Limnological status of Lake Oloidien in Kenya's Rift Valley between 2020 and 2021

Alice Mutie*, Edna Waithaka, George N. Morara, Patrick Loki, Beatrice Obegi

Kenya Marine and Fisheries Research Institute, Naivasha Station, P.O. Box 837-20117, Naivasha, Kenya

*Corresponding author email: alis.mutheu@gmail.com, (+254) 0 721 764162

Abstract

Water samples were collected between August 2020 and March 2021 and analyzed for physico-chemical parameters to ascertain the current limnological status of Lake Oloidien. The maximum mean depth of the lake recorded was 7.7 m in November, which corresponded with a high water transparency value (69.0 ± 3.4 cm) in the same month. There were no significant variations in temperatures among the sampled stations, mean ranges were 23.15 ± 1.15°C and 23.93 ± 1.09°C. Dissolved oxygen (DO) concentrations were high in September (13.99 ± 0.01 mg L^{-1}) with depth profiles of DO between August 2020 and March 2021 differing significantly (p = 7.955E-06). Conductivity mean values ranged from 414.0 ± 23.89 µS cm^{-1} and 730 ± 11.54 µS cm^{-1}, with January recording the highest value while October recorded the least value. It was observed that only pH levels had significant variation across the months sampled with p = 0.506 and a mean of 8.55 ± 0.56. The mean values for nitrates ranged from 2.04 ± 1.30 mg L^{-1} and 4.78 ± 0.045 mg L^{-1} across the months sampled and the highest chlorophyll-a levels were recorded in August at 83.3 ± 56.06 mg L^{-1}. In the past years, the lake has been alkaline-saline with high conductivity levels, and chances of fish survival were limited. Currently, the environmental factors are now favourable for fish survival.

Keywords: Lake Naivasha basin, dissolved oxygen, nitrates, phosphates, physicochemical

Introduction

Lake Oloidien is located immediately South-west of the main basin of Lake Naivasha at 1,885 meters above mean sea level (mamsl) in the central valley of the Great African Rift Valley in Kenya. It is one of the three lakes of the Naivasha basin, the other two being the main Lake Naivasha and the Crater Lake. The local climate is warm and semi-arid because much of the monsoonal rainfall in the region is intercepted by the Mau Escarpment on the West and the Nyandarua (Aberdare) Range on the East (Verschuren, 1994). Its surface area is 550 hectares, separated from the main lake by the papyrus swamp *Cyperus spp* (Benun and Njoroge, 1999).

The basin of Lake Oloidien is a caldera of a crater with the shape of a truncated cone. It is shallow and lacks direct physical input from the main lake. Verschuren *et al.* (2000) reported that the water level in Lake Oloidien is maintained by rainfall, evaporation, and subsurface inflow from Lake Naivasha through a permeable sill. When Lake Naivasha's level rises above 1,886.5 mamsl, Lake Oloidien becomes confluent with Lake Naivasha and inputs into the Oloidien Bay. Thus, the underground connection allows L. Oloidien levels to fluctuate in synchrony with the main lake (Harper *et al.*, 2011). Consequently, Lakes Naivasha and Oloidien experience periods of being one or separate water bodies. In the 1980s when decreasing lake levels led to a separation of L. Oloidien from L. Naivasha, the conductivity was 660 µS cm^{-1}. In the period 2001–2005, a conductivity of 3,890 to 5,270 µS cm^{-1} was measured (Ballot *et al.*, 2009). The lake has an open, grassy shoreline with no emergent or floating macrophytes.

It was initially believed that Lake Oloidien is too alkaline to support any freshwater fish species but currently, there are ongoing fishery activities at the lake with approximately active 26 boats. This could be attributed to the fact that recently the lake has been connected with the main lake due to an increase in water level. The main sources of nutrient input to Lake Oloidien originate from cattle and goat herds watering at the lake and local women washing clothes using detergents.

Lake Oloidien is threatened by unsuitable physicochemical conditions (Ballot *et al.*, 2009). Its water quality and quantity have been under increasing pressure due to fluctuations in water levels and increasing water demand from the fast-expanding agricultural activities around the lake (Hubble, 2000). Anthropogenic activities within the lake's catchment provide both point and non-point sources of nutrients to the water column. Changes in water quality characteristics have a direct linkage to aquatic production. The rapid growth of human settlement around the lake and the associated urban waste disposal are potential sources of biological micro-contaminants in the lake and could cause undesirable effects on the aquatic environment. This study aimed to ascertain the limnological status of Lake Oloidien over the period 2020 - 2021.

Material and methods

Study area

Lake Oloidien is located about 100 km northwest of Nairobi at an altitude of 1890 m above sea level at 0°48′ 57.3768″ S and 36°15′ 46.7748″ E (Njuguna, 1988; Hickley *et al.*, 2002) (Fig. 1). It is a satellite lake of L. Naivasha found in a hydrologically closed basin. The lake's depth and surface area usually fluctuate depending on the prevailing dry and wet seasons and range between 4-19 m and 4-7.5 km^2, respectively. During periods in which Lake Naivasha's water level is high, it dilutes L. Oloidien, making its water fresh. Conversely, during the dry seasons when the lake water level is low, the two lakes are separated, resulting in a saline Lake Oloidien (Verschuren *et al.*, 1999). Four stations representative of the lake were select-

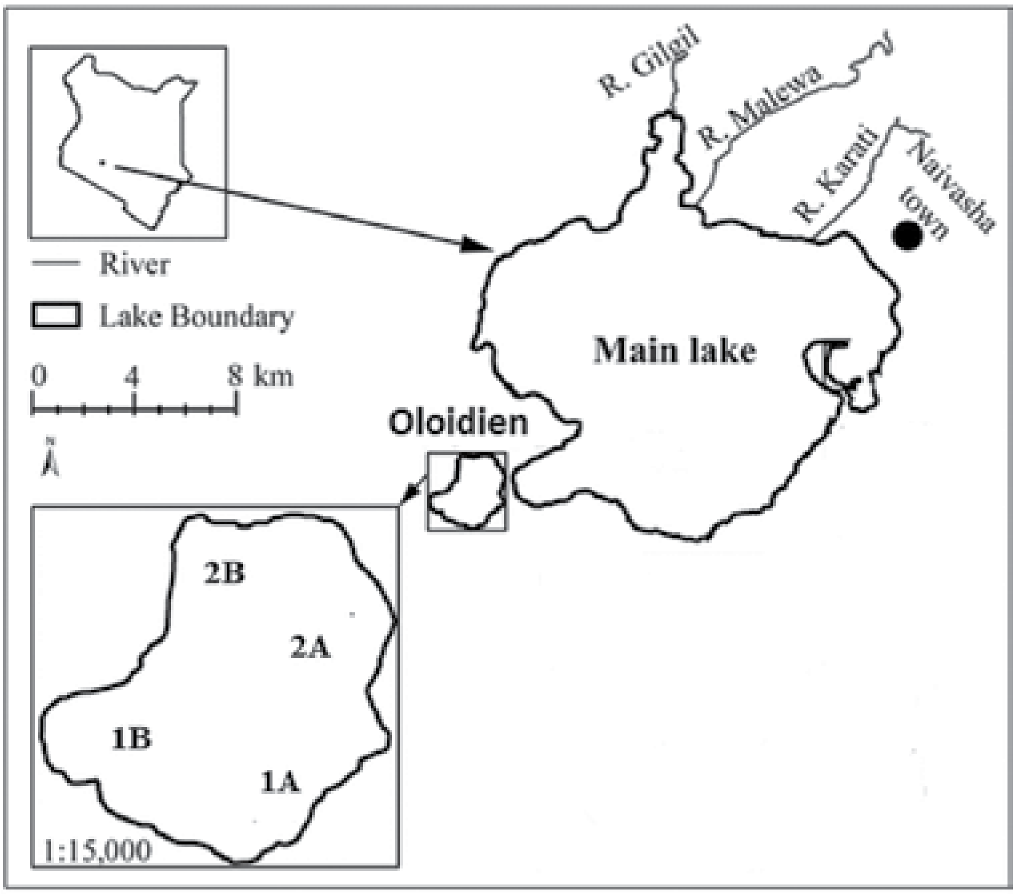

Figure 1. Map of Lake Oloidien showing the sampling stations (Oloidien 1A, 1B, 2A, and 2B) (Source: Maina *et al.* 2018).

ed during the study, i.e. Oloidein 1A, Oloidein 1B, Oloidein 2A, and Oloidien 2B. The study was done between August 2020 and March 2021.

Water sample collection and analysis

Water quality parameters including temperature, pH, dissolved oxygen (DO), conductivity, total dissolved solids (TDS) and salinity were measured *in situ* using a portable multiparameter meter (YSI Professional Pro Plus). The parameters were recorded in each site at a depth of 1 m. Water transparency was measured using a Secchi disk, 20 cm in diameter. The disk was lowered up to the point of its disappearance and lifted to the point of appearance. The average depth of the two points was recorded as water transparency (Secchi depth). Water samples for nitrates, phosphates, total suspended solids (TSS), and Chlorophyll-a (Chl-a) were collected using a Van Dorn sampler and emptied into one-liter polyethylene bottles. The samples were stored in cooler boxes at a temperature of about 4°C for analysis in the laboratory. Samples for Soluble Reactive Phosphorus (PO_4^{3-}) were filtered using 0.45 μm membrane filters followed by the analysis of the filtrate using the molybdate assay method (APHA, 1998). Nitrates (NO_3^-) were analyzed using Palintest Photometer 7500 Bluetooth method. This method uses the principles of optical absorbance and scattering of visible color light representing specific analytes upon reactions with spectrophotometric reagents. Samples for chlorophyll-a determinations were filtered through glass fiber filters and extracted in 90% acetone in distilled water. Chl-a values were measured in a 1.0 cm length cell at the absorbencies of 665 and 750 nm, respectively, using a spectrophotometer and concentration according to Pechar (1987). Total suspended solids (TSS) were determined, first by recording the initial weight of a filter paper before a known volume of sample water was filtered through the same filter paper, and dried in an oven at 104°C for 24 hours. The resultant weight of the filter was recorded as the final weight and TSS was calculated as shown below.

$$TSS\ (mgl^{-1}) = \frac{Final\ weight\ (mg) - Initial\ weight\ (mg)}{Sample\ volume\ (l)}$$

Spatial variations of the same parameters were compared using one-way analysis of variance (ANOVA) at a 95% confidence limit.

Results

Surface water temperature

Figure 2 shows the spatial and temporal variation of temperature in the surface water of L. Oloidien during the sampling period. It comprises a pair of graphs showing a) spatial and b) temporal temperature variations in the lake. Results show that there were no significant variations in temperature between the sampling sites ($p > 0.05$) with mean temperature ranges of 23.15°C to 23.93°C. Temperature values had significant variations ($p < 0.001$) among the months sampled with November and December recording high values at 24.9°C and 24.5°C respectively.

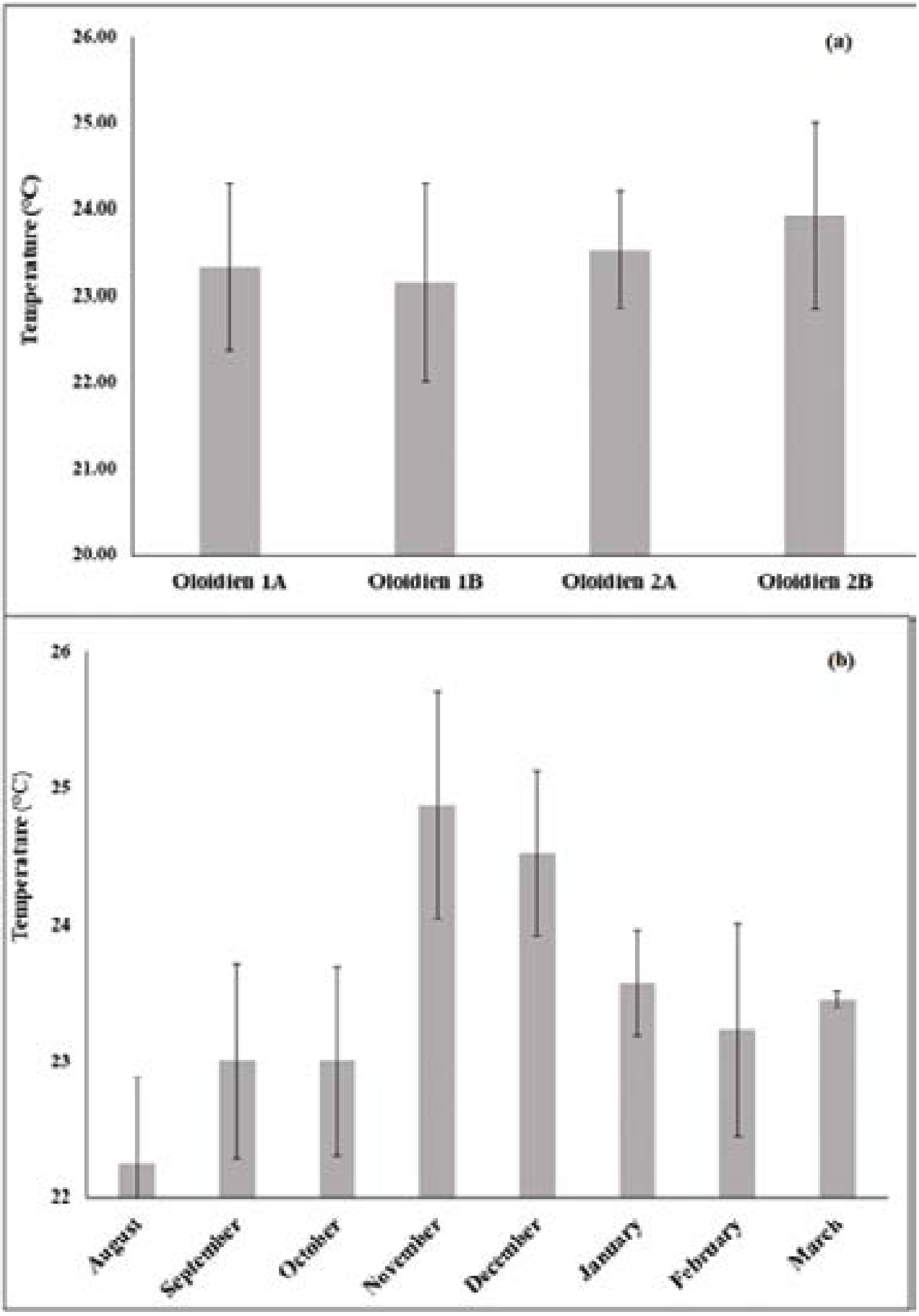

Figure 2. Spatial and temporal variations of temperature (°C) in Lake Oloidien's surface water between August 2020 and March 2021.

Surface dissolved oxygen

Figure 3 shows the spatial and temporal variations of dissolved oxygen (°C) in Lake Oloidien's surface water between August 2020 and March 2021. There was no significant variation (p = 0.69) in dissolved oxygen among the stations sampled. However, there were significant variations ($p < 0.001$) in DO concentrations among the months sampled, with September recording the highest surface DO concentrations at 13.99 ± 0.98 mg.L^{-1} while January recorded the least at 6.88 ± 0.31 mg L^{-1}.

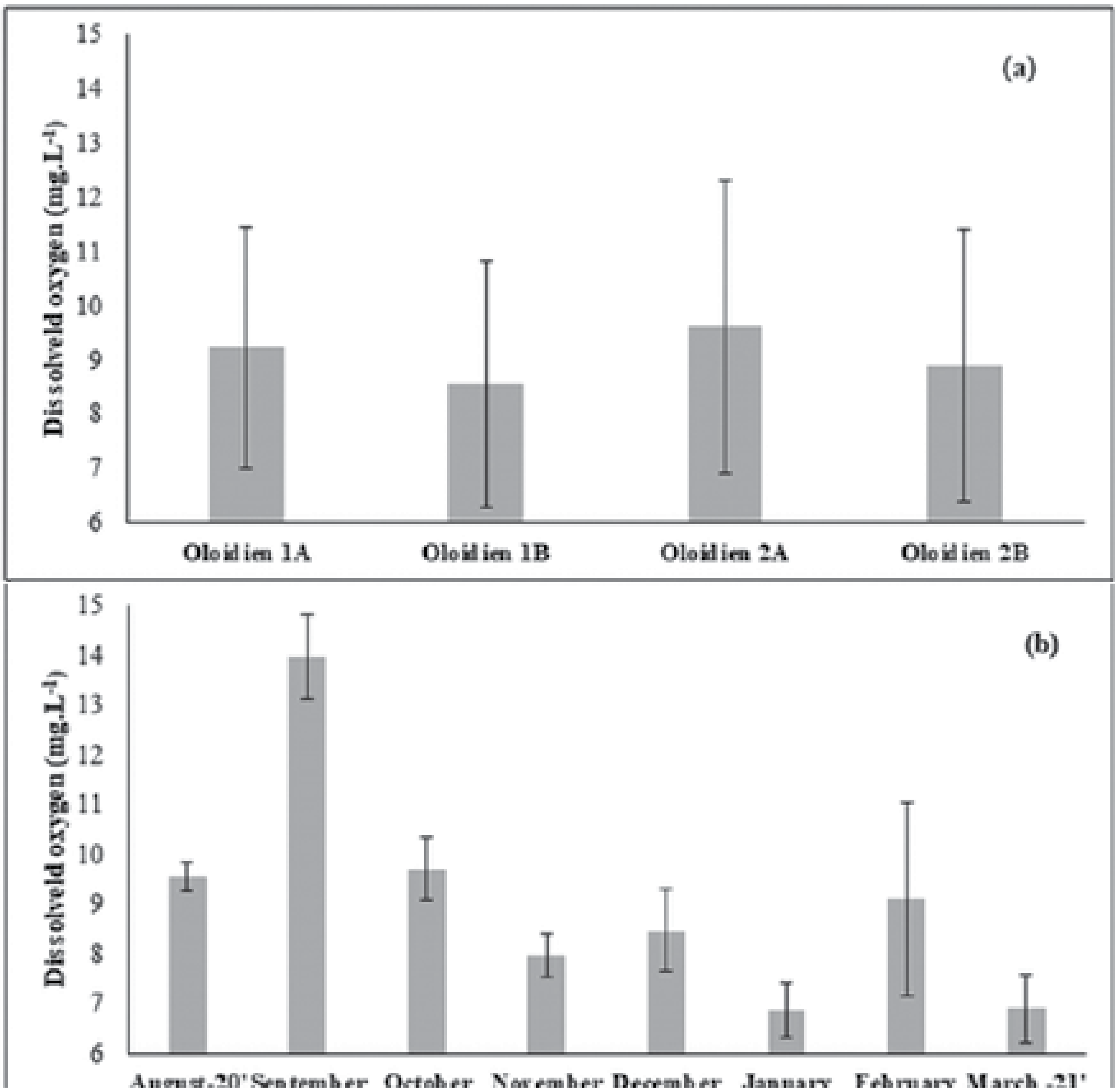

Figure 3. Spatial and temporal variations of dissolved oxygen (°C) in Lake Oloidien's surface water between August 2020 and March 2021.

Vertical patterns of water temperature and dissolved oxygen in the lake

Figure 4 shows the mean vertical temperature and oxygen profiles during the study period. The temperatures decreased gradually from the surface to the bottom with no distinct vertical stratification. Temperature fluctuation between surface water and the deepest point did not exceed 2°C. A rapid change in temperature with depth was only experienced in November, between 0 m and 2-3 m depth. The variations of DO depth profiles between the months differed significantly (p = 7.955E-06), with steep gradients in DO concentration from the surface towards the bottom observed in February while the lowest DO concentrations were recorded at 9 m in November (0.2 mg L^{-1}) and March (0.9 mg L^{-1}).

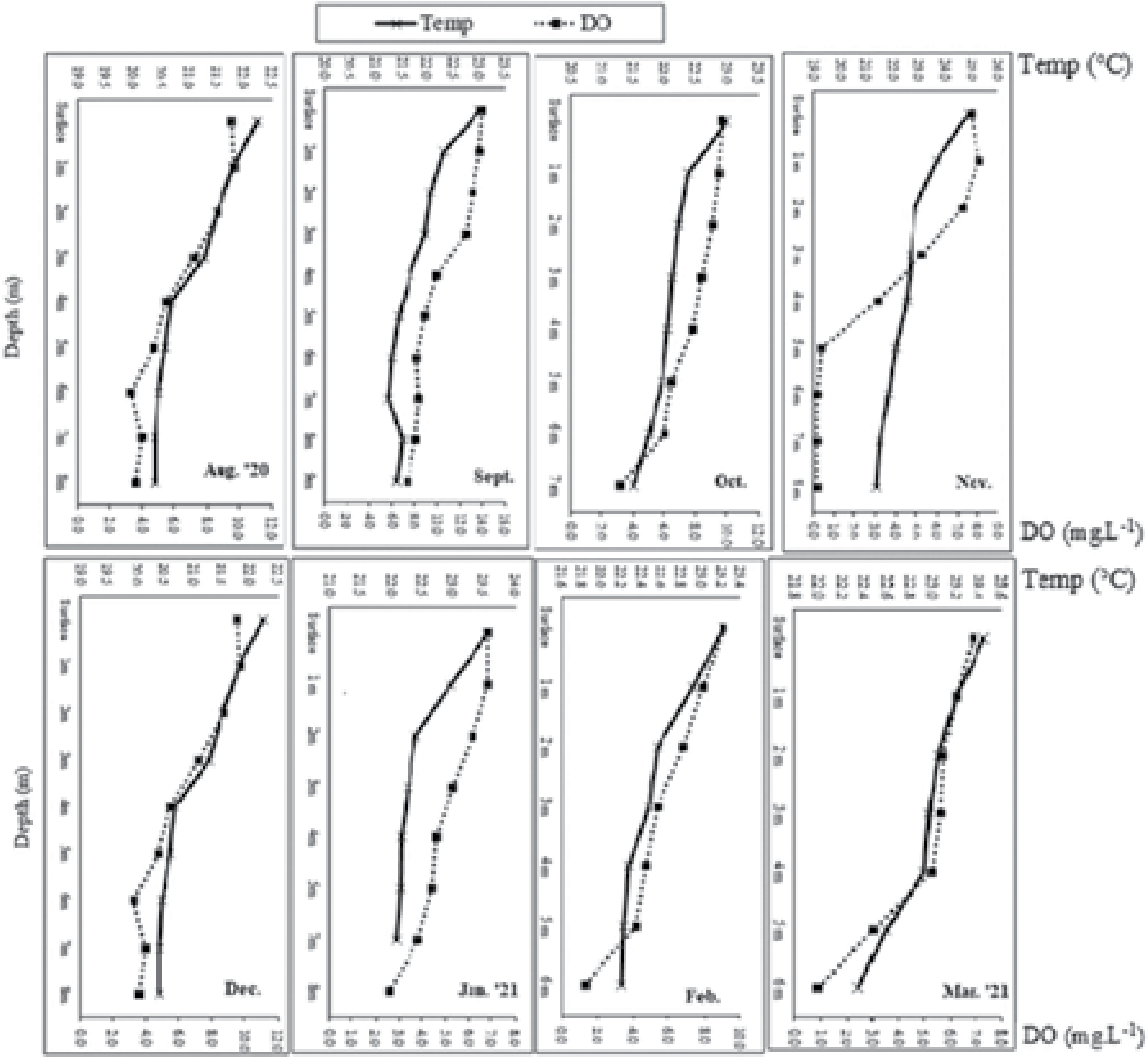

Figure 4. Mean vertical temperature and oxygen profile of L. Oloidien during the study period.

Electrical conductivity and pH

Figure 5 shows the pH levels and conductivity fluctuation in Lake Oloidien from August 2020 to March 2021. The mean conductivity values were observed to increase from August through March, with January recording the highest (730 ± 11.54 μS cm^{-1}). The study observed slightly fluctuating range of pH values between the months. pH values were lowest in August at 7.24 ± 2.00 and highest in February at 9.03 ± 0.01.

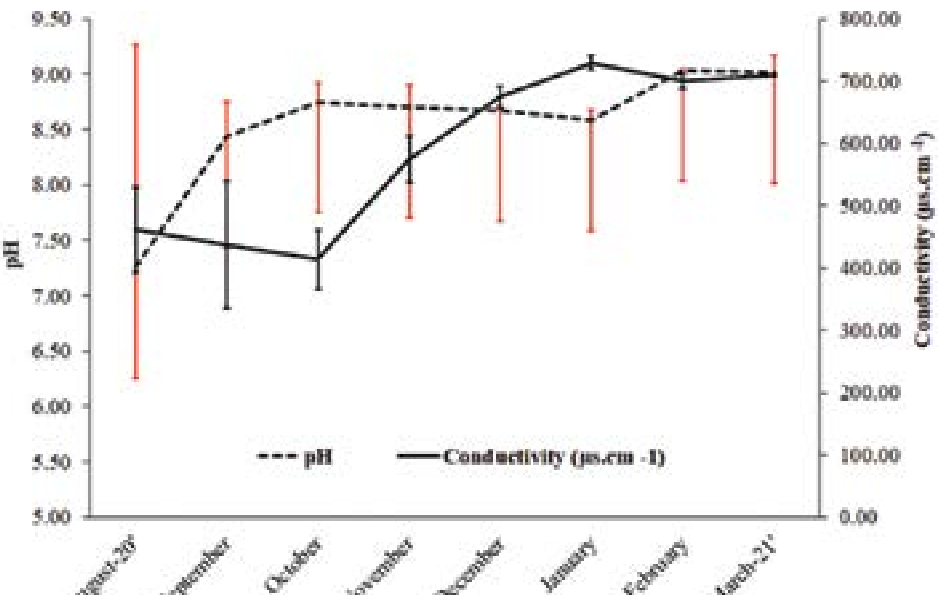

Figure 5. Water pH levels and conductivity fluctuation in Lake Oloidien for August 2020 to March 2021.

Salinity, total dissolved solids, and total suspended solids

The summary of mean values of TDS, Salinity, and TSS is shown in table 1. The results show a slightly increasing trend with small variations in TDS and salinity levels from August to March. Mean TSD values ranged from 0.28 and 0.48 g L^{-1}. It was also observed that salinity levels varied minimally between the stations with November through March having no variations (Table 1). The concentration of total suspended solids ranged between 9.75 ± 2.98 m g L^{-1} and 35.67 ± 18.01 mg L^{-1}, with the highest recorded in August and the lowest in February.

Water transparency and depth

Figure 6 shows the mean Secchi disc readings (water transparency) and mean depth in Lake Oloidien between August 2020 and March 2021. Results show the highest mean depth of the lake during the entire sampling period was 7.7 m in November with the deepest point recorded at 10.15 m in the same month at Oloidien 1B, and the least mean depth recorded in March (5.94 m). The highest water transparency was recorded during the November sampling period with a mean of 69 ± 0.34 cm, while the lowest transparency was observed in August at 36.9 ± 5.4 cm. The overall mean depth of the lake was 6.8 ± 0.71 m. Water transparency readings reflected a significant difference (*p* = 5.05E-09) across the months.

Table 1: Summary of mean values of TDS, Salinity, and TSS across the sampling months (August 2020 to March 2021)

Month	Mean (±SD)		
	TDS g L^{-1}	Salinity (ppt)	TSS (mg L^{-1})
August -'20	0.31 ± 0.04	0.22 ± 0.033	35.67 ± 18.01
September	0.30 ± 0.064	0.22 ± 0.049	11.63 ± 1.11
October	0,28 ± 0.029	0.21 ± 0.018	15.5 ± 6.02
November	0.37 ± 0.006	0.28 ± 0	18.5 ± 0.57
December	0.44 ± 0.006	0.33 ± 0	23.5 ± 9.33
January	0.48 ± 0	0.36 ± 0	14.33 ± 0.57
February	0.47 ± 0.004	0.35 ± 0	9.75 ± 2.98
March - '21	0.48 ± 0	0.36 ± 0	31.75 ± 7.27

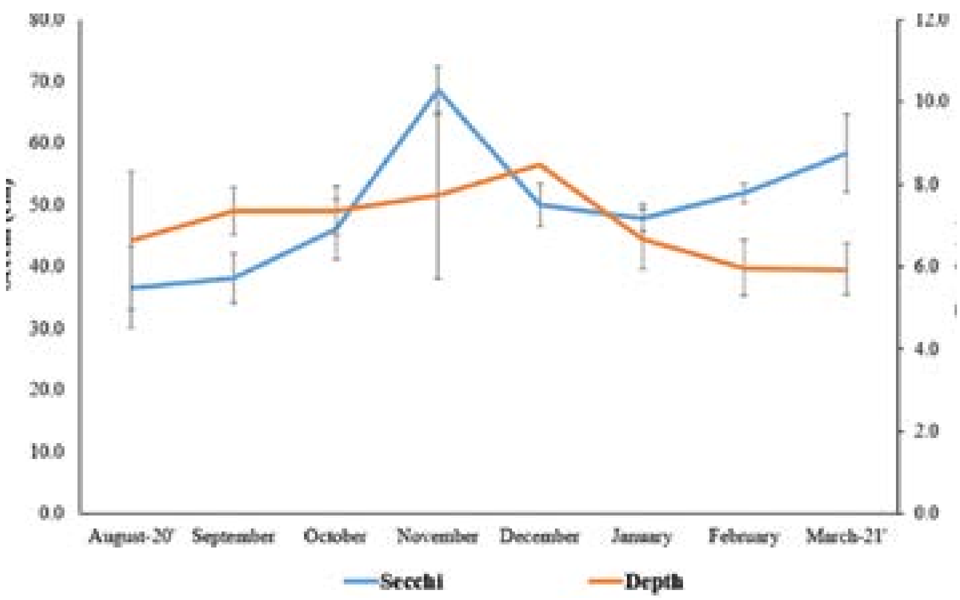

Figure 6. Mean Secchi disc readings (water transparency) and mean depth in Lake Oloidien between August 2020 and March 2021.

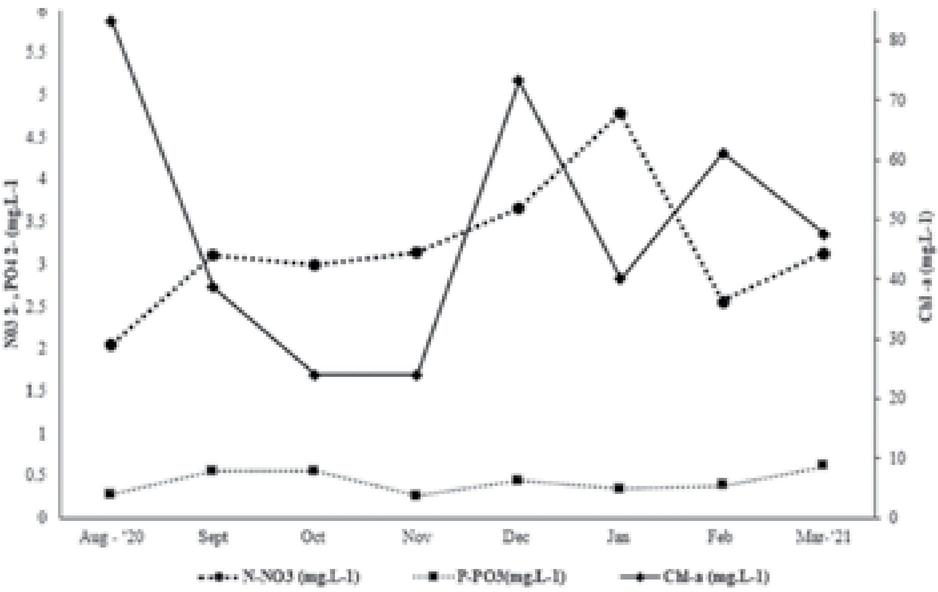

Figure 7. Trends of mean nitrates, soluble reactive phosphorus and chlorophyll-*a*, from August 2020 to March 2021 in L. Oloidien.

Nitrates, phosphates, and chlorophyll-a concentration

Figure 7 shows the trends of mean N-NO_3^- (nitrates), soluble reactive phosphorus, and Chl-a, from August 2020 to March 2021. It was observed that the mean nitrate concentrations across the months ranged between 2.04 ± 1.30 mg L^{-1} and 4.78 ± 0.45 mg L^{-1}. Soluble reactive phosphates (P-PO_4^{3-}) concentrations were below 1.0 mg L^{-1} during the entire sampling period. High levels of Chl-a concentrations were recorded in August (83.3 ± 56.06 mg L^{-1}). It was also observed that when the levels of nitrates were low, Chl-a concentrations were high, and vice versa.

Discussion

Generally, Lake Oloidien has low water transparency as is evident from the observations made in the study, which is an indication of the high biological productivity of the lake. This could be attributed to high levels of Chl-a recorded in this study of up to 83.3 mg L^{-1}. Despite low transparency levels during the sampling period, there was a slight but consistent increase in Secchi depth values over the sampling period. Similar studies have shown an increase in water transparency since the year 2017 (Mutie *et al.*, 2020). Tropical lakes are thought to be permanently stratified due to low seasonal variations in temperature (Catalán and Donato-Rondón, 2016). However, the low-temperature gradient between the surface and the maximum depth of measurement and the lack of a permanent thermocline was an indication of the total water mixing of the whole water column. This could be attributed to the shallowness of the lake and a wide-open basin, which allows exposure to the winds, which easily causes mixing. As a result, the water column was found to be well-oxygenated with DO levels ranging from 6.88 mg L^{-1} to 13.9 mg L^{-1}. Surface water was well-oxygenated, but at the bottom, it was depleted of oxygen (anoxic). Studies have shown that the depth of the lake, anaerobic conditions, and prevailing environmental conditions affect the amount of dissolved oxygen in the water (Siriwardana *et al.*, 2019). The high levels of dissolved oxygen concentration at Oloidien surface waters could be due to the effect of photosynthesis coupled with the high densities of algae in the water which is evident in the high levels of Chl-a concentration. Photosynthesis is usually highest during mid-day, hence the high production of oxygen during this period of the day led to a significant increase in the amounts of dissolved oxygen in the water. Comparable results from a study done by Grotzschel and Beer (2002) showed that oxygen concentration increased from 0 to 100% saturation due to photosynthetic activity.

Conductivity values observed in this study were generally low (414 - 730 µS cm^{-1}) compared with other studies which documented higher values of conductivity, for instance, Mutie *et al*. (2020) reported a value of 2,916 µS cm^{-1} while Ballot *et al*. (2009) reported 5,270 µS cm^{-1}. The current lower values of conductivity could be attributed to the rising levels of Rift Valley lakes whereby Lake Oloidien is currently connected to the main Lake Naivasha, therefore bringing about the dilution effect. High levels of pH observed during the sampling period were attributed to higher photosynthetic activity and also due to the dilution effect of the rains. Previous studies have shown pH levels of up to 6.6 - 6.71 (Kaoga *et al*., 2013; Mutie *et al*., 2020).

Results from this study indicate that Lake Oloidien is a phosphorus-limited aquatic system. This is in agreement with previous studies. For example, Ballot *et al*. (2009) reported total phosphorus (TP) concentrations of between 0.4 and 1.0 mg L^{-1}. In the same study, nitrogen concentrations range between 0.9 and 6.3 mg L^{-1}, which falls within the same range reported in the current study. It is observed that during the wet season, there are higher levels of nutrients in most lakes, and these are presumably the result of mixing events that redistribute nutrients to the surface water, and inputs from runoff (Zinabu, 2002). Chl-a concentration, which is a proxy for phytoplankton biomass, increased as nitrate concentration decreased. It has been shown that as phytoplankton consume nitrates and bloom, the concentration of nitrate decreases proportionally (Li *et al*., 2010). In the past years, the lake was alkaline and conductivity levels were high, and chances of fish survival were limited. Currently, the environmental factors are more favourable for fish survival as reported by a study by Mutie *et al*. (2020), with *Oreochromis niloticus* condition factor (K) of above 1.

Conclusion

The limnology of Lake Oloidien has changed over time from a shallow saline lake to mildly saline and it can be classified to be productive in its current state. This is based on the physicochemical parameters of the Lake which have changed over time from a shallow saline lake to mildly saline and could be termed as favourable for fishery production.

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References

APHA (1998) American Public Health Association Standard Methods for the Examination of Water and Wastewater, (20th ed). American Public Health Association, Washington DC, USA

Ballot A, Kotut K, Novelo E, Krienitz L (2009) Changes of phytoplankton communities in Lakes Naivasha and Oloidien, examples of degradation and salinization of lakes in the Kenyan Rift Valley. *Hydrobiologia*, 632(1): 359–363 [https://doi.org/10.1007/s10750-009-9847-0]

Benun L, Njoroge P (1999) Important Bird Areas in Kenya. East African Natural History Society, Nairobi. 318 pp

Catalán J, Donato-Rondón JC (2016) Perspectives for an integrated understanding of tropical and temperate high-mountain lakes. *Journal of Limnology*, 75(s1): 215–234 [https://doi.org/10.4081/jlimnol.2016.1372]

Grötzschel S, Beer D de (2002) Effect of Oxygen Concentration on Photosynthesis and Respiration in Two Hypersaline Microbial Mats. *Microbial Ecology*, 44(3): 208–216 [https://doi.org/10.1007/s00248-002-2011-2]

Harper DM, Morrison EHJ, Macharia MM, Mavuti KM, Upton C (2011) Lake Naivasha, Kenya: Ecology, Society and Future. *Freshwater Reviews*, 4(2): 89–114 [https://doi.org/10.1608/FRJ-4.2.149]

Hickley P, Bailey R, Harper DM, Kundu R, Muchiri M, North R, Taylor A (2002) The status and future of the Lake Naivasha fishery, Kenya. *Hydrobiologia*, 488(1): 181–190 [https://doi.org/10.1023/A:1023334715893]

Hubble DS (2000) Controls on primary production in Lake Naivasha, a shallow tropical freshwater [Doctoral Thesis, University of Leicester]. Retrieved from https://www.proquest.com/openview/bbf98cb-10148425f40e8b5ad9c16dd05/1?pq-origsite=gscholar&cbl=51922&diss=yKaoga J, Ouma G, Abuom P (2013) Effects of farm pesticides on water quality in Lake Naivasha, Kenya. *American Journal of Plant Physiology*, 8(3): 105–113

Li WKW, Lewis MR, Harrison WG (2010) Multiscalarity of the Nutrient–Chlorophyll Relationship in Coastal Phytoplankton. *Estuaries and Coasts*, 33(2): 440–447 [https://doi.org/10.1007/s12237-008-9119-7]

Maina CW, Sang JK, Mutua BM, Raude JM (2018) Bathymetric Survey of Lake Naivasha and its satellite Lake Oloiden in Kenya; using Acoustic Profiling System. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, 23: 324–332 [https://doi.org/10.1111/lre.12247]

Mutie A, Waithaka E, Morara G, Boera P, Mwamburi J, Keyombe JL, Keyombe A, Obegi B (2020) Population characteristics of *Oreochromis niloticus* (Linnaeus, 1758) in light of varying water quality conditions of adjoined Lakes Naivasha and Oloidien in Kenya. *Pan Africa Science Journal*, 1(1): 1-15 [https://doi.org/10.47787/pasj.2020.02.20]

Njuguna SG (1988) Nutrient-phytoplankton relationships in a tropical meromictic soda lake. In JM Melack (ed), Saline Lakes. Springer Netherlands. Dordrecht, pp 15–28 [https://doi.org/10.1007/978-94-009-3095-7_2]

Pechar L (1987) Use of an Acetone: Methanol mixture for the extraction and spectrophotometric determination of chlorophyll-a in phytoplankton. *Algological Studies/Archiv Für Hydrobiologie,* Supplement Volumes, 46(1987): 99–117

Siriwardana C, Cooray AT, Liyanage SS, Koliyabandara SMPA (2019) Seasonal and Spatial Variation of Dissolved Oxygen and Nutrients in Padaviya Reservoir, Sri Lanka. *Journal of Chemistry*, 2019: 1-11 e5405016 [https://doi.org/10.1155/2019/5405016]

Verschuren D (1994) Sensitivity of tropical-African aquatic invertebrates to short-term trends in lake level and salinity: A paleolimnological test at Lake Oloidien, Kenya. *Journal of Paleolimnology*, 10: 253–263 [https://doi.org/10.1007/BF00684035]

Verschuren D, Tibby J, Leavitt PR, Roberts CN (1999) The environmental history of a climate-sensitive lake in the former "White Highlands" of central Kenya. *Ambio*, 28(6): 494-501

Verschuren D, Tibby J, Sabbe K, Roberts N (2000) Effects of Depth, Salinity, and Substrate on the Invertebrate Community of a Fluctuating Tropical Lake. *Ecology*, 81(1): 164–182 [https://doi.org/10.1890/0012-9658(2000)081[0164:EODSAS]2.0.CO;2]

Zinabu G-M (2002) The effects of wet and dry seasons on concentrations of solutes and phytoplankton biomass in seven Ethiopian rift-valley lakes. *Limnologica*, 32(2): 169–179 [https://doi.org/10.1016/S0075-9511(02)80006-8]