



Spatial and temporal variations of trophic state conditions of Lake Bunyonyi, south-western Uganda

Alex Saturday^{1,2} · Thomas J. Lyimo^{1,2} · John Machiwa^{2,3} · Sijajali Pamba^{2,3}

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Abstract

The study was conducted to assess the spatial and temporal variations of the trophic state condition of Lake Bunyonyi between October 2019 and September 2020. Secchi depth (SD), total phosphorus (TP) and chlorophyll-*a* (Chl-*a*) concentration were measured to aid the quantification of trophic state condition of the lake using Carlson trophic state index (CTSI). The trophic state index (TSI) values based on SD, TP and Chl-*a* values were 60.82 ± 5.35 , 68.99 ± 11.04 and 61.74 ± 7.51 , respectively. March 2020 recorded the highest mean CSTI value (70.14 ± 4.04), while in September 2020, the lowest mean value (58.03 ± 6.22) was obtained. Based on CTSI values, the lake was eutrophic in both dry and wet seasons albeit with differences in the values. The eutrophic state of the lake is possibly attributed to nutrients inflow into the lake via runoff and drainage from farmlands. The negative value of TSI-Chl-*a*-TSI-TP deviation pointed out that the lake is not phosphorus limited, while the positive TSI-Chl-*a*-TSI-SD mean deviation value revealed the effect of Chl-*a* and TP on the lake's transparency. The study recommends the necessity to develop guidelines for the trophic status monitoring of Lake Bunyonyi since results suggest the deteriorating lake condition.

Keywords Water quality · Trophic state index · Secchi depth transparency · Lake Bunyonyi

Abbreviations

WHO	World Health Organization
APHA	American Public Health Association
USEPA	The United States Environment Protection Agency
SD	Secchi depth transparency
NWSC	National Water and Sewage Cooperation
TSI	Trophic state index
CSTI	Carlson trophic state index
Chl- <i>a</i>	Chlorophyll- <i>a</i>
TP	Total phosphorus
SD	Secchi depth
<i>H</i>	Kruskal–Wallis test
<i>U</i>	Mann–Whitney test

Introduction

Worldwide, lakes are an integral part of freshwater resources, perform ecological functions and provide a wide range of ecosystem services (Schallenberg et al. 2013). Nevertheless, freshwater lakes have suffered significant degradation due to anthropogenic activities carried out in the wake of societal transformation and economic growth (Saluja and Garg 2017). The deterioration of freshwater quality is a rapidly increasing problem that threatens the aquatic ecosystem structure and integrity especially in developing parts of the world, Uganda inclusive. Nutrient loading (nitrogen and phosphorus) resulting from human activities in lake catchment has been identified as a major causative agent in the widespread degradation of ecological structure and function of freshwater ecosystems. The trophic state condition of any aquatic ecosystem is reflective of the anthropogenic impact on water quality and its ecosystem health (Knoll et al. 2015). Therefore, an understanding of trophic state variations provides deep insight in identifying the appropriate remedial measures for aquatic ecosystem restoration. Also, sustainable management of degrading ecosystems requires insight into the spatio-temporal variations associated with their trophic status.

✉ Alex Saturday
salex@kab.ac.ug

¹ Department of Environmental Sciences, Kabale University, P.O. Box 317, Kabale, Uganda

² Department of Molecular Biology and Biotechnology, University of Dar es Salaam, P.O. Box 35064, Dar es Salaam, Tanzania

³ Department of Aquatic Sciences and Fisheries, University of Dar es Salaam, P.O. Box 35064, Dar es Salaam, Tanzania

Trophic state indices have been developed using parameters like phytoplankton biomass (Chl-*a*), total phosphorus (TP) and water transparency measured as Secchi depth (SD) (Carlson 1977). According to Knoll et al. (2015), trophic state indices classify freshwater lake ecosystems into different trophic states and have been proven useful in supporting decision making with regard to lake management. This approach has been widely used on lakes in the United States of America, Europe and Asia (Brugnoli et al. 2019; Nojavan et al. 2019; Saluja and Garg 2017; Siuda et al 2020). In contrast, it has not been widely adopted for use in assessing the trophic conditions of freshwater ecosystems in Africa, which are highly vulnerable to degradation from anthropogenic activities.

In Uganda, Lake Bunyonyi has in the recent few decades experienced human-induced changes which have resulted in lake perturbations, transforming its waters from a clear state to a turbid eutrophic state. The lake stressors such as siltation, agricultural runoff, wastewater from hotels and campsites and water demands for urban and rural consumption pose a significant threat to the sustainability of Lake Bunyonyi. The conflicting interests between conservation and exploitation of the lake, the rapid urbanizing lakeshores, population growth and climate change are among other factors responsible for the deterioration of Lake Bunyonyi. All above necessitate obtaining insight into the spatio-temporal variations of the trophic state conditions and establishing the possible causes of deviations in the trophic state of the Lake Bunyonyi ecosystem.

Materials and methods

Study area

Lake Bunyonyi is a freshwater lake situated in south-western Uganda (Fig. 1). The lake covers a total surface area of 56 km² and has a maximum depth of 40 m. In addition, the lake lies between latitude (1.2953° S) and longitude (29.9133° E) with an altitude of 1973 m above sea level (Kizza et al. 2017). The main water inputs into the lake are from Kagoma and Nyombe rivers. Other less significant water inflows into the lake are the small streams around the lake and through seepage. The lake outflow is a small stream from the northwest tip of the lake at a place commonly referred to as Heisssero in Ikamiro Sub-County. This stream drains into Ruhuma swamp valley and along Ruhezamyenda River to Mutanda and Mulehe lakes (Denny 1972).

Around Lake Bunyonyi, air temperatures range from 23.7 °C in March to 24.8 °C in August (Tibihika et al. 2016). The lake area receives bimodal rainfall with the long rainy season occurring between March and May, while short rains occur between September and November. While

June to August is the driest month, January and February are also with intermittent rains. The mean annual rainfall ranges from 800 to 1000 mm. Lake Bunyonyi catchment is a densely populated area with extensive subsistence farming where crops such as sweet potatoes, beans, sorghum, Irish potatoes and vegetables are grown. On a small scale, fishing and aquaculture are carried out in the lake water (Kizza et al. 2017). Thus, the livelihood activities of the people in the lake catchment largely depend on the health of the lake ecosystem.

Sample collection, preparation and storage

Water sampling was conducted between October 2019 and September 2020 from nine sampling stations (Table 2) marked and identified using a Global Positioning System (GARMIN etrex-12). Water samples for the determination of TP and Chl-*a* concentration levels were collected from sampling stations by dipping 1-L polyethylene plastic bottles. In total, 108 samples were collected for the determination of TP and Chl-*a* concentration levels in the water samples. All the samples were labelled according to their respective site and station codes (U1–U3, M1–M3 and L1–L3) for samples collected from stations located in the upper, middle and lower Bunyonyi sites, respectively. Before the actual collection of samples, the sampling bottles and buckets were labelled and rinsed with the lake water four times which removes any possible form of contamination. All the samples were stored in the icebox with an ice chest and then transported to NWSC Central Laboratories in Kampala for analysis within 24 h. While in the laboratory, samples were stored at 4 °C in the refrigerator waiting for analysis.

Analytical methods

Secchi depth (SD) was measured using a locally made Secchi disc (20-cm diameter and painted black and white alternately in a radial fashion). The disc attached to the calibrated chain was lowered into the lake at individual sampling sites until the observer loses sight of it. The disc was lowered a little further and then raised back and then the observer takes note of the depth at which it reappears. The SD was calculated as the average depth at disappearance and reappearance (Ballance and Bartram 2002; Nishijima 2017). All measurements were done in triplicate, and the average values are reported herein.

The HACH Method 8190 method was used to determine total phosphorus following APHA (2017) standards. In the process of persulfate digestion, the polyphosphates were converted to orthophosphate by sulfuric acid digestion, and the organic phosphorus was also be converted to orthophosphates. The resulting orthophosphate ion (PO₄³⁻) was analysed following the ascorbic acid procedure described in

APHA (2017). The spectrophotometric measurements were done at 880 nm. The TP concentration was obtained by directly reading from the UV spectrophotometric machine.

Chl-*a* concentration levels in water samples were determined using the acetone extraction method following APHA (2017) standard analysis procedures. For instance, 100 mL of water samples (aliquot) was filtered through 0.45- μ m pore size membrane filters. Before the filtration of the water sample, 1 ml of 1% MgCO₃ suspension was added to 0.45- μ m pore size membrane filters to prevent any possible acidification of extract and, thereby prevent the formation of pheophytin (Bhushan et al. 2018). After the filtration, chlorophyll filter papers were dried under suction for 2 min and carefully transferred to screw-cap test tubes, and 10 ml of 90% acetone was added. A Jenway 6405 UV/Visible spectrophotometer was used to determine Chl-*a* absorption by measuring the absorbance at 665 and 750 nm wavelengths. The Chl-*a* concentration was measured using the formula developed by Talling and Driver (1963) in Eq. (1).

$$\text{Chl-}a = \frac{13.9 * (E_{665} - E_{750}) * V_e}{V_f * Z} \quad (1)$$

where E_{665} and E_{750} are absorbances at 665 nm and 750 nm, respectively; V_e volume of the extract in mL; V_f volume of the sample filtered in litre; and Z Path length of the cuvette (1 cm).

Determination of trophic status

Across the world, scientists have developed indices for the classification of lakes and to show their trophic status. Of all, Carlson (1977) trophic state index has been selected and applied in this study to quantitatively assess the trophic status of Lake Bunyonyi. The trophic state index by Carlson (1977) is a popular and well-accepted indicator of eutrophication. It allows for the classification and ranking of the freshwater lakes based on the following equations which correlate SD, TP and phytoplankton biomass (Chl-*a*). This index classifies the lakes into four different groups: oligotrophic (> 30–40), mesotrophic (40–50), eutrophic (50–70) and hyper-eutrophic (> 70) based on doubling of Chl-*a* concentrations (Table 1). Likewise, the approach has also been

used as a quantitative measure of the degree for eutrophication, nutrient limiting status and deviations among the three indices as shown in Eqs. (2)–(5) (Carlson and Havens 2005).

$$\text{TSI}_{(\text{SD})} = 60 - 14.41\text{In}(\text{SD}) \quad (2)$$

$$\text{TSI}_{(\text{Chla})} = 9.81\text{In}(\text{Chla}) + 30.6 \quad (3)$$

$$\text{TSI}_{(\text{TP})} = 14.42\text{In}(\text{TP}) + 4.15 \quad (4)$$

$$\text{TSI} = \frac{\text{TSI}_{(\text{SD})} + \text{TSI}_{(\text{Chl-}a)} + \text{TSI}_{(\text{TP})}}{3} \quad (5)$$

where $\text{TSI}_{(\text{SD})}$ = Trophic state index referred to Secchi depth, SD = Secchi depth (m), $\text{TSI}_{(\text{TP})}$ = Trophic state index referred to total phosphorus, TP = total phosphorus (ug/L), $\text{TSI}_{(\text{Chla})}$ = Trophic state index referred to chlorophyll-*a*, Chl-*a* = chlorophyll-*a* (ug/L), In = natural logarithm and TSI-AVG = TSI averaged for all three parameters.

Carlson's two-dimensional approach was used to analyse TSI deviations within the lake ecosystem. When the TSI-Chl-*a*–TSI-TP deviation value is negative, it indicates lower phytoplankton growth than expected. Additionally, it highlights factors other than phosphorus that are limiting phytoplankton growth. Likewise, when the deviation value between TSI-Chl-*a* and TSI-SD is positive, it implies that suspended particles/sediments are the probable cause of light attenuation in the lake ecosystem.

Statistical analysis

The spatio-temporal variations within the dataset were analysed by the measure of descriptive statistics and Kruskal–Wallis test. Spearman's correlation analysis was used to evaluate whether the correlation values are significant. The Kruskal–Wallis test was used to determine differences between and within sampling stations at the confidence level of 95%. Mann–Whitney (U) test was used to determine whether there were significant differences in trophic state index values between the dry and rainy seasons. All the statistical analyses were performed in Statistica 10 software. The differences between stations addressed spatial

Table 1 Carlson's trophic state classification criteria

TSI	Classification	Description
> 30–40	Oligotrophic	Clearwater; DO is available year-round in the hypolimnion; deep lakes still exhibit classical oligotrophy, but some shallow lakes might become anoxic during the summer season
40–50	Mesotrophic	The water is moderately clear
50–70	Eutrophic	The dominance of algae and excessive macrophytes
> 70	Hyper-eutrophic	Presence of heavy algal blooms and dense macrophytic beds but extent limited by light penetration

variations, while differences among study months addressed temporal variations between parameters measured.

Results

Variability of the water quality parameters for TSI determination

The SD level ranged from 0.30 to 1.75 m with an overall mean value of 1.01 ± 0.35 m (Table 2). Statistically, the Kruskal–Wallis test revealed insignificant differences in the SD values between the study stations ($H(11, N = 108) = 11.61, p = 0.170$). TP concentration registered an overall mean value of 124.61 ± 14.50 $\mu\text{g/l}$ and its values ranged from 20 to 1200 $\mu\text{g/l}$ (Table 2). Statistically, no significant differences in the mean TP values between the different study stations were recorded ($H(8, N = 108) = 10.96, p = 0.204$). The overall mean Chl-*a* concentration of 30.44 ± 19.30 $\mu\text{g/l}$ was obtained between the

sampling stations (Table 2). Besides, the recorded mean Chl-*a* concentration values across sampling months were significantly different ($H(8, N = 108) = 22.54, p = 0.004$).

On a temporal basis, June 2020 recorded the highest mean SD value (1.32 ± 0.36 m), while in May 2020, the lowest value (0.64 ± 0.23 m) was obtained (Table 3). The Kruskal–Wallis test revealed significant differences in SD values between sampling months ($H(11, N = 108) = 52.32, p = 0.000$). The highest mean TP concentration value of 274.44 ± 351.29 $\mu\text{g/l}$ was obtained in March 2020, while in June 2020, the lowest value of 49.11 ± 6.79 $\mu\text{g/l}$ was obtained (Table 3). Statistically significant differences were recorded in the mean TP values among the sampling months ($H(8, N = 108) = 52.35, p = 0.000$). Likewise, the highest mean Chl-*a* concentration values were obtained in February, March and May 2020 (Table 3), and the Kruskal–Wallis test revealed that statistically significant differences were recorded ($H(8, N = 108) = 26.34, p = 0.006$).

Table 2 Mean \pm Std. Dev. of trophic state indicator variables at different sampling points ($n = 108$)

Station	SD (m)			TP ($\mu\text{g/l}$)			Chl- <i>a</i> ($\mu\text{g/l}$)		
	Means	Min	Max	Means	Min	Max	Means	Min	Max
Nyombe	0.84 ± 0.20	0.60	1.20	214.00 ± 16.8	44	480	45.17 ± 13.40	30	80
Ndarura	1.00 ± 0.27	0.60	1.56	87.92 ± 60.80	30	197	35.08 ± 24.90	10	70
Kariko	0.90 ± 0.27	0.50	1.30	79.83 ± 43.90	20	170	25.92 ± 19.80	4	70
Harutinda	1.00 ± 0.43	0.50	1.75	83.42 ± 47.50	30	170	36.83 ± 17.60	10	70
Akampene	1.07 ± 0.44	0.30	1.70	88.50 ± 69.20	30	280	24.33 ± 23.38	3	90
Mugyera	1.10 ± 0.38	0.40	1.65	105.58 ± 61.30	30	180	32.42 ± 18.20	4	60
Heissesero	1.24 ± 0.37	0.60	1.71	132.17 ± 95.70	40	350	18.50 ± 8.840	8	31
Rugarambiro	1.07 ± 0.37	0.40	1.50	135.33 ± 130.60	20	520	34.25 ± 19.67	10	71
Hamukaka	0.87 ± 0.24	0.50	1.20	194.75 ± 95.40	30	1200	21.42 ± 12.10	2	40
Overall	1.01 ± 0.36	0.30	1.75	124.61 ± 14.50	20	1200	30.44 ± 19.30	2	90

Table 3 Mean \pm Std. Dev. and range values of the trophic state indicators during the study period ($n = 108$)

Months	SD			TP ($\mu\text{g/l}$)			Chl- <i>a</i> ($\mu\text{g/l}$)		
	Means	Min	Max	Means	Min	Max	Means	Min	Max
Oct	0.87 ± 0.13	0.62	1.01	96.67 ± 103.20	20	280	27.78 ± 14.81	10	50
Nov	0.99 ± 0.26	0.50	1.35	110.00 ± 170.00	20	520	32.22 ± 22.24	10	70
Dec	1.08 ± 0.33	0.50	1.40	112.22 ± 46.04	50	170	35.11 ± 15.97	20	60
Jan	1.24 ± 0.30	0.80	1.70	174.44 ± 71.96	100	350	26.67 ± 11.18	10	40
Feb	0.78 ± 0.36	0.51	1.71	127.78 ± 29.06	100	170	42.22 ± 19.22	10	70
Mar	0.70 ± 0.14	0.51	0.90	274.44 ± 351.29	110	1200	44.44 ± 29.20	10	90
Apr	0.79 ± 0.16	0.45	0.99	82.22 ± 10.93	60	100	39.89 ± 17.26	11	70
May	0.64 ± 0.23	0.30	0.90	173.33 ± 115.50	90	470	30.11 ± 23.15	4	71
Jun	1.32 ± 0.36	0.80	1.75	49.11 ± 6.79	38	57	33.78 ± 14.94	25	70
Jul	1.17 ± 0.36	0.60	1.60	52.44 ± 16.88	40	84	22.56 ± 14.10	4	50
Aug	1.24 ± 0.23	0.85	1.60	149.22 ± 116.85	90	448	15.44 ± 11.92	2	40
Sept	1.27 ± 0.22	0.90	1.50	93.44 ± 145.46	30	480	15.00 ± 11.47	4	40
Overall	1.01 ± 0.35	0.30	1.75	124.61 ± 141.50	20	1200	30.44 ± 19.29	2	90

Spatial variability of the trophic state indices (TSI)

The mean TSI-SD values ranged from 57.59 ± 5.06 to 62.81 ± 3.44 obtained at Heissesero and Nyombe stations, respectively, with an overall mean value of 60.82 ± 5.35 (Table 4). Statistically, the Kruskal–Wallis test revealed insignificant differences in the mean TSI-SD values obtained between the stations ($H(11, N=108) = 11.62, p=0.168$). Likewise, the mean TSI-TP values ranged from 64.90 ± 9.28 to 76.87 ± 12.70 with an overall mean value of 68.99 ± 11.04 , which indicates the eutrophic state of Lake Bunyonyi (Table 4). Statistically, the Kruskal–Wallis test presented no significant differences in the mean TSI-TP between the stations ($H(11, N=108) = 10.94, p=0.205$). The overall mean TSI-Chl-*a* value of 61.74 ± 7.51 (Table 4) depicted the eutrophic state of Lake Bunyonyi. Statistically, the Kruskal–Wallis test presented significant differences in the mean TSI-Chl-*a* values between the stations ($H(11, N=108) = 22.585, p=0.004$).

Temporal variation of trophic state indices

The TSI-SD values ranged from 57.23 ± 3.57 to 67.51 ± 5.85 , reflecting a eutrophic state in the lake (Table 5). Statistically, the Kruskal–Wallis test revealed significant differences in TSI-SD values between the sampling months ($H(11, N=108) = 52.28, p=0.000$). Between sampling seasons (Table 6), the mean TSI-SD was high in the wet season than in the dry season with and significant differences in their mean values were recorded ($U = 888, p=0.001$).

For the case of TSI-TP, March 2020 recorded the highest mean value of 79.82 ± 10.89 , while in June 2020, the lowest value of 60.17 ± 2.08 was recorded (Table 5). Statistically, the Kruskal–Wallis test revealed significant differences in the mean TSI-TP values obtained between the sampling months ($H(11, N=108) = 52.354, p=0.000$). Although the recorded mean TSI-TP value was higher in the dry season than in the wet season (Table 6), no statistically significant differences were recorded ($U = 1330, p=0.588$).

Table 4 Mean \pm Std. Dev. of the trophic state indices at different stations ($n = 108$)

	TSI-SD			TSI-TP			TSI-Chl- <i>a</i>		
	Means	Min	Max	Means	Min	Max	Means	Min	Max
Nyombe	62.81 ± 3.44	57.37	68.36	76.87 ± 12.70	58.72	93.18	67.63 ± 2.67	63.97	73.59
Ndarura	60.48 ± 3.74	53.59	67.12	65.37 ± 10.37	53.20	80.33	62.99 ± 7.55	53.19	72.28
Kariko	62.15 ± 4.53	56.22	69.99	64.90 ± 9.28	47.35	78.21	59.16 ± 9.29	44.20	72.28
Harutinda	61.76 ± 6.51	51.94	71.51	65.51 ± 9.05	53.20	78.21	64.80 ± 5.32	53.19	72.28
Akampene	60.41 ± 7.06	52.35	77.35	65.74 ± 9.36	53.20	85.40	58.39 ± 8.92	41.38	74.74
Mugyera	59.60 ± 5.95	52.78	73.20	68.63 ± 9.70	53.20	79.03	62.62 ± 7.72	44.20	70.77
Heissesero	57.59 ± 5.06	52.27	68.61	71.49 ± 9.73	57.34	88.62	58.13 ± 4.91	51.00	64.29
Rugarambiro	59.95 ± 5.95	54.16	73.20	70.36 ± 11.99	47.35	94.33	63.53 ± 6.46	53.19	72.42
Hamukaka	62.64 ± 4.30	57.37	69.70	72.10 ± 13.55	53.20	106.39	58.46 ± 8.12	37.40	66.79
Overall	60.82 ± 5.35	51.94	77.35	68.99 ± 11.04	47.35	106.39	61.74 ± 7.51	37.40	74.74

Table 5 Mean \pm Std. Dev. and range values of the TSIs between sampling months ($n = 108$)

Months	TSI-SD			TSI-TP			TSI-Chl- <i>a</i>		
	Means	Min	Max	Means	Min	Max	Means	Min	Max
Oct	62.22 ± 2.34	59.86	66.89	62.72 ± 15.01	47.35	85.40	61.80 ± 5.83	53.19	68.98
Nov	60.66 ± 4.31	55.68	69.99	61.44 ± 16.14	47.35	94.33	62.48 ± 7.07	53.19	72.28
Dec	59.60 ± 5.38	55.15	69.99	70.93 ± 6.79	60.56	78.21	64.63 ± 4.36	59.99	70.77
Jan	57.23 ± 3.57	52.35	63.22	77.70 ± 5.12	70.56	88.62	61.76 ± 5.25	53.19	66.79
Feb	64.62 ± 5.14	52.27	69.70	73.76 ± 3.24	70.56	78.21	66.11 ± 5.72	53.19	72.28
Mar	65.33 ± 2.93	61.52	69.70	79.82 ± 10.89	71.93	106.39	65.26 ± 8.20	53.19	74.74
Apr	63.75 ± 3.46	60.14	71.51	67.61 ± 2.02	63.19	70.56	65.74 ± 5.17	54.12	72.28
May	67.51 ± 5.85	61.52	77.35	76.65 ± 6.97	69.04	92.87	60.52 ± 9.61	44.20	72.42
Jun	56.56 ± 4.20	51.94	63.22	60.17 ± 2.08	56.60	62.45	64.51 ± 3.42	62.18	72.28
Jul	58.44 ± 5.07	53.23	67.36	60.69 ± 4.07	57.34	68.04	59.06 ± 7.44	44.20	68.98
Aug	57.19 ± 2.82	53.23	62.34	73.97 ± 7.65	69.04	92.18	54.16 ± 9.50	37.40	66.79
Sept	56.74 ± 2.59	54.16	61.52	62.46 ± 12.06	53.20	93.18	54.90 ± 7.00	44.20	66.79
Overall	60.82 ± 5.35	51.94	77.35	68.99 ± 11.04	47.35	106.39	61.74 ± 7.51	37.40	74.74

Table 6 Mean ± Std. Dev. and range of the TSI values between seasons ($n = 108$)

	Wet season			Dry season		
	Means	Min	Max	Means	Min	Max
TSI-SD	62.26 ± 5.13	54.16	77.35	58.81 ± 5.05	51.94	69.70
TSI-TP	68.80 ± 12.49	47.35	106.39	69.26 ± 8.74	56.60	92.18
TSI-Chl- <i>a</i>	62.19 ± 7.48	44.20	74.74	61.12 ± 7.61	37.40	72.28

Table 7 Mean ± Std. Dev. and range of the CTSI across study sites

Station Code	Means	Min	Max	Remark
Nyombe	69.10 ± 4.91	61.11	76.27	Eutrophic state
Ndarura	62.94 ± 5.29	54.71	70.63	Eutrophic state
Kariko	62.07 ± 5.14	52.33	69.40	Eutrophic state
Harutinda	64.02 ± 4.25	57.50	70.31	Eutrophic state
Akampene	61.51 ± 6.44	54.18	74.45	Eutrophic state
Mugyera	63.61 ± 6.19	52.09	73.72	Eutrophic state
Heissesero	62.40 ± 4.40	57.00	69.99	Eutrophic state
Rugarambiro	64.61 ± 5.68	55.46	73.50	Eutrophic state
Hamukaka	64.40 ± 6.26	55.01	76.43	Eutrophic state
Overall mean	63.85 ± 5.65	52.09	76.43	Eutrophic state

Likewise, TSI-Chl-*a* mean values ranged from 54.16 ± 9.50 to 66.11 ± 5.72 obtained in August and February 2020, respectively, with an overall mean value of 61.74 ± 7.51 (Table 5). Statistically, the Kruskal–Wallis test revealed significant differences between the mean TSI-Chl-*a* values obtained during the study period ($H(11, N = 108) = 26.208, p = 0.006$). Between seasons (Table 6), the mean TSI-Chl-*a* value was high in the wet season (62.19 ± 7.48) than in the dry season (61.12 ± 7.61). The Mann–Whitney test revealed no statistical seasonal differences in the mean TSI-Chl-*a* values obtained during the study ($U = 1301, p = 0.468$).

Carlson’s trophic state index (CTSI) for Lake Bunyonyi

The mean CTSI values ranged from 61.51 ± 6.44 to 69.10 ± 4.91 obtained from Akampene and Nyombe stations, respectively, with an overall value of 63.85 ± 5.65 (Table 7). On a temporal basis, March 2020 recorded the highest mean CTSI value of 70.14 ± 4.04 , while in September 2020, the lowest value of 58.03 ± 6.22 was recorded (Table 8). Statistically, the Kruskal–Wallis test presented no significant differences in the mean CTSI values among stations ($H(8, N = 108) = 13.864, p = 0.085$). Based on the Carlson (1977) criteria for trophic state index characterization, the recorded overall value (63.85 ± 5.65) places Lake Bunyonyi into ‘the eutrophic state category’. In this category, the lake is rich in algae, nutrients and excessive macrophytes (Table 1).

Table 8 Mean ± Std. Dev. and range of the CTSI values between sampling months

Months	Mean	Min	Max	Remark
Oct	62.25 ± 5.84	56.02	72.81	Eutrophic state
Nov	61.53 ± 5.12	54.71	70.87	Eutrophic state
Dec	65.06 ± 3.22	58.57	68.56	Eutrophic state
Jan	65.56 ± 4.03	58.70	69.99	Eutrophic state
Feb	68.16 ± 3.16	60.93	71.52	Eutrophic state
Mar	70.14 ± 4.04	63.20	76.43	Hyper-eutrophic state
Apr	65.70 ± 2.32	62.00	69.25	Eutrophic state
May	68.23 ± 5.82	59.32	76.27	Eutrophic state
Jun	60.41 ± 2.16	57.50	65.16	Eutrophic state
Jul	59.40 ± 3.94	52.09	64.28	Eutrophic state
Aug	61.77 ± 5.75	55.01	73.77	Eutrophic state
Sept	58.03 ± 6.22	52.33	73.83	Eutrophic state
Overall mean	63.85 ± 5.65	52.09	76.43	Eutrophic state

Deviations between trophic state indices

The TSI-Chl-*a*–TSI-SD deviation denotes the influence of Chl-*a* concentration on the turbidity of the lake system, while TSI-Chl-*a*–TSI-TP deviation denotes the level of phosphorus limitation (Carlson and Havens 2005). Table 9 summarizes the deviations between TSI-Chl-*a*–TSI-SD and TSI-Chl-*a*–TSI-TP derived from Chl-*a*, SD and TP data. The statistical analysis revealed TSI deviation values that are both negative and positive. The mean value for TSI-Chl-*a*–TSI-SD deviation ranged from -20.0 to 14 with the overall mean value of 0.92 ± 7.17 (Table 9). In June 2020, the highest mean TSI-Chl-*a*–TSI-SD deviation value (7.95 ± 3.98) was obtained, while in May 2020, the lowest mean value (-6.99 ± 6.88) was obtained. Between seasons (Table 10), the wet season obtained a negative TSI-Chl-*a*–TSI-SD deviation value (-0.07 ± 7.54), while the dry season recorded a positive deviation value (2.31 ± 6.43). These results imply that during the wet season, the algae in the water column are responsible for light attenuation. In the dry season, something also other than algae, such as a suspended sediment particle in the water column or non-algal seston, is responsible for the light attenuation.

For the TSI-Chl-*a*–TSI-TP deviation (Table 9), values varied from -53.20 to 19.08 with an overall mean value of -7.25 ± 12.56 . In June, the highest mean deviation value

Table 9 Mean, standard deviation and range of the TSI deviations ($n=108$)

Months	TSI-Chl- <i>a</i> -TSI-SD			TSI-Chl- <i>a</i> -TSI-TP		
	Means	Min	Max	Means	Min	Max
Oct	-0.42 ± 4.68	-8.49	5.40	-0.92 ± 16.34	-32.22	16.62
Nov	1.82 ± 7.34	-6.02	12.28	1.05 ± 18.78	-41.14	19.08
Dec	5.03 ± 7.60	-7.37	13.98	-6.30 ± 6.84	-18.22	3.40
Jan	4.52 ± 3.12	-0.40	9.02	-15.95 ± 4.25	-24.66	-11.42
Feb	1.50 ± 4.66	-3.40	9.06	-7.65 ± 7.15	-24.15	1.72
Mar	-0.07 ± 9.22	-16.51	11.53	-14.56 ± 5.61	-53.20	-1.17
Apr	1.99 ± 6.27	-10.41	9.06	-1.87 ± 5.22	-13.22	4.94
May	-6.99 ± 6.88	-19.02	1.22	-16.13 ± 9.60	-26.36	-2.47
Jun	7.95 ± 3.98	2.56	13.30	4.34 ± 4.69	0.11	12.31
Jul	0.62 ± 5.37	-9.49	8.07	-1.63 ± 8.59	-14.19	10.26
Aug	-3.03 ± 8.60	-19.97	4.45	-19.81 ± 8.23	-32.87	-10.13
Sept	-1.85 ± 6.32	-13.17	5.83	-7.56 ± 9.69	-26.39	8.98
Overall	0.92 ± 7.17	-19.97	13.98	-7.25 ± 12.56	-53.20	19.08

Table 10 Mean, standard deviation and range of the TSI deviations between seasons

Season	TSI-Chl- <i>a</i> -TSI-SD			TSI-Chl- <i>a</i> -TSI-TP		
	Means	Min	Max	Means	Min	Max
Wet	-0.07 ± 7.54	-19.02	13.98	-6.61 ± 13.56	-53.20	19.08
Dry	2.31 ± 6.43	-19.97	13.30	-8.14 ± 11.10	-32.87	12.31

(4.34 ± 4.69) was obtained, while August 2020 recorded the lowest mean deviation value of -19.81 ± 8.23 . Both seasons (Table 10) recorded negative TSI-Chl-*a*-TSI-TP deviation values though lower in the wet season (-6.61 ± 13.56) than in the dry season (-8.14 ± 11.10). These results indicate that algal productivity in the lake was generally limited by non-algal turbidity rather than total phosphorus.

Discussion

Variability of the water quality parameters for TSI determination

Relatively Chl-*a* concentration is observed in the wet season perhaps due to high nutrient input from rain and agricultural runoff to the lake system. Similar studies (e.g. Harper et al. 2011; Ndungu et al. 2013; Stoof-Leichsenring et al. 2011) attributed increased Chl-*a* concentration in lake systems to runoff and farm discharge into the lake system. The temporal variations in Chl-*a* concentration depicted seasonal and environmental influences. For instance, February and March in Lake Bunyonyi sub-catchment are usually the planting season and are when farmers extensively use manure and fertilizers. In the first heavy rainfall events, there are high agricultural runoffs which increase nutrient concentration in the lake evidenced by increased Chl-*a* concentration.

Concerning SD, the observed temporal variability is possibly attributed to the seasonal variations. For instance, Lake Bunyonyi experiences high runoff inflow from the catchment has increased as a result of high discharge experience in the rain season. Similar to study results, Sitoki et al. (2010), Tran et al. (2019), reported the SD range value of 0.8–1.7 m (Lake Kyoga) and 0.17–2.3 m (Edward), respectively. On the other hand, Stoyneva-Gärtner et al. (2020), Vundo et al. (2019) and Ozguven and Demir Yetis (2020) reported an SD range significantly higher than the recorded values in the present study. The observed spatial variations in TP concentrations are attributed to proximity to agricultural farmlands that form the major sources of nutrients in the lake. Besides, seasonal changes in rainfall amounts influence the nutrient deposition intensity of the lake system. Similar to the results of the current study, Opiyo et al. (2019) reported high TP values (3.09 ± 0.09 mg/L) in the wet season than in the dry season.

Trophic state index (TSI) for Lake Bunyonyi

Based on TSI-Chl-*a* and TSI-TP, the mean trophic state of Lake Bunyonyi was eutrophic. Higher TSI values were higher in the wet season than in the dry season. This is possibly due to runoff from farmland, drainage from hotels and campsites and direct nutrient deposition via rain and soil erosion debris. These findings indicate the high biological productivity of the lake, which means microscopic plants

fuel all other parts of the ecosystem. High nutrient concentrations fuel algae growth which when out of control forms harmful algal blooms that can be extremely toxic and harmful to fish and even people. The presented study findings are supported by Kitaka et al. (2002) who associated high TSI-TP at Malewa River to surface and runoff from the sub-catchment dominated with farm crop and animal rearing. Similar to the present study findings, Ndungu et al. (2013) obtained a TSI-TP range of 50–70 albeit the TSI-Chl-*a* range value (70–80) differed significantly from the present results.

Based on mean TSI-SD, Lake Bunyonyi was to be eutrophic possibly due to variations in study station depths and seasonal changes. For instance, shallower stations recorded lower SD values which translated to higher TSI values than deeper stations. The possible explanation is that shallow stations experience much perturbation of their bottom settled sediments which are then suspended in the water column. However, this is most unlikely to happen at the deeper stations whose sediments are far away from the action of wind and other surface disturbances. High temporal variability in TSI-SD is possibly attributed to seasonal changes such as heavy rainfall events and strong wind regimes. During heavy rainfall events, rivers /streams that flow into the lake are characterized by huge quantities of suspended particles which when deposited in the lake decrease its transparency. According to Saluja and Garg (2017), SD levels in a lake system is not only affected by the autochthonous lake inputs, but also very much by allochthonous flows and inputs. Similar to the present study findings, Ganguly et al. (2015) reported an overall TSI-SD range of 57.01–78.7 irrespective of the seasons which is closely related to the results of the current study.

The overall mean CSTI value (63.9 ± 5.7) definitively classified Lake Bunyonyi as eutrophic. This implies that lake experiences a high level of biological productivity. The observed consistent eutrophic state could diminish DO concentration and hamper the ecosystem functionality of Lake Bunyonyi. Similar to our study results, Ozguven and Demir Yetis (2020) and Tibebe et al. (2019) found Lake Tana and Big Soda Lake Van in the eutrophic state with CSTI values of 69.8 and 58.3, respectively. Besides, the recorded CSTI range (52.1–76.4) for Lake Bunyonyi concurred with that of the ten lakes (59.2–75.8) studied by Viet et al. (2016) in the urban Hanoi of Vietnam. On the other hand, the eutrophic state in Lake Bunyonyi is somewhat lower than the values reported by Thuan et al. (2021) at Cu Chinh Lake.

Initially, Carlson's intention with the TSIs was to create equations that would produce the same TSI for a particular lake regardless of whether chlorophyll, phosphorus or Secchi depths were used to generate the index (Matthews et al., 2002). The deviation of TSI-SD and TSI-TP from TSI-Chl-*a* are used to describe abiotic and biotic relationships, gain insight into lake trophic structure, and infer more

information about the lake (Carlson and Havens 2005; Matthews et al. 2002). In the ideal situation, subtracting TSI-Chl-*a* from any other TSI should equal zero or nearly so (Carlson 1991). However, in reality, they differ because of the differences in the characteristics of the water system. Therefore, there are predictable deviations between the TSIs that can be used to assess the degree and type of nutrient limitation. Phosphorus limitation occurs when $TSI-Chl-a - TSI-TP > 0$. The non-algal turbidity becomes a restraining factor when $TSI-Chl-a < TSI-SD$ and $TSI-Chl-a < TSI-TP$ (Carlson and Havens 2005; Carlson and Simpson 1996; Matthews et al. 2002; Ndungu et al. 2013).

The overall mean TSI-Chl-*a*–TSI-TP deviation (> 0) infers that TP is generally not the limiting factor to the lake's biological productivity. Other factors such as ambient temperature and non-algal turbidity are the limiting factors for the biological productivity of Lake Bunyonyi. On the other hand, the mean TSI-Chl-*a*–TSI-TP deviation values for November and June depicted phosphorous as a limiting factor for algae productivity. Likewise, the negative mean TSI-Chl-*a*–TSI-SD deviation values obtained in October, March, May, August and September indicate high-level light attenuation which translated to higher TSI-SD values greater than TSI-Chl-*a* values. The positive TSI-Chl-*a*–TSI-SD deviation values denote the prevalence of high algae concentration in the lake column which is responsible for light attenuation (Edmondson 1980; Saluja and Garg 2017). The presence of suspended sediments in the water column may lead to a situation where the TSI-SD over-predicts the TSI-Chl-*a* (Carlson and Havens 2005). The TSI variations in the present study concur with the findings obtained by Markad et al. (2019) and Xu et al. (2010). On the other hand, the deviations reported by Shen et al. (2015) revealed phosphorus as the limiting factor for algal biomass since the anthropogenic phosphorus inputs were far below the actual availability for algae growth. The correlation analysis between the generated trophic state indices showed a significant positive correlation between TSI-TP and TSI-Chl-*a*, which confirms that TP content in lake water favours algal growth in the lake understudy. Likewise, TSI-SD was significantly positively correlated with TSI-Chl-*a* which confirms that Chl-*a* concentration influences the lake's light attenuation.

Conclusion

The present study evaluated the spatial and temporal variations in the trophic state conditions of Lake Bunyonyi based on Secchi depth, TP and Chl-*a* concentration for a period of one year (October 2019–September 2020). The TSI-Chl-*a* and TSI-TP were found to be consistently higher above 60 across stations, and sampling months signifying that Lake Bunyonyi are eutrophic. Consistent prevalence of eutrophic

conditions may provide the impetus for reduction of oxygen levels and, thus, hampering the ecosystem functioning. Since the TSI-Chl-*a*–TSI-TP deviation yielded an overall negative, TP in Lake Bunyonyi is not a factor limiting phytoplankton growth. Besides, the positive TSI-Chl-*a*–TSI-SD deviation revealed the effect of non-algal turbidity on the biological productivity of the lake. For sustainable management of Lake Bunyonyi, it is recommended to develop plans and take cognizance of the drainage watershed model. This would help in the management of anthropogenic phosphorus before entry into the lake ecosystem.

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