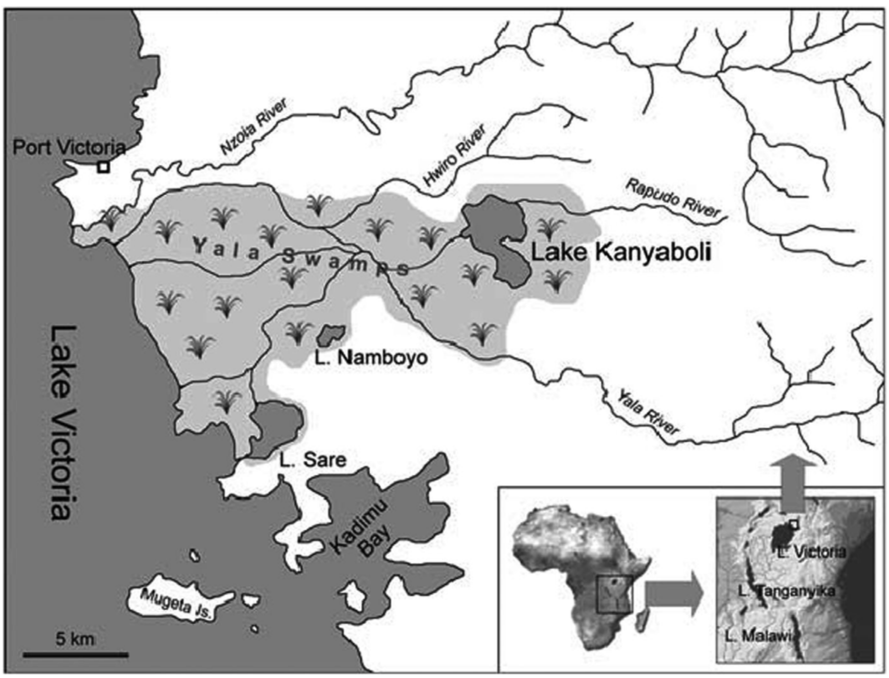


FIGURE 2 Map of Yala Swamp showing position of Lakes Kanyaboli, Sare and Namboyo (adapted from Abila et al., 2008)

Pseudocrenilabrus multicolor victoriae, *Xystichromis phytophagus*, *Astatoreochromis alluaiudi*), in addition to *O. niloticus*, *O. leucostictus*, *T. zilli*, *Clarias mossambicus*, *Protopterus aethiopicus* and *Xenoclarias* sp. (Aloo, 2003). Fish catches in Lake Kanyaboli, however, continue to decline because of overfishing and poor fishery management (BN Kondowe, unpublished data). The lake also is a vital livelihood source for riparian communities from fisheries, agriculture and handicraft industries. Abila (2005) noted fish is the most critical wetland product, with 98%–100% of the residents being dependent on fishing for subsistence or sale.

2.2 | Data sources

Both primary and secondary data were used in the present study. Primary data on physical, chemical and biological variables, including pH, electrical conductivity, dissolved oxygen concentration, temperature, Secchi depth, and nitrate, nitrite, ammonium, soluble reactive phosphorus, total nitrogen, total phosphorus and chlorophyll-*a* concentrations were collected monthly from February 2020 to February 2021. Chlorophyll-*a* data, however, were collected for only six months, from June 2020 to November 2020. The sampling period covered the wet season (March–June; October–December) and dry season (January and February; July–September). Similarly, secondary data on physical and chemical variables and chlorophyll-*a* were reviewed from published and grey literature (i.e. theses and reports). Further, since studies on the limnology and trophic status of Lake Kanyaboli are limited or lacking, the results of studies from other African lakes and elsewhere were also used to inform the interpretation of data and inform management recommendations.

2.3 | Sampling sites

Six sampling sites located in the littoral zone 15 m from the shore (Sites 1, 3, 4, 5 and 6) and limnetic zone (Site 2) were selected for monitoring surface water quality in Lake Kanyaboli. The sampling sites represented various fish landing sites and villages around the lake (Figure 3), including Site 1 (Gangu), Site 2 (Open Water), Site 3 (Prince's Hotel), Site 4 (Kadenge), Site 5 (inlet from lake side) and Site 6 (outlet from lake side).

2.4 | Sample collection and analysis

Water variables such as temperature, pH, Secchi depth, dissolved oxygen concentration and electrical conductivity were measured in situ at all the sampling sites using a YSI multiprobe water quality metre (556 MPS; Yellow Springs Instruments). Determination of filterable nutrients, including ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-) and soluble reactive phosphorus (SRP) was conducted in the laboratory at the University of Eldoret. Surface water samples from all the sampling sites were collected and filtered immediately in the field using precombusted 0.4-µm GF/C Whatman filters into triplicates of sampling bottles and placed in an icebox for transportation to the laboratory for analysis. Filter papers were placed in an icebox in a dark container for analyzing the chlorophyll-*a* content. Similarly, unfiltered water samples were collected in triplicate to analyze total phosphorus (TP) and total nitrogen (TN) concentrations, with their preservation and transportation to the laboratory conducted in the same manner as for the filterable nutrients.

Standard colorimetric methods (APHA, 2017) were used to analyze the NH_4^+, NO_3^-, NO_2^-, SRP, TP and TN concentrations. These methods included the molybdenum blue method, dichloroisocyanurate–salicylate method, cadmium reduction method and azo–dye complex formation for SRP, NH_4^+, NO_3^- and NO_2^- respectively. TP was analyzed using the ascorbic acid reduction method, while the persulfate digestion method was used for TN. The chlorophyll-*a* concentrations were determined following pigment extraction from the thawed filters using 90% acetone and following the APHA (2017) procedure.

2.5 | Data analysis

Primary data on physical, chemical and biological variables were analyzed using descriptive statistics, Pearson correlations and two-way ANOVA for comparing interactions between sampling sites and seasons. Where there were no interactions between sampling sites and seasons, one-way ANOVA was used, followed by the Tukey's post hoc test for significant mean values among sampling sites. The data were log-transformed prior to analysis of variance (ANOVA) to meet assumptions for parametric tests. Further, the Levene's homogeneity test was used on the original data to test the equality of variance. Descriptive statistics and correlation were performed with Microsoft Excel 2015, while the Levene's homogeneity test and two-way and one-way ANOVA were done in Minitab 17.

2.5.1 | Trophic status

Carlson trophic status index (TSI) equations, based on Secchi depth transparency (SD), chlorophyll-*a* (Chl-*a*) and TP, were used to calculate the trophic status of Lake Kanyaboli, as follows (Carlson, 1977):

$$\mathrm{TSI\ (SD)} = 10\,(6 - \mathrm{lnSD}/\mathrm{ln2}) \tag{1}$$

$$\mathrm{TSI\ (Chl} - a) = 10\,(6 - 2.04 - 0.68\mathrm{lnChl} - a/\mathrm{ln2}) \tag{2}$$

$$\mathrm{TSI\ (TP)} = 10\,(6 - \mathrm{ln}\,(48/\mathrm{TP})\,/\mathrm{ln2}) \tag{3}$$

where SDD = Secchi depth (m); TP = total phosphorus concentration (mg/m^3); Chl-*a* = chlorophyll-*a* concentration (mg/m^3); TSI

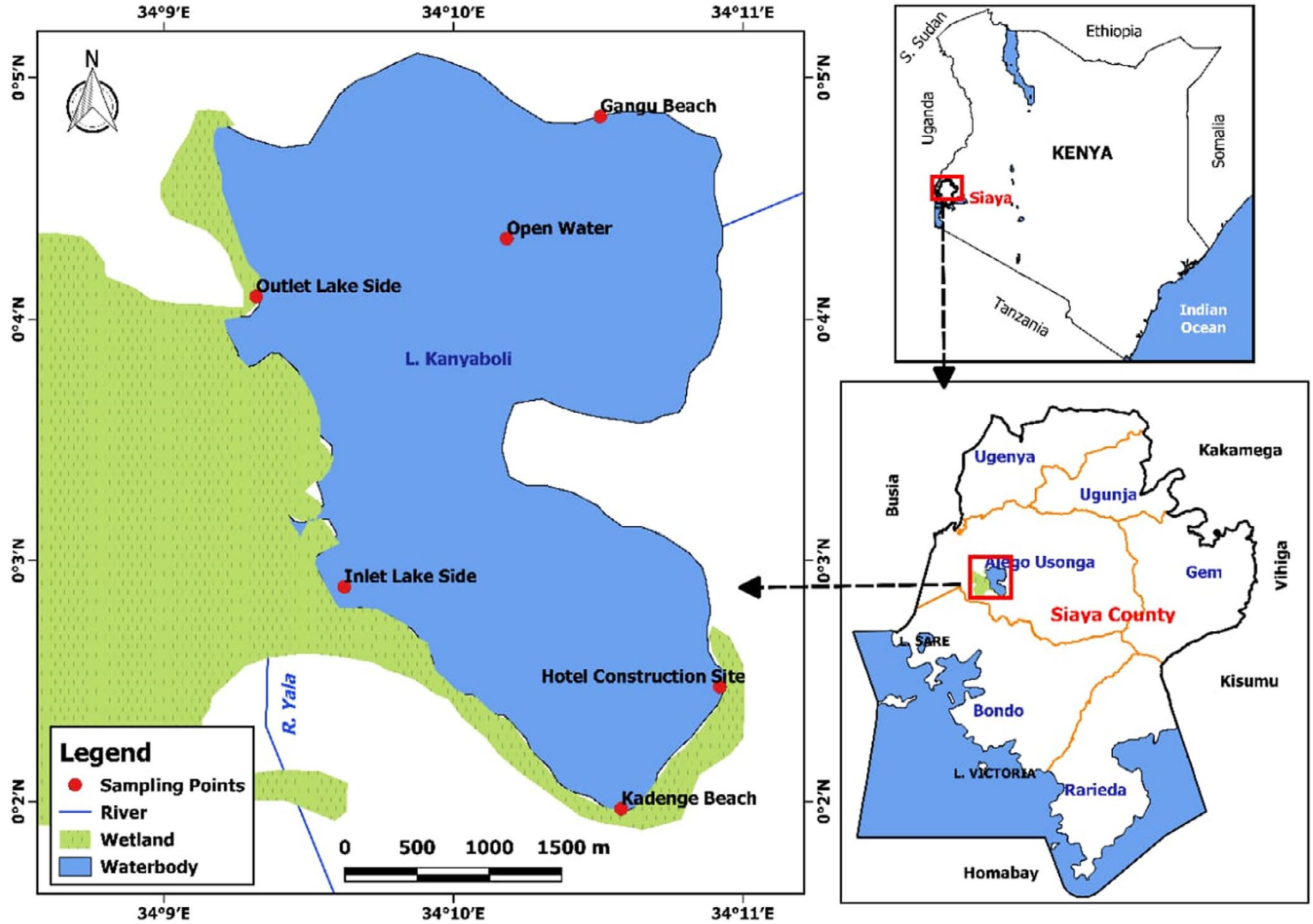


FIGURE 3 Map showing sampling sites in Lake Kanyaboli from February 2020 to February 2021

TABLE 1 Carlson (1977) criteria for lake trophic status (TSI)

TSI	Chlorophyll-*a* concentration (μg/L)	Total phosphorus concentration (μg/L)	Secchi depth (m)	Trophic status
<30–40	0–2.6	0–12	>8–4	Oligotrophic
40–50	2.6–7.3	12–24	4–2	Mesotrophic
50–70	7.3–56	24–96	2–0.5	Eutrophic
70–100+	56–155+	96–384+	0.5–<0.25	Hypereutrophic

Source: Sheela et al. (2011).

(SD) = trophic state index based on Secchi depth transparency; TSI (TP) = trophic state index based on total phosphorus concentration; and TSI (Chl-*a*) = trophic state index based on chlorophyll concentration.

The trophic state classifies lakes based on the greenness of a lake, being a surrogate of the quantity of algal biomass in the water column (Brown & Simpson, 2001). The Carlson (1977) trophic index is a commonly used classification of surface waters' trophic conditions, ranking lakes on a continuous numeric scale ranging from 0 to 100 as illustrated in Table 1.

3 | RESULTS

3.1 | Historical changes in Lake Kanyaboli water quality

Table 2 summarizes the mean annual values for 2020 based on measurements from Lake Kanyaboli, and the mean values obtained from grey and published literature on the lake. The reviewed literature identified temperature, pH, Secchi depth and electrical conductivity as the most studied physical and chemical variables. Only one

TABLE 2 Summary of mean physical, chemical and biological variables in Lake Kanyaboli over time from various studies (minimum and maximum values are highlighted in bold)

Variable	References/data sources: Okemwa (1981)	LBDA (1988)	Anyona (1997)	Maithya (1998)	LVEMP (2002)	Mutune et al. and Wilfred et al. (2005)	Babu et al. (2015)	Jalau (2017)	Present study (2020)
DO (mg/L)	5.4		7.08 ± 1.36	**10.6**	6.79	7.4	7.9	**47**	10.50 ± 0.48
pH	7.7		7.47 ± 0.44	7.7	8.28	7.2		8.3	7.05 ± 0.18
EC (µS/cm)		**600**		349		**287**			424.43 ± 1.88
Temperature (°C)				**24.5**	25.28	27		25.6	**27.98 ± 0.39**
Secchi depth(m)	**0.75**			**0.28**	0.48			0.67	0.76 ± 0.06
SRP (µg/L)									51.67 ± 9.83
NH_4^+ (µg/L)									983.33 ± 121.11
NO_2^- (µg/L)									210.00 ± 23.66
NO_3^- (µg/L)									306.67 ± 17.51
TP (µg/L)									503.33 ± 109.12
TN (µg/L)									3041.67 ± 280.10
Chl-*a* (µg/L)						18.30			21.46 ± 9.94

Abbreviations: Chl-*a*, chlorophyll-*a*; DO, dissolved oxygen; EC, electrical conductivity; NH_4, nitrate; NO_2, nitrite; NO_3, nitrate; SRP, soluble reactive phosphorus; TN, total nitrogen; TP, total phosphorus.

study (Wilfred et al., 2005), however, investigated the chlorophyll-*a* concentrations in Lake Kanyaboli (Table 2). The data indicate that the dissolved oxygen (DO) concentration has fluctuated between 4.7 and 10.6 mg/L over the years. The pH indicated less variability, with the current study recording the lowest pH value of 7.05, with the highest value (8.3) being observed in 2017. In contrast, the electrical conductivity exhibited a declining trend after a peak in 1988 (600 µS/cm) before an increase in 2020 (424.43 µS/cm). Further, the temperature and Secchi depth also exhibited fluctuations within the ranges of 24.50–27.98, and 0.28–0.76 m, respectively, over the years. An increased chlorophyll-*a* concentration was observed in the present study (21.46 µg/L), compared with the previously reported concentration (18.30 µg/L) by Wilfred et al. (2005). Unfortunately, the literature on nutrient levels in Lake Kanyaboli is scarce, limiting comparability over the years. Overall, except for pH, all the reviewed physical, chemical and biological variables exhibited considerable variations over the years. The results revealed intrayear seasonal variations potentially related to seasonality linked with rainfall and drought.

3.2 | Trophic status of Lake Kanyaboli

Chlorophyll-*a* concentrations in 2005 and 2020 indicated Lake Kanyaboli is eutrophic, while the total phosphorus concentrations from 2020 indicated a hypereutrophic condition (Table 3). Similarly, the 2020 Secchi depth also indicated the lake is eutrophic. The Secchi depth observed in previous studies (Jalau, 2017; LVEMP, 2002; Maithya, 1998; Okemwa, 1981), however, indicated the lake was eutrophic in 1981 and 2017, while hypereutrophic conditions were observed in 1998 and 2002 (Table 3). The data from 2020 indicated the TN (3041.67 ± 280.10 µg/L):TP (503.33 ± 109.12 µg/L) ratio of 6:1.

The changes in the Lake Kanyaboli water transparency were also available from five years representing the period from 1981 to 2020 (Figure 4). The Secchi depth in 2020 (0.76 m) was the highest, while the lowest water transparency was observed in 1998 (0.28 m).

3.3 | Lake Kanyaboli water quality changes

The mean physical, chemical and biological variables between wet and dry seasons are summarized in Figure 5. The spatial data from six sites satisfying the homogeneity of variance ($p > .05$) were pooled (Table S2). All physical and chemical variables and chlorophyll-*a* were high in the dry seasons, except for the pH, which was high during the wet season in all sampling sites. Significant seasonal variations were observed only for the Secchi depth ($p = .008$), and dissolved oxygen ($p = .017$), ammonium ($p = .002$), nitrite ($p = .013$) and chlorophyll-*a* ($p = .002$) concentrations (Table S1).

Site-wise mean variations indicated Secchi depth and chlorophyll-*a* varied more than all the water variables studied (Table 2). Kadenge (sampling site 4) exhibited the lowest Secchi

TABLE 3 Trophic status index (TSI) of Lake Kanyaboli over time based on Secchi depth, total phosphorus and chlorophyll-*a* concentrations

Source	Secchi depth (m)	TSI	Trophic status	Total phosphorus (µg/L)	TSI	Trophic status	Chlorophyll-*a* (µg/L)	TSI	Trophic status
Okemwa (1981)	0.75	64.15	Eutrophic	-	-	-	-	-	-
Maithya (1998)	0.28	78.37	Hypereutrophic	-	-	-	-	-	-
LVEMP (2002)	0.48	70.59	Hypereutrophic	-	-	-	-	-	-
Wilfred et al. (2005)	-	-	-	-	-	-	18.30	68.12	Eutrophic
Jalau (2017)	0.67	65.78	Eutrophic	-	-	-	-	-	-
Present study (2020)	0.76	63.96	Eutrophic	500	93.81	Hypereutrophic	21.46	69.68	Eutrophic

depth (0.69 ± 0.29 m), while Open Water (site 2) had the lowest chlorophyll-*a* concentration (9.03 ± 0.81 µg/L). In contrast, Open Water (site 2) exhibited the highest Secchi depth (0.87 ± 0.34 m), while Prince's Hotel (site 3) had the highest chlorophyll-*a* concentration (34.97 ± 3.36 µg/L). Two-way ANOVA (Table S1) indicated no significant interactions between sampling site and season for the physical and chemical variables ($p = .931$) and chlorophyll-*a* ($p = .463$). There also were no significant differences between sites for physical and chemical variables ($p > .05$), although chlorophyll-*a* was statistically different among the sites ($p = .000$) (Table 2).

There were significant positive correlations among selected water quality variables (Table 5), including between SRP and temperature ($r = .86$), NO_3^- and NH_4^+ ($r = .68$), NO_2^- and NH_4^+ ($r = .80$), TN and NH_4^+ ($r = .85$), NO_3^- and NO_2^- ($r = .65$), NO_3^- and TN ($r = .59$), NO_2^- and TN ($r = .57$) and NO_2^- and chlorophyll-*a* ($r = .57$). Conversely, Secchi depth was negatively significantly correlated with NH_4^+ ($r = -.77$), NO_3^- ($r = -.82$), NO_2^- ($r = -.77$) and TN ($r = -.64$) and chlorophyll-*a* ($r = -.51$).

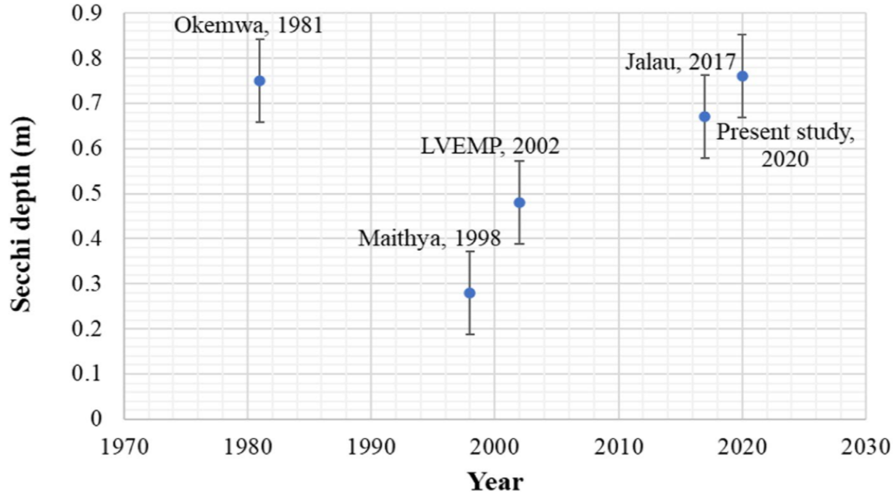
4 | DISCUSSION

Lake Kanyaboli is a strategic waterbody that provides riparian communities with water for domestic purposes, irrigation, livestock watering and fisheries activities. Data on the ecology of the lake, however, is scanty despite its socioeconomic importance. Some notable previous studies on the lake include those on fisheries and limnology (Mavuti, 1989; Okemwa, 1981), feeding ecology of *O. esculentus* (Opiyo, 1991) and a biodiversity survey (Aloo, 2003). Lack of detailed and consistent studies on the lake's ecology hinders decision-making and conservation efforts. The few studies on the lake (Table 2) do indicate some water quality and nutrient variables (temperature, turbidity, electrical conductivity, DO and pH) have been considered more than other variables (chlorophyll-*a*, TSS, ammonium, phosphorus, nitrate and nitrite). The limited studies on Lake Kanyaboli contrast with other lakes in Kenya such as Lakes Naivasha, Baringo and Victoria. Ecological studies are well documented, however, for Lake Naivasha (Gaudet, 1979; Gaudet & Muthuri, 1981; Kitaka et al., 2002), Lake Baringo (Ballot et al., 2003; Nyakeya et al., 2018; Ouma & Mwamburi, 2014) and Lake. Victoria (Hecky, 1993; Kishe, 2004; Ngupula et al., 2012) probably because of the existing commercial fishing and tourism industry. Thus, the present study provides a baseline of critical variables (chlorophyll-*a*, ammonium, phosphorus, nitrate and nitrite), filling some missing variables data gaps regarding the lake.

4.1 | Ecological status of Lake Kanyaboli

Available data, including unpublished surveys, indicate that none of the water quality variables occur in concentrations toxic to aquatic life. Electrical conductivity has always been below 1000 µS/cm, while the pH has ranged between 6 and 8 (Table 4). Goshu et al.

FIGURE 4 Lake Kanyaboli water transparency over time



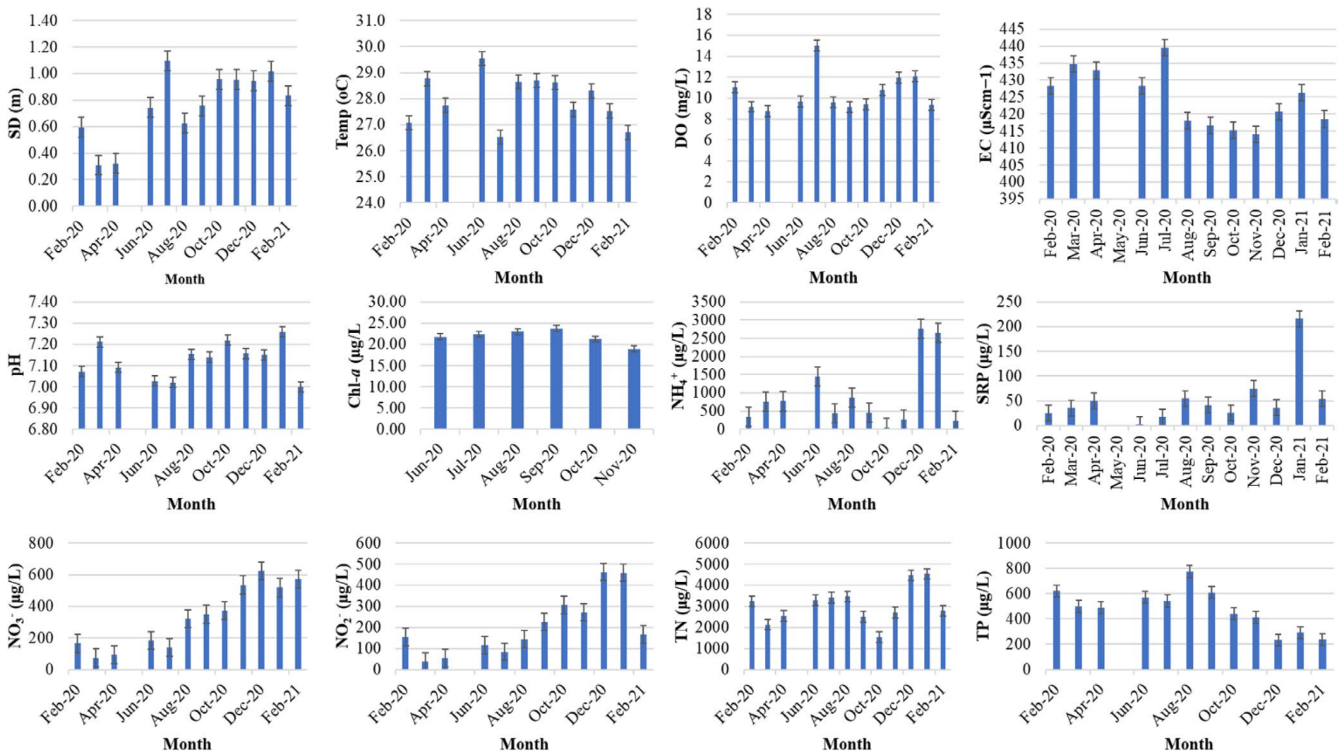


FIGURE 5 Temporal variation in physical, chemical and biological variables in Lake Kanyaboli, February 2020 to February 2021 (Chl-*a*, Chlorophyll-*a* concentration; DO, dissolved oxygen concentration; EC, electrical conductivity; NH_4^+, ammonium concentration; NO_2^-, nitrite concentration; NO_3^-, nitrate concentration; SD, Secchi depth; SRP, soluble reactive phosphorus concentration; Temp., temperature; TN, total nitrogen concentration; TP, total phosphorus concentration)

(2017) reported the conductivity of most freshwaters ranges from 10 to 1000 µS/cm but can exceed 1000 µS/cm, especially in polluted waters or those receiving large quantities of runoff. They also noted that the pH of most natural waters is between 6.0 and 8.5, although lower pH values can occur in groundwater brines and salt lakes. The dissolved oxygen concentration in Lake Kanyaboli has been within the optimum range (Table 4) for most aquatic living resources such as fish (Svobodová et al., 1993). The data available on chlorophyll-*a* from 2005 and 2020 (Table 4) indicated intermediate nutrient concentrations (Brown & Simpson, 2001). The nitrogen nutrient species have also been in a non-toxic range (<10 mg/L), while the phosphorus concentration exceeded the recommended limit of <0.1 mg/L, based on United States Environmental Protection Agency (USEPA) standards (Fried et al., 2003). Lack of data from previous studies, however, hindered trend analysis of the historical nutrient loadings to the lake.

At the same time, inorganic nitrogen levels in the lake from 2020 indicated the ammonium nitrogen concentration is much higher than nitrite or nitrate (Table 4), similar to the Lake Naivasha Swamp (Muthuri & Jones, 1997). High ammonium nitrogen levels, compared with other

TABLE 4 Mean values (±SD*) of samping sites at Lake Kanyaboli, Kenya, February 2020–February 2021 (mean values with different letters are significantly different at $\alpha = 0.05$, as determined by one-way ANOVA followed by post hoc Tukey). Bold values mean the variable is significantly different among sites

Variable	Gangu	Open water	Hotel	Kandenge	Lake inlet	Lake outlet	p-Value
SD (m)	0.74 ± 0.30^{a}	0.87 ± 0.34^{a}	0.72 ± 0.27^{a}	0.69 ± 0.29^{a}	0.80 ± 0.24^{a}	0.74 ± 0.25^{a}	.795
Temp. (°C)	27.63 ± 1.11^{a}	27.49 ± 0.79^{a}	27.86 ± 1.03^{a}	28.26 ± 1.26^{a}	28.14 ± 1.78^{a}	28.50 ± 1.51^{a}	.452
DO (mg/L)	10.76 ± 2.03^{a}	10.84 ± 2.99^{a}	9.69 ± 2.46^{a}	10.14 ± 2.38^{a}	10.86 ± 2.04^{a}	10.71 ± 2.77^{a}	.779
EC (µS/cm)	423.61 ± 9.83^{a}	427.59 ± 14.70^{a}	423.62 ± 10.57^{a}	423.37 ± 10.69^{a}	422.59 ± 8.20^{a}	425.81 ± 12.99^{a}	.918
pH	7.12 ± 0.09^{a}	7.13 ± 0.11^{a}	6.68 ± 1.50^{a}	7.14 ± 0.09^{a}	7.11 ± 0.09^{a}	7.14 ± 0.10^{a}	.433
NH_4^+ (µg/L)	786.22 ± 999.79^{a}	938.13 ± 1143.72^{a}	1134.77 ± 1042.21^{a}	1023.10 ± 1085.10^{a}	1075.82 ± 1023.98^{a}	941.36 ± 839.70^{a}	.356
SRP (µg/L)	46.09 ± 60.83^{a}	44.45 ± 60.98^{a}	51.03 ± 64.02^{a}	46.99 ± 55.16^{a}	48.07 ± 56.27^{a}	74.45 ± 61.49^{a}	.613
NO_3^- (µg/L)	331.43 ± 225.70^{a}	279.58 ± 184.06^{a}	317.44 ± 175.06^{a}	297.23 ± 197.77^{a}	307.96 ± 216^{a}	301.01 ± 191.51^{a}	.992
NO_2^- (µg/L)	168.51 ± 142.43^{a}	200.41 ± 162.21^{a}	241.27 ± 183.66^{a}	220.72 ± 178.41^{a}	221.90 ± 168.96^{a}	205.56 ± 139.78^{a}	.835
TN (µg/L)	3233.03 ± 1142.68^{a}	3488.47 ± 982.08^{a}	3024.04 ± 1325.53^{a}	2927.87 ± 1265.82^{a}	2696.22 ± 1247.00^{a}	2881.66 ± 1399.40^{a}	.544
TP (µg/L)	441.88 ± 137.78^{a}	425.22 ± 144.40^{a}	487.08 ± 113.58^{a}	446.57 ± 146^{a}	719.45 ± 683.36^{a}	489.85 ± 94.35^{a}	.733
Chl-*a* (µg/L)	23.52 ± 1.11^{c}	9.03 ± 0.81^{d}	34.97 ± 3.36^{a}	28.49 ± 3.06^{b}	21.45 ± 4.19^{c}	11.29 ± 2.03^{d}	**.000**

Abbreviations: NH_4^+, ammonium; NO_3^-, nitrate; Chl-*a*, chlorophyll-*a*; DO, dissolved oxygen; EC, electrical conductivity; NO_2, nitrite; SD*, standard deviation; SD, Secchi depth; SRP, soluble reactive phosphorus; Temp., temperature; TN, total nitrogen; TP, total phosphorus.

forms of inorganic nitrogen, are mainly attributable to anaerobic conditions wherein the normal denitrification pathway switches to one producing ammonia (Muthuri & Jones, 1997). Thus, Lake Kanyaboli is likely experiencing conditions similar to those in Lake Naivasha, considering the comparability of the two lakes. The results also indicated elevated total nitrogen concentrations in Lake Kanyaboli, possible related to inflows from the catchment area and the presence of large quantities of organic matter such as aquatic vascular plants undergoing decomposition and releasing large quantities of organic nitrogen (Nichols & Keeney, 1973). Excretory wastes from aquatic animals and livestock watering in the lake and feeder canal also contribute to the loading. Livestock grazing in the swamp also contribute to nutrient loadings from their excretion and egestion, and from runoff (Iteba et al., 2019). Yala Swamp is estimated to support an average of 1820 herds of cattle, 497 goats and 322 sheep daily (Mwaura et al., n.d.). The observed trend, therefore, may suggest nitrogen available for plant uptake in Lake Kanyaboli is mainly ammonium ions, meaning ammonium concentrations are important in determining whether or not nitrogen is a growth-limiting nutrient (Muthuri & Jones, 1997).

Phosphorus is generally considered a limiting factor in the aquatic environment because of its often-low ambient concentration in the water column, meaning that TP availability limits productivity (Stephen et al., 2020). However, nitrogen rather than phosphorus often limits phytoplankton growth in tropical and subtropical regions, compared with lakes in the temperate zone (Havens, 2000; Maberly et al., 2020). The total nitrogen (N):total phosphorus (P) ratio of 9:1 for phytoplankton was utilized to assess the limiting nutrient, with N:P ratios >9 being considered to indicate phosphorus limitation, whereas ratios <9 are considered evidence of nitrogen limitation (Salas & Martino, 1991). The N:P ratio of 6:1 in 2020, therefore, suggested N was a limiting factor for primary production in Lake Kanyaboli, a finding consistent with other lakes studies suggesting N was the limiting nutrient in tropical regions (Havens, 2000; Maberly et al., 2020; Salas & Martino, 1991).

All the variables assessed for the year 2020 exhibited high values during the dry season, except for pH, which exhibited some variability between the wet and dry seasons. The observed trend may indicate the combined effects of nutrient enrichment from the catchment area and saturation of solutes because of evaporation that reduces the lake water volume and concentrates the solutes, as noted by others (Lesack & Melack, 1991; Talling, 2001). Further, Lake Kanyaboli drains the Yala Swamp, which is an active agriculture site that might be introducing nutrients into the lake through runoff that subsequently becomes concentrated due to evaporation and the big catchment area drained by the lake (Wetzel, 2001).

The year 2020 also exhibited a positive and negative correlation between some variables (Table 5). A positive relation between TN and NO_2^- was observed, a finding in contrast to that of Yu et al. (2020), who reported TN to be positively and negatively correlated with NH_3 and NO_2^- respectively. The positive correlation between the nutrients may indicate a common source along with remineralization occurring in the lake. A positive correlation also was observed between temperature and SRP, in agreement with the findings of

TABLE 5 Pearson correlation coefficients regarding physical, chemical and biological variables of water in Lake Kanyaboli, February 2020 to February 2021

	SD	Temp.	DO	EC	pH	NH_4^+	SRP	NO_3^-	NO_2^-	TN	TP
Temp.	−0.43										
DO	−0.15	−0.13									
EC	0.45	−0.34	0.00								
TDS	0.12	−0.42	0.44	−0.02							
pH	−0.25	0.22	0.21	0.15							
NH_4^+	−0.77*	0.23	0.23	−0.31	0.37						
SRP	−0.43	0.86*	−0.04	−0.21	0.17	0.39					
NO_3^-	−0.82*	0.28	0.11	−0.33	0.37	0.68*	0.41				
NO_2^-	−0.77*	0.38	0.28	−0.36	0.22	0.88*	0.41	0.65*			
TN	−0.64*	−0.02	0.37	−0.04	0.46	0.85*	0.23	0.59*	0.57*		
TP	−0.02	−0.16	−0.17	−0.26	0.04	0.38	0.01	0.23	0.31	0.11	
Chl-*a*	−0.51*	0.12	−0.36	−0.42	−0.30	0.35	0.20	0.57*	0.41	0.17	0.16

Abbreciations: Chl-*a*, chlorophyll-*a*; DO, dissolved oxygen; EC, electrical conductivity; NH_4^+, ammonium; NO_2^-, nitrite; NO_3^-, nitrate; SRP, soluble reactive phosphorus; TDS, total dissolved solids; Temp., temperature; TN, total nitrogen; TP, total phosphorus.

*Correlation coefficient is significant at $\alpha = 0.05$.

Saturday et al. (2021). Further as observed elsewhere (Bachmann et al., 2017), Secchi depth exhibited a relatively strong relationship with chlorophyll-*a* and TN. The chlorophyll-*a* and Secchi depth correlation indicates algae and associated dead organic materials are significant, although not the only components of particulate materials in the lake related to Secchi depths (Bachmann et al., 2017). The feeder canal possibly contributes to the non-agal total suspended material in the lake. Likewise, the relationship between Secchi depth with TN and TP indicates these nutrients are limiting factors for algal growth, and that increasing algal biomass decisively reduces light penetration.

Overall, fluctuating physical, chemical and biological variables were observed in Lake Kanyaboli for the 1981–2020 period. These findings perhaps accrue from anthropogenic activities in Yala Swamp (Kinaro, 2008; Owiyo et al., 2014) that previously affected water replenishment in the lake attributable to blockage of the feeder canal, in turn producing poor water quality (Aloo, 2003; LBDA, 1988). The non-toxic levels of water quality variables in Lake Kanyaboli may be attributable to the maintenance of the feeder canal and an outlet by Dominion Group of Companies in 2004 that facilitated recharge of the lake water. Further, the dense anchored and floating macrophytes (predominantly *Cyperus papyrus* and *Phragmites australis*) and Yala Swamp likely help filter the excess nutrients. To this end, Muoria et al. (2015) also reported that Yala Swamp plays a vital role as a filter for pollutants arising from the upper Yala River catchment.

4.2 | Trophic status

A lake's trophic state depends on nutrient availability sufficient to support primary production and, in turn, can affect a lake's clarity and chlorophyll-*a* concentration. High nutrient levels in a lake supports eutrophication, which refers to the directional movement of a lake's condition from a lower trophic state to a eutrophic state over time, typically attributable to both natural and human factors. Natural eutrophication is the process by which lakes gradually become aged and more productive. However, excess nutrients (primarily N and P) from human activities that subsequently enter a lake, including untreated or partially treated domestic sewage, agricultural and urban runoff, etc., can greatly accelerate this process (Sheela et al., 2011). Phosphorus is considered the algal growth-limiting nutrient to be addressed in attempting to control eutrophication, with excessive growths ('blooms') of algae resulting from phosphates negatively changing a lake's water quality.

The chlorophyll-*a* concentration in 2005 and 2020 indicated Lake Kanyaboli exhibited a eutrophic status, while the total phosphorus concentration from 2020 indicated a hypereutrophic conditions (Table 3). Similarly, the Secchi depth from 2020 also indicated the lake was eutrophic, although the Secchi depth from previous studies (Jalau, 2017; LVEMP, 2002; Maithya, 1998; Okemwa, 1981) indicated the lake fluctuated between eutrophic and hypereutrophic conditions. These findings suggest nutrient availability in the lake have been increasing and subsequently leading to its current eutrophic status. The agreement between the calculated TSI values based on Chl-*a* and Secchi depth infer algae dominate the lake's light attenuation. At the same time, however, the lower TSI value for Chl-*a* compared to that for TP indicated less algal material was present in the lake than expected on the basis of the TP concentration (Havens, 2000). Thus, the 2020 results probably indicate algal growth in Lake Kanyaboli inversely affected the light attenuation, while its growth was affected either by a combination of TN and light attenuation, or any of these two factors. The lake's trophic status changes between 1981 and 2020 could be linked to human activities in the catchment area (Yala Swamp). The Yala River initially drained to the lake after passing through the swamp, facilitating the filtration of excess nutrients before they reached the lake (Muoria et al., 2015), thereby reducing nutrient enrichment and sedimentation. The construction of the retention dike along lake Kanyaboli, however, and the subsequent construction of the feeder canal from the Yala River likely reduced the swamp's buffering effect. The situation worsened in the past after the destruction of the feeder canal, resulting in reduced or no water reaching the lake (LBDA, 1988), which possibly concentrated the nutrients in the lake and leading to more primary production that induced the lake's eutrophic and hypertrophic status conditions (Table 5). After 2004, however, the feeder canal and an outlet were maintained to improve the lake's water exchange and trophic status. Nevertheless, the persistence of the lake's eutrophic status suggests a continued nutrient input from the catchment area and the remineralization of the nutrients already in the lake.

4.3 | Changes in biological communities in Lake Kanyaboli

The literature review conducted in the present study indicated that the Lake Kanyaboli biological community is composed of plankton, macrophytes, invertebrates and fish. Although diatoms, green algae and euglenophytes are also present in the lake, the cyanobacteria are dominant and account for more than 50% of a given sample (Aloo, 2003; Babu et al., 2015; Wilfred et al., 2005). The cyanobacteria dominance is linked to the nutrient supply from the drainage basin (Wilfred et al., 2005). Further, livestock watering in such water bodies directly deposit large quantities of organic matter and nutrients from dung and urine during their excretion and egestion while watering (Iteba et al., 2019; Masese et al., 2020). These nutrients and carbon sources are fodder for the rapid proliferation of bacterio- and phytoplankton (Shevah, 2017). Cyanobacteria also become dominant in eutrophic lakes because of their efficiency in utilizing CO_2 at high pH levels, thereby outcompeting other algal groups (King, 1970). Lake Victoria, for example, exhibits a regular occurrence of cyanobacterial blooms in the Nyanza Gulf (Simiyu et al., 2018) and also experiences an annual shift in its phytoplankton community attributable to enrichment in P and N, and the depletion of Si (Hecky et al., 2010). Progression of current Lake Kanyaboli conditions, therefore, could replicate Lake Victoria's water quality problems if unchecked. Unfortunately, algal blooms can also produce and release sufficient toxins causing deterioration of both water quality and safety.

The zooplankton community in Lake Kanyaboli is represented by copepods (*Thermocyclops* spp.), a few cladocerans and rotifers (*Brachionus* spp.) (Aloo, 2003; Mutune et al., 2005). The animal plankton community is poor in Lake Kanyaboli (Aloo, 2003; Mutune et al., 2005), probably due to the dominance of cyanobacteria that can outcompete other phytoplankton. The unpalatability of cyanobacteria also inhibits their use as food by zooplankton, resulting in their dominance in aquatic systems and a poor zooplankton community (De Bernardi & Guisanni, 1990).

Lake Kanyaboli supports many fish species, including *O. esculentus*, *O. variabilis*, six haplochromine species, *O. niloticus*, *O. leucostictus*, *Tilapia zilli*, *Clarias gariepinus*, *Protopterus aethipicus* and *Xenoclarias* spp. (Abila, 2005; Aloo, 2003). At the same time, however, the fish from Lake Kanyaboli display stunted growth, due perhaps to a limited food supply since cyanobacteria, which are rarely utilized by fish, dominate primary production. Opiyo and Dadzie (1994), for example, reported that cyanobacteria and green algae were the least utilized food items by *O. esculentus* in Lake Kanyaboli and that they passed through the gut undigested after being ingested. The few available fish are also experiencing overfishing and poor management (Abila, 2005; Aloo, 2003). *L. maxilaris* and *A. nubila* are currently classified as vulnerable, while *O. esculentus* and *O. variabilis* are critically endangered (IUCN, 2019).

4.4 | Threats to Lake Kanyaboli

Lake Kanyaboli faces several serious threats attributable to extractive services and development activities in the lake and its catchment area. Papyrus, the swamp's most dominant vegetation, and which provides handcrafts and animal feed resources, is slowly disappearing. The papyrus form floating islands that shelter fish and protect them from predatory fish species such as Mbiru (*O. variabilis*), Fulu (*Haplochromis nubilus*), Kamongo (*Protopterus aethiopicus*), Okoko (*Synodontis afrofischeri*), Nyamami (*Oreochromis niloticus*), Ningu (*Labeo victorianus*), Fwani (*Labeobarbus altianalis*) and Adel (*Enteromius apleurogramma*) that used to be common in lakes Kanyaboli, Sare and Namboyo are now rarely found (CGS, 2015). The lake is probably facing overfishing threats due to uncontrolled and increasing fishing efforts along with the use of small mesh-size gillnets (between 1 and 2 inches) (Abila, 2005).

The reclamation of Yala Swamp was undertaken without evaluating its potential effects on the ichthyofauna and ecology of Lakes Kanyaboli, Sare and Namboyo (Aloo, 2003), which threaten the biological diversity of the lakes because of continued anthropogenic activities and lack of relevant data and information. Further, clearance of vegetation around the lake and Yala Swamp facilitate water runoff, with resultant sedimentation and increasing nutrient loads, possibly affecting the lake's ecology. Moreover, excess fertilizer, animal wastes and poor agricultural practices in the Lake Kanyaboli catchment area pose eutrophication and high electrical conductivity problems for the lake since the inputs of limiting factors (P and N) affect ecosystem health (Khatri & Tyagi, 2015). On the other hand, a high electrical conductivity, which depends on the geology of the catchment and agricultural land use (Hamid et al., 2020), affects potable water acceptability by changing its taste (Kah et al., 2016). All these factors affect the domestic useability of water, fisheries and recreational value of the lake.

Although massive papyrus separates Lake Kanyaboli and Lake Victoria inhibiting faunal exchanges between the two lakes, there's a potential threat of Nile Perch (*Lates niloticus*) from Lake Victoria colonizing the lake. Although Nile Perch is absent in Lake Kanyaboli, it has found its way into Lake Sare (in Yala Swamp) from Lake Victoria via the direct link between these two lakes (Gichuki et al., 2005).

The presence of Nile Perch in Lake Sare possibly contributes to variations between the fisheries of Lake Kanyaboli and Sare. *O. esculentus*, for example, while dominating in Lake Kanyaboli, is vulnerable to predation by Nile Perch, thereby being poorly represented in Lake Sare (Abila & Othina, 2006). Thus, Lake Kanyaboli's pristine status, considered a replica of Lake Victoria before the introduction of Nile perch, is definitely threatened. Further, water hyacinth (*Eichhornia crassipes*) patches noticed within the Yala Swamp (Aloo, 2003) are currently within a 20–50 m radius from Lake Kanyaboli, thereby posing more threat of their introduction to the lake.

5 | CONCLUSIONS

Understanding the physico-chemistry variability of surface waters, such as lakes, reservoirs and rivers, and linking them to potential drivers are essential for developing management and conservation strategies. The physical, chemical and biological characteristics of Lake Kanyaboli, (e.g. trophic state index) indicate a strong influence of human activities on a temporal scale. At the same time, however, commonly monitored water quality variables (temperature, DO, electrical conductivity, turbidity/Secchi depth and pH) by themselves surprisingly indicate Lake Kanyaboli is in relatively good condition despite the growing threat of human disturbances in its catchment area. Human influences on the lake are likely to increase in the future because the adjoining lake areas and its catchment are under increasing human population and livestock pressures. The catchment is utilized for growing various crops, using varying levels of fertilizer application that contain high levels of nitrogen, phosphorus and potassium (Wilfred et al., 2005). If unchecked, these nutrients have the potential to maintain the lake in a eutrophic condition. Because the lake is of significant socioeconomic and ecological importance to local communities, strengthening water quality monitoring is vital to safeguard the sustainability of its ecosystem goods and services to people living in adjoining areas. Management and conservation efforts should also foster the lake's role as a refuge for endangered fish species representing remnants of the Lake Victoria's original cichlids flock. There are fears of extinction of many haplochromine species in Lake Victoria attributable to predation by the introduced Nile perch. Accordingly, the following recommendations, among other measures, are proposed for priority attention to safeguard the sustainability of the lake, its ecosystem services and its catchment area:

- Constant monitoring of water quality to enrich the literature about the lake since there are currently inconsistencies and gaps in the available data over the years, including nutrient concentrations (inorganic and total N and P) and biological variables such as plankton composition and chlorophyll-*a* concentration;
- Strengthening of the Yala Swamp National Reserve guidelines and regulations on using the wetland and Lake Kanyaboli;
- Improved enforcement of fishery regulations, noting that despite participatory structures (beach management units) being in place around the lake, the County and National government support is minimal, resulting in open-access fishing;
- Rehabilitating the reclaimed area of Yala Swamp that is unutilized in order to restore vegetation to reduce sedimentation and nutrient enrichment in the lake;
- Maintaining the retention dike to avoid direct, unregulated water entry from the Yala Swamp into Lake Kanyaboli. Routine fish biodiversity and fish stock assessment studies on the lake and feeder canal should also be conducted to monitor the potential introduction of exotic species.

ACKNOWLEDGEMENTS

The present study was funded by the Intra-Africa Academic Mobility Project 'Collaborative Training in Fisheries and Aquaculture in East, Central and Southern Africa (COTRA)', which is funded by the European Union (EU). We specially thank due fishers at Kadenge, Gangu and Kombo beach for their assistance during fieldwork. We are also grateful to Henry Lubanga and Augustine Sitati of the University of Eldoret for assistance during field sampling and laboratory analysis of samples.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

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

ORCID

Benjamin N. Kondowe https://orcid.org/0000-0002-7763-2642
Riziki Jacques Walumona https://orcid.org/0000-0003-1054-3925

REFERENCES

Abila, R. (2005). Biodiversity and sustainable management of a tropical wetland lake ecosystem: A case study of Lake Kanyaboli, Kenya. *FWU – Water Resources Publications*, *3*, 1–11.

Abila, R., & Othina, A. (2006). *What is the socio-economic value of the wetland's fisheries? The case of Yala Wetland in Kenya*. Ministry of Water and Irrigation.

Abila, R., Salzburger, W., Ndonga, M. F., Owiti, D. O., Barluenga, M., & Meyer, A. (2008). The role of the Yala Swamp lakes in the conservation of Lake Victoria region haplochromine cichlids: Evidence from genetic and trophic ecology studies. *Lakes & Reservoirs: Research & Management*, *13*, 95–104. https://doi.org/10.1111/j.1440-1770.2008.00366.x

Aloo, P. A. (2003). Biological diversity of the Yala Swamp lakes, with special emphasis on fish species composition, in relation to changes in the Lake Victoria Basin (Kenya): Threats and conservation measures. *Biodiversity and Conservation*, *12*, 905–920.

Anyona, G. O. (1997). *An investigation into some water quality problems of Lake Kanyaboli in Kenya*. MSc Thesis, University of Nairobi.

APHA (2017). *Standard methods for the examination of water and wastewater* (p. 1545). American Public Health Association. American Water Works Association. Water Environment Federation.

Babu, J. M., Getabu, A. M., Nyaundi, K., Jembe, D., Boera, P., Sitoki, L., Mwayuli, G. A., Omondi, R. O., & Olilo, C. O. (2015). Phytoplankton distribution and abundance in small water bodies of the Lake Victoria Basin of Kenya. *International Journal of Fisheries and Aquatic Studies*, *2*(6), 166–169.

Bachmann, R. W., Hoyer, M. V., Croteau, A. C., & Canfield, D. E. (2017). Factors related to Secchi depths and their stability over time as determined from a probability sample of US lakes. *Environmental Monitoring and Assessment*, *189*(5), 1–17. https://doi.org/10.1007/s10661-017-5911-9

Ballot, A., Pflugmarcher, S., Wiegand, C., Kotut, K., & Krienitz, L. (2003). Cyanobacterial toxins in Lake Baringo, Kenya. *Limnologica*, *33*(1), 2–9. https://doi.org/10.1016/S0075-9511(03)80003-8

Brown, T., & Simpson, J. (2001). Determining the trophic state of your lake. *Watershed Protection Techniques*, *Urban Lake Management*, *3*(4), 771–781.

Burgess, C. (2008). *Overview of dominion farms*. https://landmatrix.org/media/uploads/dominionfarmskenyablogspotcoza200801overview-of-dominion-farmshtml.pdf

Carlson, R. E. (1977). A trophic state index for lakes. *Limnology & Oceanography*, *22*, 361–369.

Chapman, D., & Kimstach, V. (1996). Selection of water quality variables. In D. Chapman (Ed.), *Water quality assessments: A guide to the use of biota, sediments and water in environment monitoring (2188–2187)* (2nd ed., pp. 59–126). E FN Spon.

County Government of Siaya (CGS) (2015). *Report of the joint committee on agriculture, tourism, water and delegated legislation on Yala Swamp*. Clerk's Chambers, County Assembly of Siaya.

De Bernardi, R., & Guisanni, G. (1990). Are blue-green algae suitable food for zooplankton? An overview. *Hydrobiologia*, *200*(201), 29–41.

Doyle, R. D., & Smart, R. M. (2001). Impacts of water column turbidity on the survival and growth of *Vallisneria americana* winter-buds and seedlings. *Lake and Reservoir Management*, *17*, 17–28.

Ellah, R. G. (2020). Physical properties of inland lakes and their interaction with global warming: A case study of Lake Nasser, Egypt. *The Egyptian Journal of Aquatic Research*, *46*(2), 103–115. https://doi.org/10.1016/j.ejar.2020.05.004

Fried, S., Mackie, B., & Nothwehr, E. (2003). Nitrate and phosphate levels positively affect the growth of algae species found in Perry Pond. *Tillers*, *4*, 21–24.

Garn, H. S., Elder, J. F., & Robertson, D. M. (2003). *Why study lakes? An overview of USGS lake studies in Wisconsin*. U.S. Geological Survey Fact Sheet No. 063-03, 8 p.

Gaudet, J. (1979). Seasonal changes in nutrients in a tropical swamp: North Swamp, Lake Naivasha, Kenya. *Journal of Ecology*, *67*(3), 953–981. https://doi.org/10.2307/2259223

Gaudet, J. J., & Muthuri, F. M. (1981). Nutrient relationships in shallow water in an African Lake, Lake Naivasha. *Oecologia*, *49*, 109–118. https://doi.org/10.1007/BF00376907

Gichuki, J., Maithya, J., & Masai, D. M. (2005). *Recent ecological changes in of Lake Sare, western Kenya*. 11th World Lake Conference. Nairobi, Kenya.

Goshu, G., Koelmans, A., & de Klein, J. (2017). Water quality of Lake Tana Basin, Upper Blue Nile, Ethiopia. A review of available data. In S. Krystyna, G. Goshu, & S. Aynalem (Eds.), *Social and ecological system dynamics* (pp. 127–141) Springer.

Hamid, A., Bhat, S. U., & Jehangir, A. (2020). Local determinants influencing stream water quality. *Applied Water Science*, *10*, 24. https://doi.org/10.1007/s13201-019-1043-4

Havens, K. E. (2000). Using Trophic State Index (TSI) values to draw inferences regarding phytoplankton limiting factors and seston composition from routine water quality monitoring data. *Korean Journal of Limnology*, *33*(3), 187–196.

Hecky, R. E. (1993). The eutrophication of Lake Victoria. *SIL Proceedings, 1922–2010*, *25*(1), 39–48. https://doi.org/10.1080/03680770.1992.11900057

Hecky, R. E., Muginne, R., Ramlal, P. S., Talbot, M. R., & Kling, G. W. (2010). Multiple stressors cause rapid ecosystem change in Lake Victoria. *Freshwater Biology*, *55*(Suppl. 1), 19–42. https://doi.org/10.1111/j.1365-2427.2009.02374.x

Iteba, J. O., Hein, T., & Singer, G. A. (2019). Masese FO (2021) Livestock as vectors of organic matter and nutrient loading in aquatic ecosystems in African savannas. *PLoS One*, *16*(9), e0257076. https://doi.org/10.1371/journal.pone.0257076

IUCN (2019). *The IUCN Red List of threatened species*. Version 2019–2. Downloaded on 23 July 2019.

Jalau, P. O. (2017). *Effect of physicochemical factors and dyke on conservation of Oreochromis esculentus and Oreochromis variabilis in lake Kanyaboli, Kenya*. MSc Thesis, Maseno University. Kisumu, Kenya.

Jarosiewicz, A., & Witek, Z. (2014). Where do nutrients in an inlet-less lake come from? The water and nutrient balance of a small mesotrophic lake. *Hydrobiologia*, *724*, 157–173. https://doi.org/10.1007/s10750-013-1731-2

Kah, H. L., Isa, B. K., Hafizan, J., Azman, A., Shima, B., Rabia, I., Hamisu, A. M., & Sharifuddin, M. Z. (2016). Evaluation of water quality variation in lakes, rivers, and ex-mining ponds in Malaysia (review). *Desalination and Water Treatment*, *57*(58), 28215–28239. https://doi.org/10.1080/19443994.2016.1185382

Kalff, J. (2002). *Limnology*. Prentice Hall.

Khatri, N., & Tyagi, S. (2015). Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in Life Science*, *8*(1), 23–39. https://doi.org/10.1080/21553769.2014.933716

Kinaro, Z. O. (2008). *Wetland conversion to large-scale agricultural production; implications on the livelihoods of rural communities, Yala Swamp, Lake Victoria Basin, Kenya*. Department of Water and Environmental Studies, Linkopings University.

King, D. L. (1970). The role of carbon in eutrophication. *Journal of Water Pollution Control Federation*, *42*, 2035–2051.

Kishe, M. A. (2004). Physical and chemical characteristics of water in selected locations in Lake Victoria, Tanzania. *Tanzania Journal of Science*, *30*, 65–72.

Kitaka, N., Harper, D. M., & Mavuti, K. M. (2002). Phosphorus inputs to Lake Naivasha, Kenya, from its catchment and the trophic state of the lake. *Hydrobiologia*, *488*, 73–80. https://doi.org/10.1023/A:1023362027279

Lake Basin Development Authority (LBDA) (1988). *Rural domestic water resources assessment*. Rural domestic water supply and sanitation programme. Siaya district, Kenya.

Lake Victoria Environmental Management Programme (LVEMP) (2002). *Fish biology and biodiversity subcomponent. Report of regional sampling of satellite lakes*. Kanyaboli, (Kenya), Nabugabo, (Uganda), Ikimba, (Tanzania). A report to Kenya Marine and Fisheries Research Institute.

Lam, D. C. L., & Schertzer, W. M. (1999). *Potential climate change effects on Great Lakes hydrodynamics and water quality*. American Society of Civil Engineers.

Lesack, L. F. W., & Melack, J. M. (1991). The deposition, composition, and potential sources of major ionic solutes in rain of the central Amazon basin. *Water Resources Research*, *27*(11), 2953–2977. https://doi.org/10.1029/91WR01946

Low, K. H., Koki, I. B., Juahir, H., Azid, A., Behkami, S., Ikram, R., Mohammed, H. A., & Zain, S. M. (2016). Evaluation of water quality variation in lakes, rivers, and ex-mining ponds in Malaysia (review). *Desalination and Water Treatment*, *57*(58), 28215–28239. https://doi.org/10.1080/19443994.2016.1185382

Maberly, S. C., Pitt, J.-A., Davies, P. S., & Carvalho, L. (2020). Nitrogen and phosphorus limitation and the management of small productive lakes. *Inland Waters*, *10*(2), 159–172. https://doi.org/10.1080/20442041.2020.1714384

Maithya, J. (1998). A survey of ichthyofauna of Lake Kanyaboli and other small water bodies in Kenya: Alternative refugia for endangered fish species. *Naga, ICLARM Quarterly*, *21*, 54–56.

Masese, F. O., Kiplagat, M. J., Gonzalez-Quijano, C. R., Subalusky, A. L., Dutton, C. L., Post, D. M., & Singer, G. A. (2020). Hippopotamuses are distinct from domestic livestock in their resource subsidies to and effects on aquatic ecosystems. *Proceedings, Royal Society B*, *287*(1926), 20193000.

Mavuti, K. M. (1989). An account of some important freshwater wetlands of Kenya. In: S. A. Crafter, S. G. Njuguna, & G. W. Howard (Eds.), *IUCN conference proceedings, wetlands of Kenya* (pp. 23–35).

Melack, J. (1997). Freshwater ecosystems: Revitalizing educational programs in limnology. *EOS Transactions*, *78*, 552–557. https://doi.org/10.1029/97EO00334

Merga, L. B., Mengistie, A. A., Faber, J. H., & van den Brink, P. J. (2020). Trends in chemical pollution and ecological status of Lake Ziway, Ethiopia: A review focusing on nutrients, metals and pesticides. *African Journal Aquatic Science*, *45*(4), 386–400. https://doi.org/10.2989/16085914.2020.1735987

Muoria, P., Field, R., Matiku, P., Munguti, S., Mateche, E., Shati, S., & Odeny, D. (2015). *Yala Swamp ecosystem service assessment*.

Muthuri, F. M., & Jones, M. B. (1997). Nutrient distribution in a papyrus swamp: Lake Naivasha, Kenya. *Aquatic Botany*, *56*(1), 35–50. https://doi.org/10.1016/S0304-3770(96)01093-5

Mutune, M. D., Omondi, R., & Owili, M. (2005). *Systematics and distribution of zooplankton in Lake Victoria basin, Kenya*. 11th World lakes Conference, Nairobi, Kenya.

Mwaura, F. M., Kagure, E., Ngugi, M., Wanjohi, L. W., Mbuthia, J. W., Makala, M. W., & Otieno, J. (n.d.). *Options of the Yala Wetland management for sustainable development and biodiversity conservation*. https://www.conservationleadershipprogramme.org/media/2014/11/2003_KENYA_YALA-WETLAND.pdf

Ndungu, J., Augustijn, D., Hulscher, S., Fulanda, B., Kitaka, N., & Jude, M. (2015). A multivariate analysis of water quality in Lake Naivasha, Kenya. *Marine and Freshwater Research*, *66*, 177–186. https://doi.org/10.1071/MF14031

Ngatia, L., Iii, J., Moriasi, D., & Taylor, R. (2019). *Nitrogen and phosphorus eutrophication in marine ecosystems*. IntechOpen.

Ngupula, G. W., Ezekiel, C. N., Kimirei, I. A., Mboni, E., & Kashindye, B. B. (2012). Physical and chemical characteristics of the Tanzanian inshore and offshore waters of Lake Victoria in 2005–2008. *African Journal of Aquatic Science*, *37*(3), 339–345. https://doi.org/10.2989/16085914.2012.712503

Nichols, D. S., & Keeney, D. R. (1973). Nitrogen and phosphorus release from decaying water milfoil. *Hydrobiologia*, *42*, 509–525. https://doi.org/10.1007/BF00047023

Nirmala, E., Remani, K. N., & Nair, S. R. (1991). Limnological status of a freshwater lake ecosystem in a humid tropic region. *International Journal of Environmental Studies*, *39*(3), 223–229. https://doi.org/10.1080/00207239108710696

Nyakeya, K., Odoli, C., Miruka, J. B., & Mugo, J. (2018). *A report on assessment of primary productivity of Lake Baringo for sharing the findings. KMF/RS/2018/C2.8(i)*. Kenya Marine and Fisheries Research Institute.

O'Gorman, E. J., Olafsson, O. P., Demars, B. O. L., Friberg, N., Guðbergsson, G., Hannesdottir, E. R., Jackson, M. C., Johansson, L. S., McLaughlin, O. B., Olafsson, J. S., Woodward, G., & Gíslason, G. M. (2016). Temperature effects on fish production across a natural thermal gradient. *Global Change Biology*, *22*, 3206–3220. https://doi.org/10.1111/gcb.13233

Okemwa, E. N. (1981). *A preliminary Survey of the Fishes and Limnology of Lake Kanyaboli and Lake Sare in Western Kenya*. Proceedings, Workshop of the Kenya Marine and Fisheries Research on 'Aquatic Resources of Kenya. pp. 192–211.

Oladipo, A. E., & Williams, A. B. (2003). Physical and chemical parameters and phytoplankton community of some selected fish ponds in Lagos, Nigeria. *Journal of Aquatic Sciences*, *18*(1), 53–57.

Opiyo, S. V. (1991). *Feeding ecology of Oreochromis esculentus (Graham) (Pisces: Cichlidae) in Lake Kanyaboli, Kenya*. M.Sc. Thesis. University of Nairobi.

Opiyo, S., & Dadzie, S. (1994). Diet and food utilization in *Oreochromis esculentus* (Graham) in Lake Kanyaboli, Kenya. *Fisheries Management and Ecology*, *1*, 79–90. https://doi.org/10.1111/j.136524001970.tb00008x

Ouma, H., & Mwamburi, J. (2014). Spatial variations in nutrients and other physicochemical variables in the topographically closed Lake Baringo freshwater basin (Kenya). *Lakes and Reservoirs: Research and Management*, *19*(1), 11–23. https://doi.org/10.1111/lre.12052

Owiyo, P., Kiprono, E., & Sutter, P. (2014). The effect of dominion irrigation project on environmental conservation in Yala Swamp, Siaya District, Kenya. *International Journal of Science and Research*, *3*(10), 82–87.

Salas, H., & Martino, P. (1991). A simplified phosphorus trophic state model for warm-water tropical lakes. *Water Research*, *25*(3), 341–350. https://doi.org/10.1016/0043-1354(91)90015-i

Saturday, A., Lyimo, T. J., Machiwa, J., & Pamba, S. (2021). Spatio-temporal variations in physicochemical water quality parameters of Lake Bunyonyi, Southwestern Uganda. *SN Applied Science*, *3*(684), 1–14. https://doi.org/10.1007/s42452-021-04672-8

Scott, J. T., & McCarthy, M. J. (2010). Nitrogen fixation may not balance the nitrogen pool in lakes over timescales relevant to eutrophication management. *Limnology and Oceanography*, *55*, 1265–1270. https://doi.org/10.4319/lo.2010.55.3.1265

Sheela, A. M., Letha, J., & Joseph, S. (2011). Environmental status of a tropical lake system. *Environmental Monitoring Assessment*, *180*(1–4), 427–449. https://doi.org/10.1007/s10661-010-1797-5

Shevah, Y. (2017). Challenges and solutions to water problems in the middle east. In A. Satinder (Ed.), *Chemistry and water* (pp. 207–258). Elsevier. https://doi.org/10.1016/b978-0-12-809330-6.00006-4

Simiyu, B. M., Oduor, S. O., Rohrlack, T., Sitoki, L., & Kurmayer, R. (2018). Microcystin content in phytoplankton and in small fish from eutrophic Nyanza Gulf, Lake Victoria, Kenya. *Toxins*, *10*, 275. https://doi.org/10.3390/toxins10070275

Stephen, C. M., Pitt, J., Davies, P. S., & Carvalho, L. (2020). Nitrogen and phosphorus limitation and the management of small productive lakes. *Inland Waters*, *10*(2), 159–172. https://doi.org/10.1080/20442041.2020.1714384

Sterner, R. W., Elser, J. J., Fee, E. J., Guildford, S. J., & Chrzanowski, T. H. (1997). The light: Nutrient ratio in lakes: The balance of energy and materials affects ecosystem structure and process. *The American Naturalist*, *150*, 663–684. https://doi.org/10.1086/286088

Svobodová, Z., Lloyd, R., Máchová, J., & Vykusová, B. (1993). *WSater quality and fish health* (59 p). EIFAC Technical Paper. No. 54. FAO.

Talling, J. (2001). Environmental controls on the functioning of shallow tropical lakes. *Hydrobiologia*, *458*, 1–8. https://doi.org/10.1023/A:1013121522321

USAID (2016). *Lake Victoria basin ecosystem profile assessment report*. https://www.climatelinks.org/sites/default/files/asset/document/2016_USAID-PREPARED_Lake-Victoria-Basin-Ecosystem-Profile-Assessment.pdf

Walker, J. L., Younos, T., & Zipper, C. E. (2007). *Nutrients in lakes and reservoirs – A literature review for use in nutrient criteria development*. Virginia Polytechnic Institute and State University Virginia Water Resources Research Centre.

Wetzel, R. G. (2001). *Limnology: Lake and river ecosystems* (3rd ed.). Academic Press.

Wilfred, O., Wakwabi, E., Sitoki, L., Guya, F., Jembe, T., & Ogutu, Z. (2005). *Effects of physical mixing on the environment of satellite lakes* *and dams of Lake Victoria, Kenya*. 11th World Lakes Conference. Nairobi, Kenya.

Yu, Y., Song, X., Zhang, Y., & Zheng, F. (2020). Assessment of water quality using chemometrics and multivariate statistics: A case study in chaobai river replenished by reclaimed water, North China. *Water*, *12*(9), 2551. https://doi.org/10.3390/w12092551

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Kondowe, B. N., Masese, F. O., Raburu, P. O., Singini, W., & Walumona, R. J.. (2022). Water quality and ecology of Lake Kanyaboli, Kenya: Current status and historical changes. *Lakes & Reservoirs: Research & Management*, *27*, e12401. https://doi.org/10.1111/lre.12401