Water Practice & Technology

 Water Practice & Technology Vol 18 No 8, 1970 doi: 10.2166/wpt.2023.116

Abating eutrophication on urban lakes: a case study of Kabaka's Lake, Uganda

Anne Nakagiri *, Abel Mutyaba, Charles Onyutha and Kenan Okurut
Department of Civil and Environmental Engineering, Faculty of Engineering, Kyambogo University, P.O. Box 1, Kyambogo – P. O. BOX 7181, Kampala, Uganda
*Corresponding author. E-mail: anakagiri@gmail.com

AN, 0000-0002-1969-698X

ABSTRACT

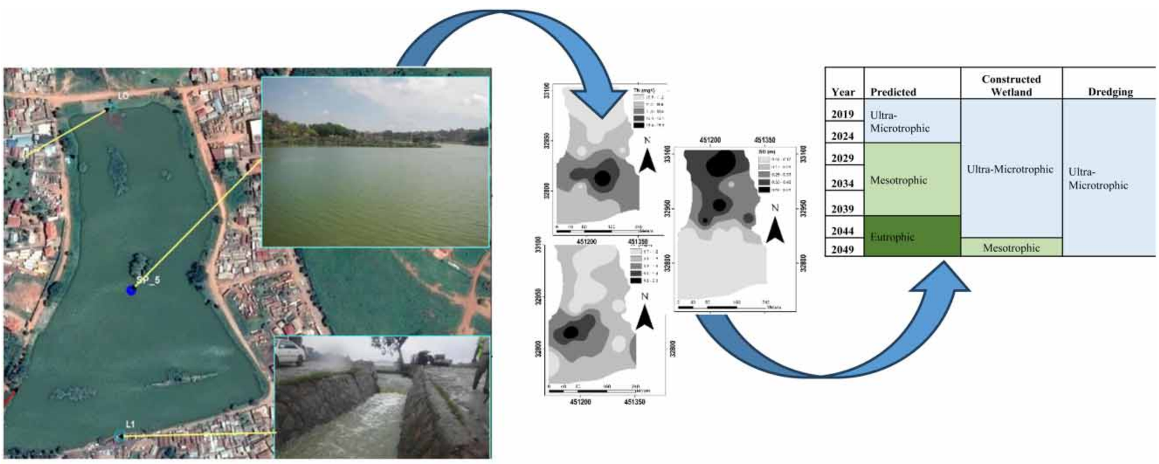
Eutrophication of water bodies is a challenge in many urban areas. This study measured and modelled quantitatively the pollutant nutrient load of an urban lake (80,596 m^2), and assessed both external (constructed wetland) and internal (dredging) eutrophication extenuation measures. For the past 25 years, there has been redistribution ($p < 0.005$) of the lake's catchment land use, with built-up area increasing by 78.5%, and a reduction in vegetated (37.2%) and water surface (1.8%) areas. A 92.2% reduction in the lakes receiving wetland footprint ($p = 0.000003$) was noted, with increased nutrient load. The lake's light attenuation was found to be dominated by algae, limited by nitrogen and classified under the oligotrophic class (Trophic State Index < 40), with a threat of eutrophication in an estimated 25 years. Scenario analyses show that the construction of a wetland in the remaining 0.54 hectares of natural wetland will reduce total phosphorus by 35% and total nitrate by 45% ($p = 0.05$), whereas dredging the lake could reduce them by 80% each ($p = 0.0005$). Watershed management is the only sustainable solution to control nutrient flow into the lake and enable self-cleansing, factoring in the design of the receiving wetland and groundwater sources.

Key words: dredging, eutrophication, lake watershed, land use, water quality, wetland

HIGHLIGHTS

- Quantitative measurement and modelling pollutant nutrient load of an urban lake.
- Redistribution of lake catchment area lid to reduced lake footprint and increased nutrient load.
- Lake's light attenuation is dominated by algae and limited by nitrogen.
- Lake classified under the oligotrophic class of lakes (Trophic State Index < 40)
- Dredging significantly increases lake storage capacity and allows for thermal self-purification.

GRAPHICAL ABSTRACT



INTRODUCTION

Urbanisation land use changes in cities around the world have reduced the natural pollutant filtration value of the wetlands in their catchments. This has led to the gradual eutrophication of available water bodies (Costa *et al.* 2018). Eutrophication, an indicator of high nutrient concentrations, and development of algal biomass, leads to water quality decline through discolouration, foul smells and tastes, diurnal pH changes, temperature changes, depletion of dissolved oxygen (DO) and degraded aesthetic values (Leng 2009). The effects of eutrophication are often realised while treating water for drinking, and through its negative impact on recreation and health. For instance, there is a link between eutrophication and the formation of trihalomethanes and other chlorinated organics in drinking water. Eutrophication has been associated with parasitic diseases of amphibians and carcinogens in humans (Paerl & Otten 2013). Cyanobacteria, the most important phytoplankton associated with harmful algae bloom, are known to be poisonous to animals and humans, and responsible for compounds like methylisoborneol and geosmin that cause off-flavours in municipal water systems, as well as in aquaculture-raised fish (Watson *et al.* 2016; Chorus & Welker 2021).

The challenges associated with eutrophication are mostly felt in developing countries, especially those in the tropics, where steady solar input and high temperatures sustain algal blooms throughout the year (Wells *et al.* 2015). There is an urgent need to use previously developed mitigation options, strategies, techniques and measures, to enable accurate assessment and effective long-term control of lake eutrophication. Extensive field research and process-based modelling of individual catchments, have improved understanding of the source and transport of nutrients from land to water, around the world. For example, the effects of factors that relate land use to water body quality have been quantified (Soranno *et al.* 2015). Statistical models have been used to: predict water quality conditions resulting from potential changes in lake operations and/or environmental conditions, conduct scenarios with respect to forecasting nutrient loads under different catchment management strategies, simulate thermal stratification and evaluate the trophic status in reservoirs (Dwarakish & Ganasri 2015) This has provided useful information for developing abatement management strategies for priority water quality management (McCutcheon 1990; Zyfi *et al.* 2014). The HELCOM Baltic Sea Action Plan (BSAP), used to combat eutrophication in a marine environment, relies on the integrated ecosystem approach to achieve good environmental status and sustainability, by setting eutrophication indicator targets (Jetoo 2018). Studies on eutrophication abatement external measures – advanced wastewater treatment, wastewater or runoff diversion, constructed wetlands, laws and regulations, and buffer strips – and internal measures such as chemical control, biomanipulation, dredging, plant harvesting, etc, are limited in developing countries. In this study, quantitative methods and multi-criteria assessment were applied (Kasim 2015) to evaluate strategies for sustainable management of eutrophication effects on water quality in Kabaka's Lake, Uganda, a typical urban lake catchment.

METHODS

Study area (Kabaka's Lake catchment)

Kabaka's Lake's catchment is in Lubaga Division, in the Western part of Kampala, Uganda's capital (Figure 1). It covers approximately 1.69 km^2, located at 0°17′51.16322″N, 32°33′41.78801″E. Currently, the largest man-made lake in Africa, Kabaka's Lake is home to hundreds of water animals, birds, and plants; and is an important historical feature of Buganda Kingdom, making it a prime tourism centre in Uganda. Rapid population growth and zone urbanisation characterised by poverty in most of Kampala, have caused the Lake's catchment – e.g., various wetlands that also form part of Lake Victoria's catchment to be reclaimed for different land uses over the years. Residential and economic developments include multi-residential buildings, small housing units, hotels, churches, schools, shopping centres, washing bays, parking yards, and numerous unpaved and paved roads (Kiggundu *et al.* 2018). Increased development in Kampala has also resulted in an increase in the wastes generated, while their collection, for treatment and/or disposal, remains inadequate (Richmond *et al.* 2018). Sewerage coverage in Kampala is very low at about 9%, and non-existent in Lubaga Division, implying that most establishments rely on on-site sanitation with inadequate faecal sludge management practices. Thus, most bathroom, latrine and septic tank waste is released into nearby drains and ultimately discharged into Kabaka's Lake, which is in a low-lying area and acts as a runoff sink.

The removal of the lake's watershed has left the lake in need of the former wetland's primary ecosystem service, including; naturally cleansing received human waste, processing nutrients in the water, and releasing 'filtered' wastewater downstream – i.e., from which the bacteria and sediments have largely been removed. Loss of the

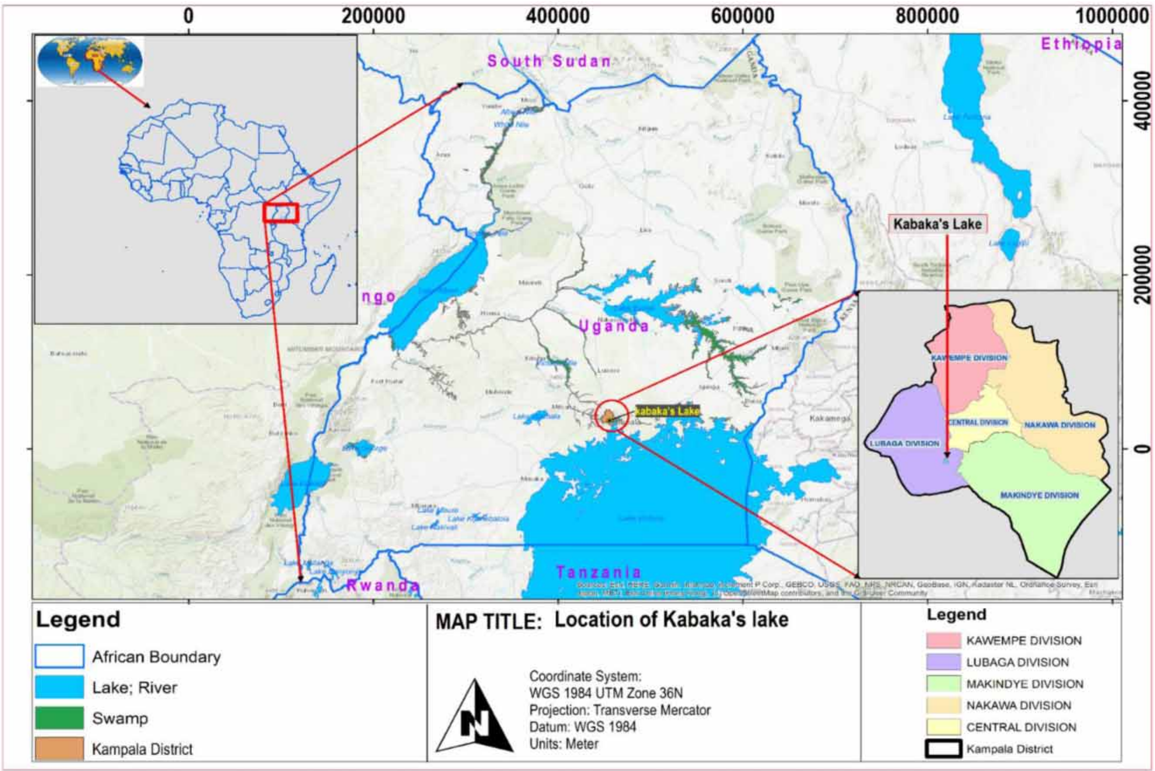


Figure 1 | Study area location.

wetlands has impacted recent disease outbreaks, including malaria and diarrhoea, in the area, degradation of the living environment, and damage to the lake's ecosystems. As a consequence, eutrophication abatement strategies are needed to address the lake's deteriorating water quality, due to the increasing change in land activities within its catchment/watershed.

Data collection and analysis

Catchment land use classification

Assessing the eutrophication abatement strategies for Kabaka's Lake necessitated the classification of the catchment's land use activities. The Multispectral Landsat satellite images for 1995, 2003 and 2019, produced by USGS in GeoTIFF format were downloaded from https://earthexplorer.usgs.gov on 1 May 2019. Using the Landsat natural and standard false colour [band 5 (SWIR 1), band 4 (NIR), band 3 (red), band 2 (green), and band 1 (blue)], composite images were generated to achieve a general description of LU/LC changes. GIS was applied to process the data, extract clipped Landsat scenes from the delineated catchment extent, and produce change detection maps. Areas showing the various defined land-covers were digitised from the aerial photographs and topographic maps.

Nutrient loading quantification

To assess the lake's nutrient load, data from the Kabaka's Lake report (AWE 2017) were used while samples were collected at various depths, in shaded areas, from 7 points in the lake, in February and March 2019, using a Vendome 78-300 Fieldmaster. Measurements of pH and DO were taken immediately after sampling, using portable water quality metres (Hanna HI991003, USA and Milwaukee MW600, USA). The samples were then transported in a cool box to Makerere University Public Health and Environmental Engineering Laboratory for analysis. Total nitrogen and total phosphate were determined using the cadmium reduction and ascorbic acid method, after digestion with persulphate (APHA 2012), and final readings were made with a HACH DR/4000 spectrophotometer (USA). Chlorophyll-a was determined using the fluorometric method at the National Water and Sewerage Corporation laboratory.

Assessing eutrophication abatement management strategies

Two abatement management strategies were assessed, constructed wetlands and dredging. Their selection was guided by an integrated ecosystem approach aimed at achieving good environmental status and sustainability (Jetoo 2018). First, a number of options proposed by (Kasim 2015) were evaluated (Table 1), and control technique longevity was noted as the most important criterion for eutrophication management. The increase in lake sedimentation, benchmarked on the 2017 bathymetric study, and the degraded wetland upstream of the lake's inlet and its attribute of reducing the lake inlet nutrient concentrations effectively, supported the ranking decision. On that basis, wetland construction (as an external measure) and dredging (internal control measure) were ranked best for this study.

Table 1 | Ranked eutrophication management strategies

Best management strategies applicable to this study (Kasim 2015)			Selected management options for this study
Option ID	**Identified option**	**Scenario ranking**	**Option ID**
External measures			
A4	Constructed wetlands	1	OP-1
A5	Laws and regulations	2	
A1	Advanced wastewater treatment (AWT)	3	
A2	Wastewater or runoff water diversion	4	
Internal measures			
A12	Dredging/sediment removal	1	OP-2
A7	Chemical control	2	
A14	Biomanipulation	3	
A8	Plant harvesting	4	

Google Earth historical satellite imagery of the lake's receiving wetland footprint for the period 2002–2019 was used to delineate the receiving wetland footprint. Nutrient reduction efficiency ranges of 40–60% for TN and 30–40%) for TP were adopted, based on a number of studies (Mthembu *et al.* 2013; Ilyas & Masih 2017). The ranges were benchmarked from studies of constructed wetlands in Italy and Uganda (Okurut 2000; Foladori *et al.* 2013).

The lake's volume and depth were established to enable determination of the amount of dredging required. The lake's total area was sub-divided into 30 × 30 m grids using Arcmap. A handheld depth finder (H22FX Handheld Sonar System with LED Flashlight) was used to take water depth readings at various points along the grid lines, from which data were input to GIS software for bathymetric modelling.

Data analysis and presentation

The data were analysed using descriptive statistics. A mass balance approach was adopted using the Vollenweider model and Haggard's linear regression equation (Equations (1) and (2)). The lake's absorbed phosphorus concentrations were estimated from its surface phosphorus concentrations (Abu-Hmeidan *et al.* 2018). A standardised residual normal Q–Q plot was done for each water quality parameter of the training dataset to assess the normality distribution of the residuals for the two variables (dependent and independent). A comparison of the observed versus the predicted values of raw water quality was plotted and the line of best fit was determined. The Pearson correlation coefficient (R^2) was then used to understand how well the predicted values were related to the observed raw water quality values.

$$P_{lake} = \frac{P_{in}}{1 + \sqrt{tw}} \quad (1)$$

$$P_{sed} = 0.213 \times P_{lake} - 0.007 \quad (2)$$

The Trophic State Index (TSI) index – range: 0–100 – was used to assign a trophic state 'grade' to the lake (Table 2, Equations (3)–(8)). on the assumption that the current lake status is nitrogen limited, the relationship between total phosphorus and chlorophyll was established using Equations (9) and (10) for prediction modelling.

Table 2 | TSI equations

Secchi disk	$\text{Ln(SD)} = 2.04–0.68\text{Ln(CHL)}$	(3)
	$\text{TSI(SD)} = 60 - 14.41\text{Ln(SD)}$	(4)
Chlorophyll-a	$\text{TSI(CHL)} = 9.81\text{Ln(CHL)} + 30.6$	(5)
TP	$\text{TSI(TP)} = 14.42\text{Ln(TP)} + 4.15$	(6)
TN	$\text{TSI(TN)} = 10*[5.96 + 2.15\text{Ln(TN} + 0.001)]$	(7)
Nitrogen limited lakes (TN/TP) < 10)	$\text{TSI} = [\text{TSI(CHL)} + \text{TSI(TN)}]/2$	(8)

A multiple linear regression (MLR) model (Equations (11) and (12)) was run to forecast the TSI of the lake for the next 30 years and determine the significance of the management strategies in eutrophication abatement, and validated through smoothing and de-seasonalising at 0.0001 tolerance (Carlson 1977). The model was used to predict the lake's TP and TN loads, and TSI for a 5-year range period (5, 10, 15, 20, 25, and 30 years), and an average end method (Equation (13)) was used to estimate the likely dredge volume.

$$\text{Ln Chl} = 1.449 \text{ Ln TP} - 2.616 \quad (9)$$

$$\text{Ln SD} = 3.876 - 0.98 \text{ Ln TP} \quad (10)$$

$$\text{TE} = 11.485 + 0.029 \times t \quad (11)$$

$$\text{TP} = 1.574 - 0.034 \times t \quad (12)$$

$$V = \sum L \frac{A_1 + A_2}{2} \quad (13)$$

where V (m^3) is the volume; A_1 and A_2 (m) is the area between two sections of the lake; and $L(m)$ is the perpendicular distance between the two sections.

RESULTS AND DISCUSSION

The lake's catchment has three main land use classes; built-up (buildings and impervious surfaces), vegetated (agriculture, forestry, large green compounds, and wetlands and the lake's riparian area), and water (waterways and the lake) that have been redistributed ($p < 0.005$) significantly since about 2000 (Figure 2). The built-up area increased by 78.5%, the vegetated area reduced by 37.2% and the extent of water reduced by 1.8% (Figure 2(a)). This has led to a substantial decrease in receiving wetland footprint ($p < 0.00001$) (Figures 2(b) and 3), which translated into a gradual loss of nutrient reduction efficiency (Watson *et al.* 2016; Kiggundu *et al.* 2018). The

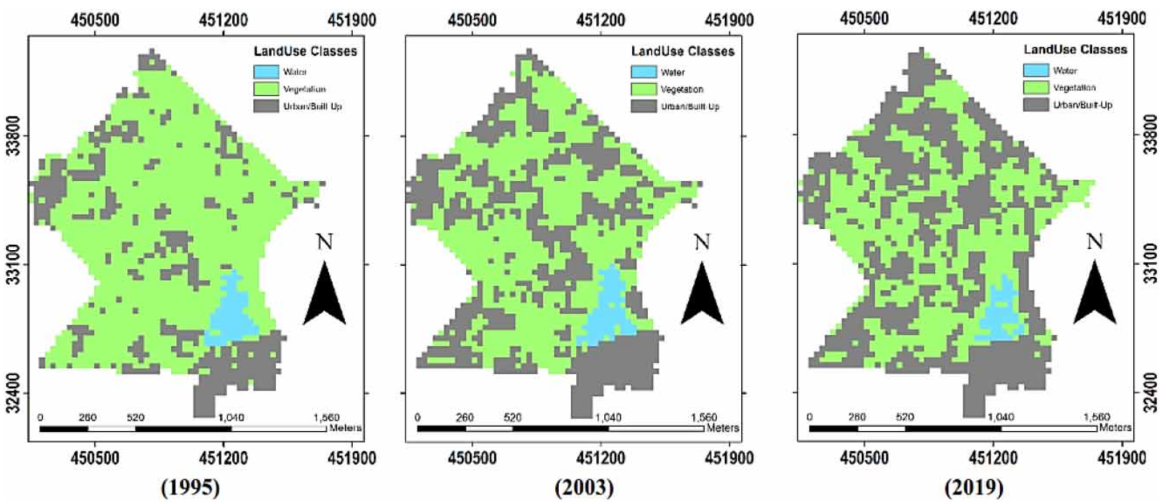


Figure 2 | Lake catchment land use delineation.

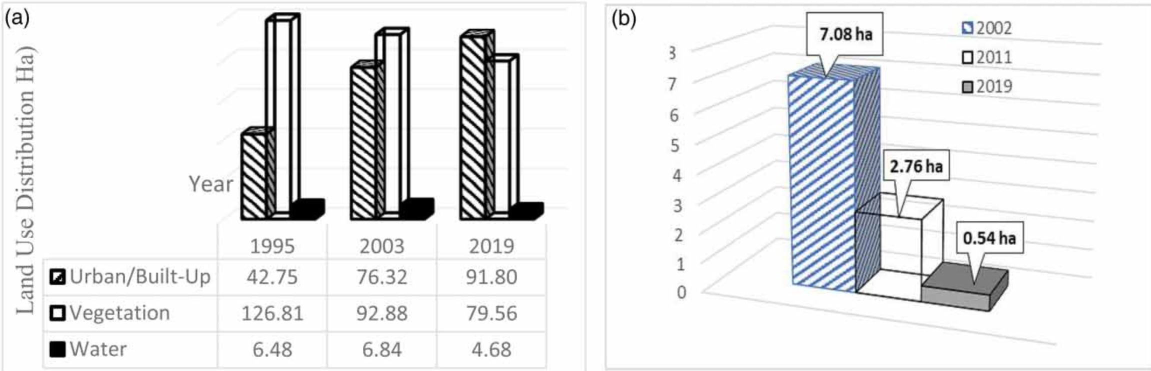


Figure 3 | Kabaka's Lake catchment information: (a) land use distribution and (b) the lake's receiving wetland footprint.

redistribution of land use in the lake catchment noted in this study is similar to that found in other catchments in or close to urban areas and is mainly attributed to unplanned settlements (Kundu *et al.* 2017).

The bathymetric zoning of Kabaka's Lake (Figure 4(a)) indicated depths of between 2.8 and 0.8 m, respectively, with an approximate volume of 128,000 m^3. The mean water depth is just over 1.3 m, which characterises it as a shallow lake. An assessment of the lake's depths in 2017 and 2019 (Figure 4(b)) found a significant difference ($p < 0.0001$) in its horizontal profile, probably caused by siltation from stormwater runoff.

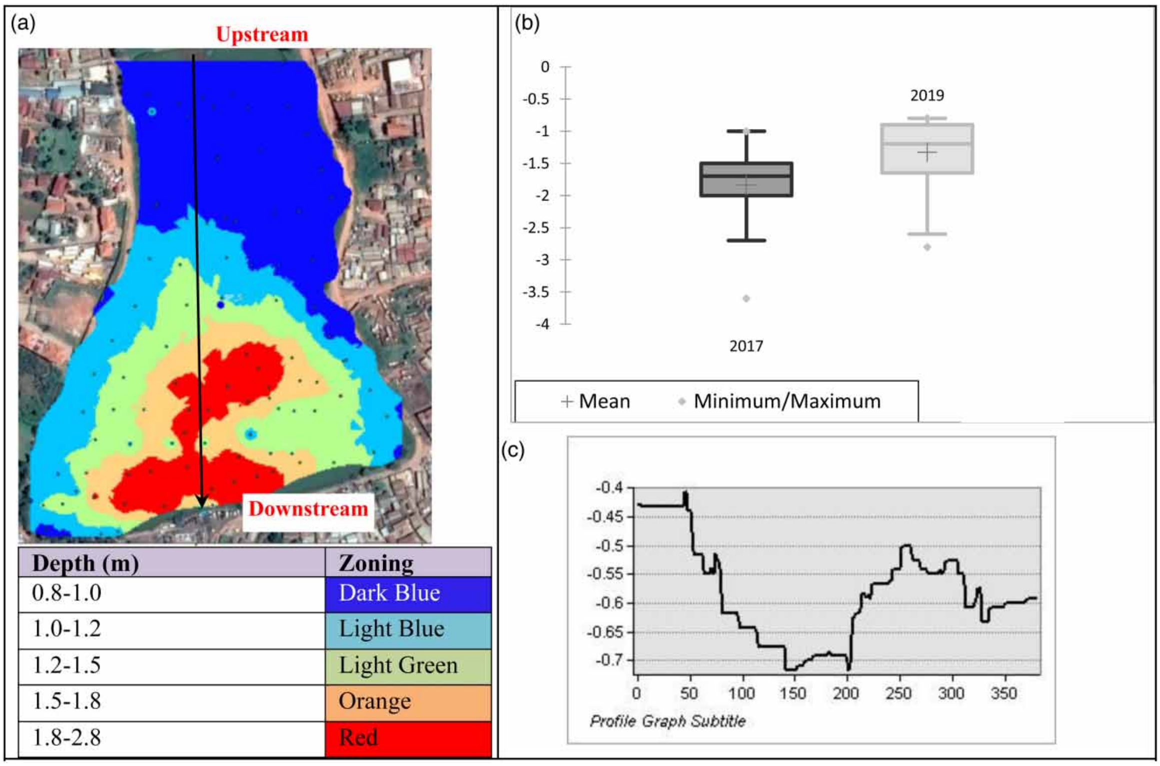


Figure 4 | Kabaka's lake: (a) bathymetric zoning, (b) depth, and (c) sediment profiling.

A spatial interpolation of the lake's water eutrophication parameters is presented in Figure 5. Nutrient concentration assessment showed TN and TP concentrations ranging from 10.5 to 15.3 mg/L and 1.00 to 2.37 mg/L respectively. This is attributed to anthropogenic activity in the catchment, including oil spillages from mechanical works at garages, water recycled to the lake from washing bays, and sewage inflow from hostels and houses. Nutrient concentrations in the lake were lower than those in the receiving drains – TN $14.7 > 11.85$ mg/L and TP $3.65 > 1.43$ mg/L – indicating that, while the wetland has been reduced significantly, it still has significant nutrient reduction efficiency ($p = 0.0006$) – 33% TN (0.1–5.6 mg/L) and 68% TP (1.8–2.65 mg/L). Nutrient profiling along the catchment showed a 14% variation trend in nitrogen and phosphorus concentrations, as they reduce downstream (from the furthest point in the catchment to its discharge point), attributed to the catchment's soil profile. The ecological turnover in the catchment is significantly affected by nitrate inputs (TN/TP = 5.89 ± 3), implying that the lake is nitrate limited. This is in contrast to findings from the Lake Victoria basin, to which Kabaka's Lake is a sub-catchment, which is phosphate limited (TN/TP = 8.0–42.0) (Gikuma-Njuru & Hecky 2005).

Green algae thrive in the lake's environmental conditions – pH > 8.5, low salinity (0.13 ± 0.00 mg/L), temperature of 25–35 °C – and are responsible for the lake water's green colour (874 ± 210 PtCo), hence exposing the lake to eutrophication enrichment. A Secchi disk transparency variation (0.5–0.1 m) was obtained along the lake's profile (Figure 5(b)), indicating a eutrophic factor. The combination of a large surface area and relatively shallow depth means that the lake does not react homogeneously, with mixing occurring at different times and to different degrees in different places. Biological accumulations in the lake have influenced fluctuations between TSI (SD = 18.66 and Chl-a = 18.65) and TSI (TN = 24.88 and TP = 20.146), confirming the dominance of algae in light attenuation. This is due to the similarity between the Secchi disk and Chlorophyll-a TSI values [TSI (Chl-a) = TSI (SD)], and the nitrogen factor limiting the algal biomass, confirmed by [TSI (TP) > TSI (Chl-a) = TSI (SD)], as argued by (Brown & Simpson 2001). Florida Department of Environmental Protection (FDEP), would classify a lake with a TSI of 21.57 as oligotrophic (TSI < 40) due to its low nutrient concentration. it has the potential, however, to support the highest level of biological productivity (e.g., an abundance of algae, aquatic plants, birds, fish, insects, and other wildlife).

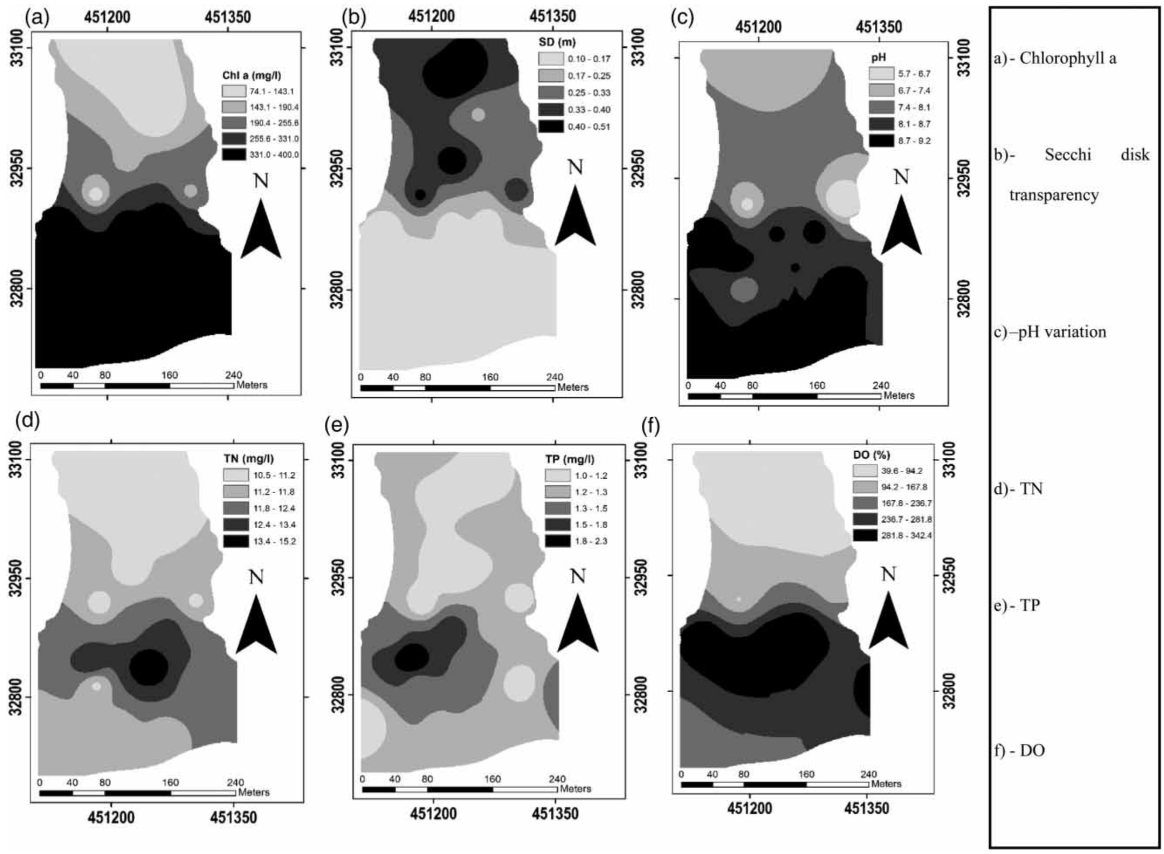


Figure 5 | Kabaka's Lake: eutrophication water quality parameters.

Regression modelling was performed to predict the lake's TP and TN loads, and TSI for a 5-year range period (5, 10, 15, 20, 25, and 30 years). A 63% root mean square model fitting the data with fit goodness of minimal residual sum of squares (3.439) and acceptable P values (TN = 0.005492 and TP = 0.000139) was obtained.

The model's normality standardised residual plots for TN and TP followed a normal distribution (spread homogenously along the line [$y = 0$]) validating its reliability. Plots show a reasonable correlation between the observed and predicted values. The model predicted an average annual increment of 1.14 (5.2%) in nutrient pollution load for the next 30 years.

The increase in wetland encroachment has translated into a gradual loss of nutrient reduction efficiency for the lake. Modelling of the lake's nutrient load over time shows that with the current 0.54 hectares of natural wetland, significant TP ($p = 0.0102$) and TN reductions ($p = 0.000083$) will continue to be noticed over the next 25 years. This implies that, if the current natural wetland is not destroyed, it will continue reducing the nutrient input load effectively for the next 25 years, after which the lake will be eutrophic, while the construction of a wetland in the catchment will increase the nutrient reduction efficiency over time.

Dredging the lake as an internal measure will reduce nutrient loading by 80% [TP ($p = 0.00017$) and TN ($p = 0.00027$)] The lake self-cleansing after dredging will cause an ultra-microtrophic status for the next 30 years – (Figure 6). This is thought to be because the lake has a significant ($p = 0.00003$) ability to attenuate and control flooding downstream, which has led to significant ($R^2 = 0.930$, $p < 0.0001$, $n = 103$) sediment loading. It is also noted that there is no distinct boundary between the water and sediment at the bottom of the lake, with wave action disturbing the sediment to a depth of about 0.5 m, creating conditions where significant amounts of the nutrients stored in the sediment ($p < 0.0001$) can contribute to those in the water column. This is supported by the strong correlation ($R^2 = 0.98$, $p < 0.0001$, $n = 6$) of the lake's phosphorus content ($P_{lake} = 0.517$ mg/L and $P_{sed} = 0.103$ mg/L) at a hydraulic residence time ($tw = 4$ h), as benchmarked on the χ^2 analysis under characterising of TP dissolved from the sediment in Utah Lake (Abu-Hmeidan *et al.* 2018). It is estimated that approximately 77,000 m^3 dredged volume would be sufficient for the lake to become self-cleansing.

<table>
<tr><th>Year</th><th>Predicted</th><th>Constructed Wetland</th><th>Dredging</th></tr>
<tr><td>2019</td><td rowspan="2">Ultra-Microtrophic</td><td rowspan="6">Ultra-Microtrophic</td><td rowspan="7">Ultra-Microtrophic</td></tr>
<tr><td>2024</td></tr>
<tr><td>2029</td><td rowspan="3">Mesotrophic</td></tr>
<tr><td>2034</td></tr>
<tr><td>2039</td></tr>
<tr><td>2044</td><td rowspan="2">Eutrophic</td></tr>
<tr><td>2049</td><td>Mesotrophic</td></tr>
</table>

Figure 6 | The lake's predicted eutrophication management trophic status through time.

IMPLICATIONS AND CONCLUSIONS

The study's findings suggest that Kabaka's Lake's eutrophication is attributable largely to anthropogenic disturbance in the catchment, where increased human settlement has increased the lake's potential nutrient loading. The findings show that the lake is not yet eutrophic but is oligotrophic. With the current state of activities in the catchment, this will remain the case for about the next 25 years. Constructing a wetland with the current footprint will reduce the anticipated nutrient load significantly and sustain the lake's trophic status. Dredging the lake will not only increase its storage capacity but also enable thermal self-cleansing to remove the green colour. These findings are strong justification for watershed management as a sustainable solution to control nutrient flow into the lake.

ACKNOWLEDGEMENTS

The authors acknowledge AWE for the data used in this study. The authors acknowledge that this paper was partly based on an MSc study by Mutyaba (2019) under the supervision of A.N. and K.O.

AUTHORS' CONTRIBUTIONS

All authors were involved in the study's conception. A.M. and A.N. were further involved in data acquisition, analysis, interpretation, and manuscript drafting and revisions. C.H. and K.O. reviewed and made comments on the draft manuscripts. All authors reviewed and approved the manuscript for submission.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abu-Hmeidan, H. Y., Williams, G. P. & Miller, A. W. 2018 Characterizing total phosphorus in current and geologic Utah lake sediments: implications for water quality management issues. *Hydrology* **5**(1), 8.

APHA 2012 *Standard Methods for the Examination of Water and Wastewater*, 22nd edn. American Public Health Association, American Water Works Association and Water Environment Federation Publication, Washington, DC, USA.

AWE 2017 *Kabaka's Lake Environmental and Social Impact Assessment*. Air Water Environment (AWE), Kampala.

Brown, T. & Simpson, J. 2001 Managing phosphorus inputs to urban lakes: I. Determining the trophic state of your lake. *Watershed Protection Techniques* **3**(4), 771.

Carlson, R. E. 1977 A trophic state index for lakes 1. *Limnology and Oceanography* **22**(2), 361–369.

Chorus, I. & Welker, M. 2021 Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring and Management. *CRC Press Taylor & Francis group, Boca Raton (FL), on behalf of the World Health Organization*. Geneva, CH.

Costa, J. A. d., Souza, J. P. d., Teixeira, A. P., Nabout, J. C. & Carneiro, F. M. 2018 Eutrophication in aquatic ecosystems: a scientometric study. *Acta Limnologica Brasiliensia* **30**. e2. http://dx.doi.org/10.1590/S2179-975X3016.

Dwarakish, G. & Ganasri, B. 2015 Impact of land use change on hydrological systems: a review of current modeling approaches. *Cogent Geoscience* **1**(1), 1115691.

Foladori, P., Ruaben, J. & Ortigara, A. R. 2013 Recirculation or artificial aeration in vertical flow constructed wetlands: a comparative study for treating high load wastewater. *Bioresource Technology* **149**, 398–405.

Gikuma-Njuru, P. & Hecky, R. 2005 Nutrient concentrations in Nyanza Gulf, Lake Victoria, Kenya: light limits algal demand and abundance. *Hydrobiologia* **534**, 131–140.

Ilyas, H. & Masih, I. 2017 Intensification of constructed wetlands for land area reduction: a review. *Environmental Science and Pollution Research* **24**, 12081–12091.

Jetoo, S. 2018 Barriers to effective eutrophication governance: a comparison of the Baltic Sea and North American Great Lakes. *Water* **10**(4), 400.

Kasim, N. Z. 2015 *Mititgation and Management Strategies for Reducing Eutrophication in Tropical Humid Regions*. University of Leeds, Leeds.

Kiggundu, N., Abugri Anaba, L., Banadda, N., Wanyama, J. & Kabenge, I. 2018 Assessing land use and land cover changes in the Murchison Bay catchment of Lake Victoria basin in Uganda. *Journal of Sustainable Development* **11**(1), 44–55.

Kundu, R., Aura, C. M., Nyamweya, C., Agembe, S., Sitoki, L., Lung'ayia, H. B., Ongore, C., Ogari, Z. & Werimo, K. 2017 Changes in pollution indicators in Lake Victoria, Kenya and their implications for lake and catchment management. *Lakes & Reservoirs: Research & Management* **22**(3), 199–214.

Leng, R. 2009 The impacts of cultural eutrophication on lakes: a review of damages and nutrient control measures. *Freshwater Systems and Society* **20**, 37–38.

McCutcheon, S. C. 1990 *Water Quality Modeling: River Transport and Surface Exchange*. CRC press, Boca Raton.

Mthembu, M., Odinga, C., Swalaha, F. M. & Bux, F. 2013 Constructed wetlands: a future alternative wastewater treatment technology. *African Journal of Biotechnology* **12**(29), 4542–4553.

Okurut, T. O. 2000 *A Pilot Study on Municipal Wastewater Treatment Using A Constructed Wetland in Uganda*. CRC Press, A. A. Balkema, Rotterdam.

Paerl, H. W. & Otten, T. G. 2013 Blooms bite the hand that feeds them. *Science* **342**(6157), 433–434.

Richmond, A., Myers, I. & Namuli, H. 2018 Urban informality and vulnerability: a case study in Kampala, Uganda. *Urban Science* **2**(1), 22.

Soranno, P. A., Cheruvelil, K. S., Wagner, T., Webster, K. E. & Bremigan, M. T. 2015 Effects of land use on lake nutrients: the importance of scale, hydrologic connectivity, and region. *PloS one* **10**(8), e0135454.

Watson, S. B., Monis, P., Baker, P. & Giglio, S. 2016 Biochemistry and genetics of taste-and odor-producing cyanobacteria. *Harmful Algae* **54**, 112–127.

Wells, M. L., Trainer, V. L., Smayda, T. J., Karlson, B. S., Trick, C. G., Kudela, R. M., Ishikawa, A., Bernard, S., Wulff, A. & Anderson, D. M. 2015 Harmful algal blooms and climate change: learning from the past and present to forecast the future. *Harmful Algae* **49**, 68–93.

Zyfi, A., Grazhdani, S. & Ahmeti, A. 2014 Application of CE-QUAL-W2 model to water quality simulation in Prespa lakes. *International Journal of Innovative Research in Science, Engineering and Technology* **3**(5), 12021–12029.

First received 15 May 2023; accepted in revised form 14 July 2023. Available online 31 July 2023