

Article

Assessing the Potential Impacts of Contaminants on the Water Quality of Lake Victoria: Two Case Studies in Uganda

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Abstract: Nutrients are essential for the growth of aquatic life; however, in excess, they can result in a decline in water quality, posing serious risks to both human and aquatic organisms. Human activities, such as urbanisation, industry, and farming, can increase the amount of nutrients and other elements that reach receiving waterbodies like Lake Victoria in Uganda, which can be problematic at elevated levels. There is therefore a strong need to evaluate recent changes in pollutant concentrations and their potential negative effects. To contribute to this gap and to explore the pollutant changes in Lake Victoria, a series of water chemistry data (phosphate, nitrate, potassium, ammonium, sodium, sulphate, silica and chlorine) was collected between 2016 and 2023 in Uganda's Napoleon Gulf (NG) and Murchison Bay (MB), primarily by the Ministry of Water and Environment (MWE). These locations were chosen based on their vicinity to expanding urban centres and agriculture, and they are also areas where fishing frequently occurs. The datasets were collected at different water depths (0.5–24 m). Data were analysed with the use of IBM's Statistical Package for the Social Sciences (SPSS 28.0) software and confirmed the excessive concentrations of pollutants within MB compared to NG. The analysis identified the different nutrient types that exceeded internationally recognised thresholds relating to acceptable water quality during the data collection period. Seasonal variations were observed, during the dry season; nutrient levels, however, in NG showed higher nutrient concentrations during the wet season. The study's capacity to inform local authorities and policymakers about such potential major sources of pollution is of crucial importance for beginning to address the potential impacts on human health and aquatic life.

Keywords: Lake Victoria; nutrients; pollutants; Murchison Bay; Napoleon Gulf; threshold; consequences



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1. Introduction

Anthropogenic pollution continues to pose a growing threat to the African Great Lakes, particularly Lake Victoria [1–5]. Lake Victoria, as shown in Figure 1, is located in East Africa and has a surface size of approximately 68,600 km² [6], making it Africa's largest lake by area and the world's second largest freshwater lake after Lake Superior in North America [6,7]. Lake Victoria is the major source of food, employment, and drinking water for over 42 million people in East Africa [8]. Lake Victoria is home to more than 500 recorded fish species [9], including indigenous cichlids [9]. Fishing is by far the most important economic activity for the lakeside residents [10] with more than 5 million people

in Uganda depending on subsistence fishing for their livelihoods [11]. In addition, the lake serves as an important source of water for Kampala residents, as the city depends on it for its drinking water supply. The National Water and Sewerage Corporation (NWSC) in Kampala extracts water from Lake Victoria through water treatment plants, such as Ggaba II and Ggaba III, supplying roughly 240 million litres per day [12] and Katosi plant supplying 160 litres per day to meet Kampala's total drinking water demand of 300 million litres per day [13].

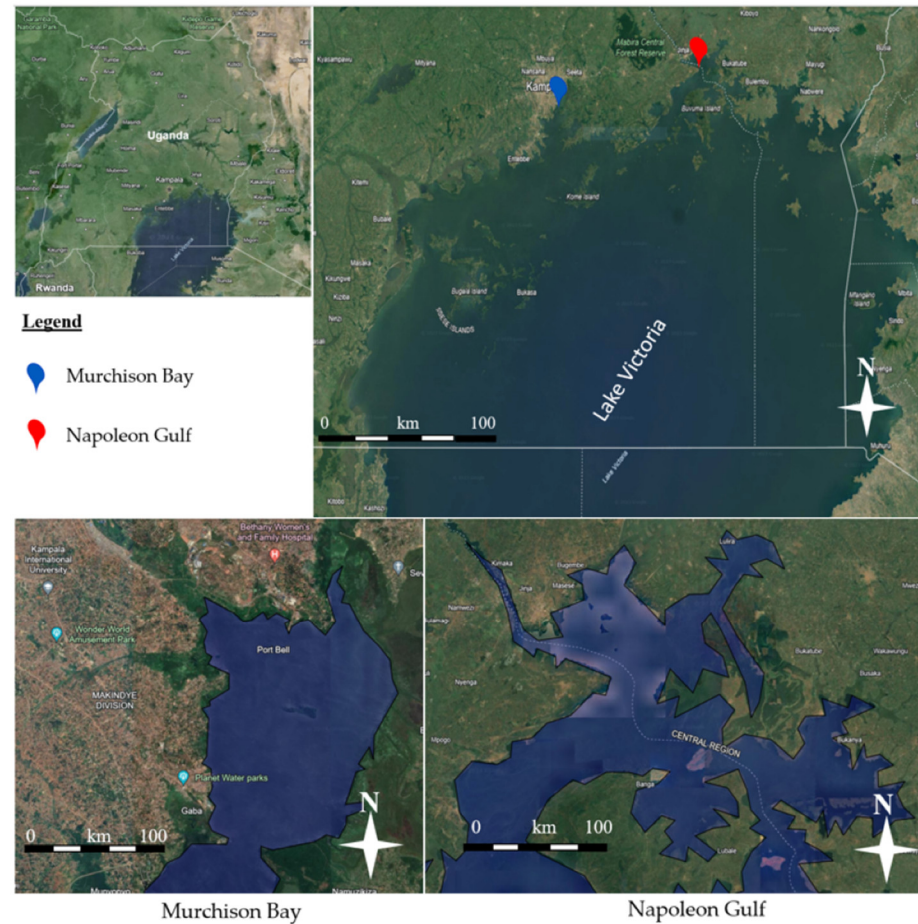


Figure 1. A map of Lake Victoria showing the locations of the sampling sites.

Water quality and ecosystem health in Lake Victoria have declined greatly over the past few decades due to nutrients that come from all countries bordering the lake [14]. In terms of inputs from Uganda alone, Lake Victoria receives substantial amounts of either raw or inadequately treated waste from home, industrial, and pharmaceutical sources [15,16], particularly from Kampala, Entebbe, and Jinja towns. Furthermore, agricultural runoff like pesticides used on flower farms, sugar cane and tea estates in the catchment into the lake. According to Wasswa et al. [17], and Kakuba and Kanyamurwa [18], wetlands of Lake Victoria in Uganda have been seriously degraded (converting them to settlement areas, industries, agriculture and roads) to the extent that they can no longer perform the natural function of removing contaminants from the water that goes to the lake. Nakivubo wetland receives channelised streams carrying wastewater from industrial and residential areas of Kampala Uganda's largest city to Murchison Bay [19–21]. Prolonged dry seasons and unpredictable rainfall [22,23] caused by climate change in Uganda have increased nutrient runoff from sources into Lake Victoria; in addition, an increase in water temperature has contributed to a decrease in the dissolved oxygen level in the lake [24]. All of these factors have impacted the water quality of Lake Victoria.

There have been notable changes in the biological, chemical and physical properties of the water body [25–27]. Several of Lake Victoria’s bays and gulfs, such as Murchison Bay, NG, Waiya Bay, Entebbe Bay, Bunjako Bay and Thurston Bay, appear to be more affected by eutrophication than the open lake. However, the anthropogenic pollution is not uniformly distributed among these locations. For example a study conducted by Nantaba et al. [15] showed that the concentration of personal care products, like insect repellents, disinfectants and cosmetics, were higher in Murchison, Waiya, and Entebbe Bays compared to Napoleon and Thurston Bays. This is possibly because Murchison, Waiya and Entebbe Bays receive domestic wastewater from Kampala and Entebbe cities that are densely populated [15]. Subsequently, Ugandans who live around the lake and depend on it for their daily livelihoods face increased food and water safety threats, economic pressures and health-related challenges, which have gradually increased over the previous few decades [28,29].

The rise in nutrient levels, particularly phosphorus and nitrogen have been a major contributing factor to eutrophication in the lake leading to various changes that have impacted its economic, social and ecological functions. For example, the increase in water hyacinth (*Pontederia crassipes*) near the lake’s shoreline, limits the social and economic activities pursued by the local residents for their livelihood, such as fishing, water transport and leisure activities [30,31]. The increase in nutrients has also stimulated algal growth, which has led to de-oxygenation of the water, causing threats to human and animal health, clogging water intake filters and increasing chemical treatment costs for urban centres. Although studies (e.g., [32–35]) have been conducted in order to improve the water quality in Lake Victoria, the management of issues with a high nutrient concentration and both suspended and dissolved organic matter seems far from being achieved. Therefore, this study investigates the concentration increases in nutrients in MB and NG and the potential sources of the nutrients in the dry and wet seasons. The study was conducted on MB and NG because the two bays have contrasting ecological conditions. MB receives more urban and industrial effluents as it is surrounded by the city of Kampala, leading to higher nutrient loading though NG is less impacted by urban pollution sources.

2. Materials and Methods

2.1. Description of the Study Areas

The Murchison Bay (MB) and Napoleon Gulf (NG) are located in the northern region of Lake Victoria (Uganda) as shown in Figure 1 and their characteristics are summarised in Table 1. MB is surrounded by the Greater Kampala Metropolitan Area (KMA), which contains the highly industrialised and densely populated districts of Kampala and Wakiso [36]. This bay receives direct wastewater discharge, primarily from the KMA via the Nakivubo canal and associated wetland systems [37]. NG is bordered by Jinja City, Buikwe, and Buvuma districts. According to Oguttu et al. [38], The Gulf receives non-point source chemical contaminants, fertilizers and wastewater from wetland systems near the source of the Nile.

Table 1. Major characteristics of the study sites [36].

	Murchison Bay	Napoleon Gulf
Catchment area (km ²)	593.92 km ²	187.92 km ²
Estimated population	Five million	Nine hundred thousand
Major wetlands	Nakivubo I and II (4.3 and 4.91 km ²) and Namanve (38.3 km ²)	Masese (2.2 km ²) and Budumbuli (4.3 km ²)

2.2. Data Analysis

A flame photometer was used to measure the concentration of sodium and potassium in the samples collected from MB and NG. This analytical instrument is effective for measuring sodium and potassium in surface and ground water [39]. The sample solution was

introduced into the instrument as a fine mist using a nebuliser. The sample was atomised in a high-temperature flame by burning a fuel gas with oxidant. A photodetector measured the intensity of the emitted light at the selected wavelengths, which are proportional to the concentrations of the elements in the sample. The measured signal was compared to standards to determine the concentration of the element in the sample solution.

A gallery plus discrete analyser was used to measure the concentrations of phosphate, nitrate, ammonium, sulphate, silica and chlorine. Masindi et al. [40] and Namatovu et al. [41] used a gallery plus discrete analyser in the studies that they conducted. The specific required reagents for the nutrients analysis were prepared. The analyser was calibrated to the standards of the nutrient being measured to ensure accurate measurement. The prepared water samples were then loaded into the sample tray of the discrete analyser. A specific nutrient analysis program from the analyser software was selected. Then, the analyser was started and it automatically dispensed reagents and mixed, incubated and measured the absorbance of the samples. The analyser provided the reading of a specific nutrient basing on the calibration curve.

A digital thermometer was used to measure the temperature of the water. A study by Kurniawan et al. [42] used the digital thermometer to measure the temperature of evenly distributed and stable water bath temperatures. The thermometer was allowed to stabilise. Then, the measured temperature was displayed and noted down.

A total dissolved solid meter was used to measure the concentrations of total dissolved solids in Lake Victoria, as used previously by Dewangan et al. [43]. The meter was calibrated before taking the measurements; then, the probe of the total dissolved meter was placed into the water sample, ensuring it was fully submerged. The meter was left to stabilise and display the total dissolved reading. The parameter values are displayed in milligrams per litre.

The gravimetric method was used to measure the concentration of total suspended solids in the lake, and the same method was used in studies conducted by Wiyantoko et al. [44] and Adjovu et al. [45]. The water was passed through a pre-weighed filter to trap suspended solids. The filter was dried with the trapped solids in an oven at a temperature of (103–105) until a constant weight was achieved. The dried filter was weighed to determine the mass of the suspended solids. The difference in weight before and after drying was calculated to find the total suspended solids concentration which is expressed in milligrams per litre.

An electrochemical dissolved oxygen sensor was used to measure the concentration of dissolved oxygen in the Lake Victoria. The electrochemical probe was submerged into the lake, allowing it to come into direct contact with the water. The sensor continuously monitored the DO levels as the probe was lowered through different water depths, capturing variations in oxygen concentration. Measurements were taken between 6 a.m. and 7 p.m. from the lake in order to capture the daily variations in DO levels, which can fluctuate based on temperature, biological activity (such as photosynthesis), and water movement. The electrochemical dissolved oxygen sensor has been used before in a study conducted by Martin et al. [46].

2.3. Statistical Analysis

The descriptive statistical tool within the IBM SPSS statistical software package was used to calculate the sum, range, minimum, maximum, mean and the standard deviation of the nutrient concentrations in MB and NG (see Section 3.2). The 'Compare mean' tool (IBM SPSS) was used to compare the mean of a nutrient's concentration according to the period of testing and also for each catchment bay. Scatter plots were used to display the relationship between the nutrient concentrations in Lake Victoria based on the dry and wet seasons in Uganda. The data were split based on the specific dates within the dry and wet seasons of the year in Uganda. The formulas used to calculate nutrient concentrations can be found below.

The formula to calculate the range of values for each nutrient is as follows:

$$R = x^2 - x^1 \quad (1)$$

The formula to calculate the mean value for each nutrient is as follows:

$$\bar{x} = \frac{\sum x}{n} \quad (2)$$

The formula to calculate the standard deviation is as follows:

$$SD = \sqrt{\frac{\sum (x - \bar{x})^2}{n}} \quad (3)$$

ANCOVA was employed to determine whether the effects of sampling locations (independent variables) and sampling period (continuous variables) were significantly or nonsignificant on the concentrations of nutrients in Lake Victoria. It was also used to examine the interaction between sampling location and sampling period on the nutrient concentrations in the lake. A *p*-value less than or equal to 0.05 indicates that an observed effect was statistically significant, allowing us to reject the null hypothesis. A total of thirteen ANCOVA analyses were used, and to account for multiple testing, a Bonferroni adjustment was used so that the significance level used was $0.05/13 = 0.004$.

3. Results

3.1. Annual Sample Rate for Murchison Bay and Napoleon Gulf

The sampling of nutrients at MB and NG was conducted over five separate years across a seven-year period (2016, 2017, 2021, 2022, and 2023). The total sampling frequency differed between the two stations and also between the years when the sampling was conducted, as shown in Table 2. The average rate for the sampling occurrences at MB was 88 times (frequency = 438 sample total) compared to an average of 17 times (frequency = 66 sample total) at Napoleon bay. The National Water Quality Reference Laboratory (NWQRL) in Entebbe is Uganda's primary facility for wide-ranging water quality monitoring, analysis and data generation, which is important for understanding and addressing water quality challenges, protecting aquatic ecosystems and safeguarding public health across the country [41,47].

Table 2. Total number of nutrient samplings per year.

Year	Bay	
	Murchison	Napoleon
2016	4	0
2017	1	6
2021	131	15
2022	61	32
2023	240	13

3.2. Concentrations of Nutrients in Lake Victoria at Murchison Bay (MB) and Napoleon Gulf (NG)

A total of eight nutrients, as shown in Table 3, were analysed to identify the concentrations of nutrients in MB and NG. The results indicate that the average nutrient concentration was higher in MB compared to NG. Sodium (Na) was the nutrient with the highest concentration in both the catchment areas, and it also had the highest difference between averages (2.91 mg/L) between MB and NG. Phosphate (PO₄) had the lowest difference between averages (0.04 mg/L) between the two catchment locations. Some nutrient concentrations in both bays were below the detection limit (bdl) (phosphate was bdl in both MB and NG). The results indicate that the dissolved oxygen (DO) levels were

higher in NG compared to MB, as shown in Table 3. The average water temperature in NG was slightly higher in NG compared to the water temperature in MB. The overall mean pH across the studied areas was 8.2, indicating slightly alkaline conditions. Both bays exhibited pH levels within the acceptable range for freshwater ecosystems, though the slightly higher pH in Napoleon Gulf may require closer monitoring to prevent potential environmental stress on sensitive aquatic species.

Table 3. Water quality parameters in Lake Victoria according to sample site.

Parameters	Murchison Bay					Napoleon Gulf				
	Range	Min	Max	Mean	Std	Range	Min	Max	Mean	Std
Phosphate (PO ₄) (mg/L-P)	0.91	/	0.91	0.12	0.13	0.80	/	0.80	0.08	0.13
Nitrate (NO ₃ ⁻) (mg/L-N)	23.00	0.002	23.00	0.81	1.44	2.42	/	2.42	0.25	0.40
Potassium (K) (mg/L)	15.40	2.60	18.00	5.20	1.92	1.10	2.30	3.40	2.82	0.31
Sodium (Na) (mg/L)	17.90	7.10	25.00	12.07	1.89	1.90	8.10	10.00	9.16	0.44
Ammonium (NH ₄ ⁺) (mg/L-N)	17.00	0.002	17.00	0.48	1.14	0.64	0.002	0.64	0.14	0.14
Sulphate (SO ₄) (mg/L)	69.41	/	69.00	1.17	4.68	5.45	0.20	5.65	0.73	0.98
Silica (Si) (mg/L)	15.30	/	15.00	2.39	2.17	3.60	0.30	3.90	1.72	0.97
Chlorine (Cl) (mg/L)	20.57	0.43	21.00	7.94	2.24	34.70	3.30	38.0	6.10	5.91
Total Dissolved Solids (TDS) (mg/L)	443.10	/	443.10	112.71	55.00	11.90	85.40	97.30	88.48	2.32
Total Suspended Solids (TSS) (mg/L)	1769.00	1.00	1770	67.39	212.72	63.00	1.00	64.00	9.46	12.20
Dissolved Oxygen (DO) (mg/L)	12.17	0.02	12.19	5.70	2.30	10.46	0.54	11.00	6.98	2.19
Temperature (°C)	6.23	21.71	27.94	25.89	0.68	3.42	25.50	28.92	26.75	1.02
pH	3.51	6.49	10.00	8.16	0.67	2.47	7.40	9.87	8.31	0.54

/ Stands for a nutrient concentration in a bay that is below detection.

3.3. Variability in Mean Value Nutrient Concentrations in MB and NG from 2016–2023 and Potential Causes

Figure 2 shows changes in nutrient concentrations over the five years sampling within a seven year period in MB and NG from 2016–2023. The results indicate that the concentrations of nutrients over the 5 years of sampling were much higher in MB than NG. For some years between 2016 and 2023 no sampling was conducted. This was due to insufficient finances to support the collection of data for a specific nutrient, such as potassium in 2016. The statistical test (ANCOVA) revealed the effects of sampling locations, sampling periods, and their interaction on the water quality parameters, as shown in Table 4.

Table 4. The ANCOVA results for the effects of the sampling locations, sampling periods and their interaction on the water quality parameters.

Dependant Variable	Bay	Year	Bay × Year
PO ₄	F(1,453) = 36.77, <i>p</i> < 0.001	F(1,453) = 2.41, <i>p</i> = 0.121	F(1,453) = 32.94, <i>p</i> < 0.001
NO ₃ ⁻	F(1,451) = 2.57, <i>p</i> = 0.109	F(1,451) = 0.81, <i>p</i> = 0.369	F(1,451) = 1.04, <i>p</i> = 0.309
K	F(1,485) = 3.10, <i>p</i> = 0.079	F(1,485) = 3.42, <i>p</i> = 0.065	F(1,485) = 0.22, <i>p</i> = 0.639
Na	F(1,485) = 8.48, <i>p</i> = 0.004	F(1,485) = 0.94, <i>p</i> = 0.333	F(1,485) = 1.44, <i>p</i> = 0.231
NH ₄ ⁺	F(1,427) = 0.03, <i>p</i> = 0.854	F(1,427) = 0.28, <i>p</i> = 0.596	F(1,427) = 0.03, <i>p</i> = 0.860
SO ₄	F(1,424) = 0.03, <i>p</i> = 0.859	F(1,424) = 0.61, <i>p</i> = 0.434	F(1,424) = 0.01, <i>p</i> = 0.920
Si	F(1,316) = 7.18, <i>p</i> = 0.008	F(1,316) = 0.36, <i>p</i> = 0.549	F(1,316) = 5.52, <i>p</i> = 0.019
Chlorine	F(1,482) = 1.05, <i>p</i> = 0.307	F(1,482) = 1.88, <i>p</i> = 0.171	F(1,482) = 3.47, <i>p</i> = 0.063
DO	F(1,452) = 1.92, <i>p</i> = 0.167	F(1,452) = 2.38, <i>p</i> = 0.124	F(1,452) = 0.56, <i>p</i> = 0.457
Temperature	F(1,399) = 5.36, <i>p</i> < 0.021	F(1,399) = 13.23, <i>p</i> < 0.001	F(1,399) = 12.90, <i>p</i> < 0.001
TDS	F(1,282) = 0.003, <i>p</i> = 0.957	F(1,282) = 0.04, <i>p</i> = 0.852	F(1,282) = 0.05, <i>p</i> = 0.833
TSS	F(1,159) = 0.12, <i>p</i> = 0.733	F(1,159) = 0.005, <i>p</i> = 0.944	F(1,159) = 0.01, <i>p</i> = 0.919
pH	F(1,493) = 0.25, <i>p</i> = 0.615	F(1,493) = 2.43, <i>p</i> = 0.120	F(1,493) = 0.71, <i>p</i> = 0.402

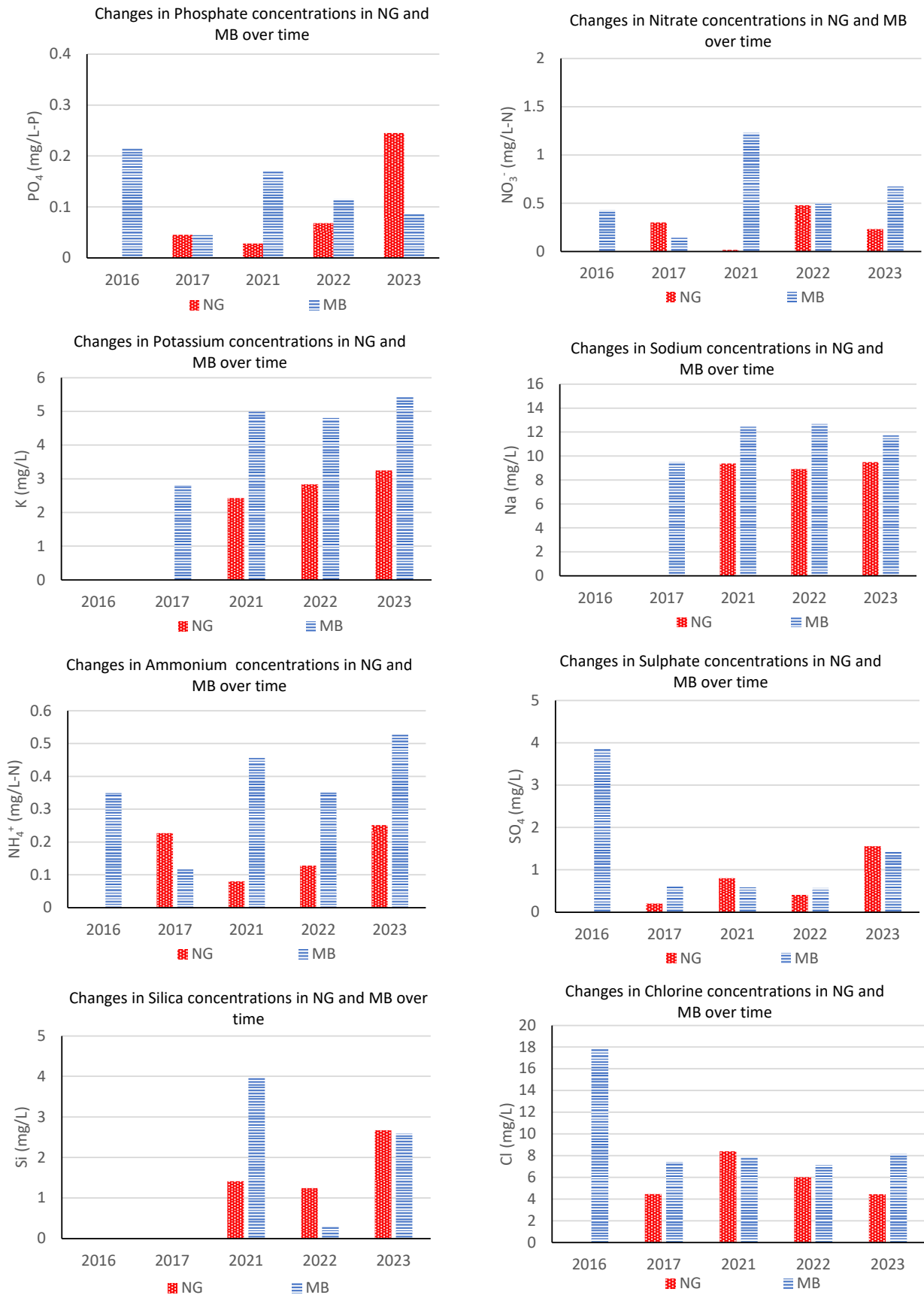


Figure 2. Cont.

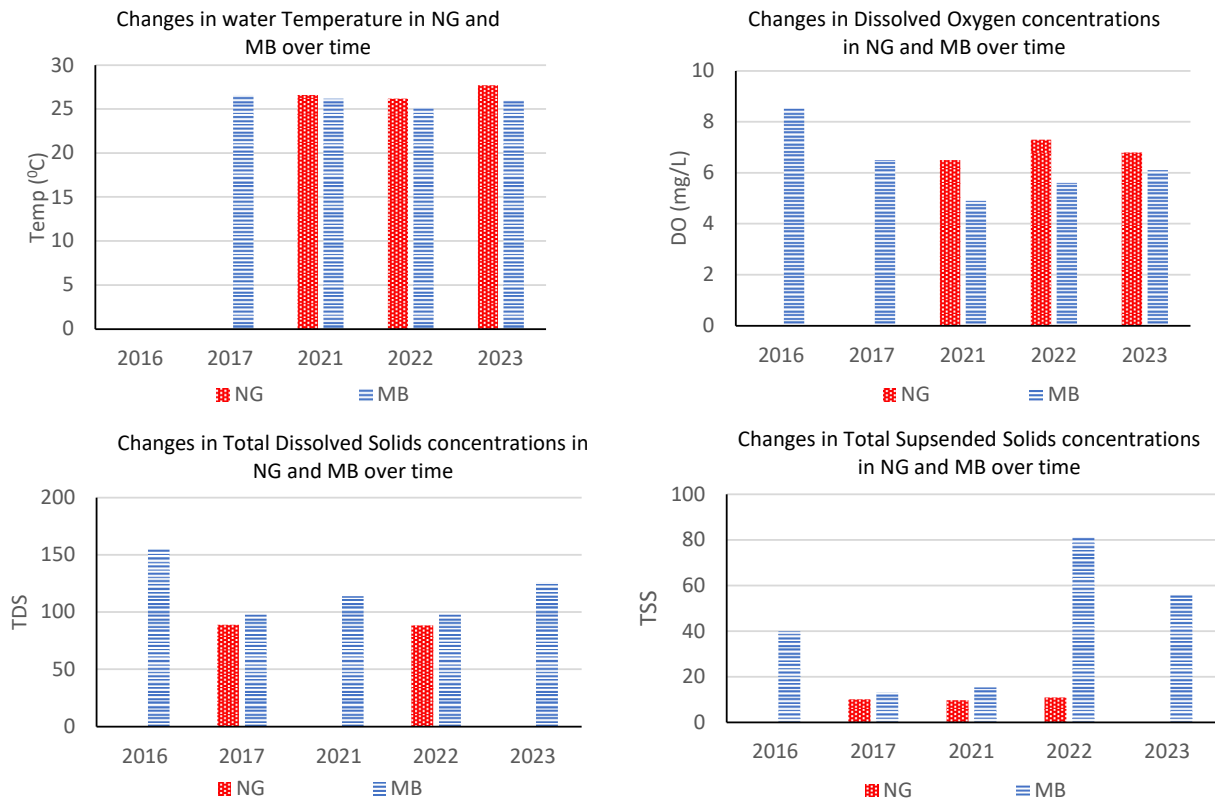


Figure 2. Changes in nutrient concentrations throughout the five years of sampling within a seven year period in MB (Murchison Bay) and NG (Napoleon Gulf) from 2016 to 2023. A zero indicates that no data were available.

3.3.1. Phosphate (PO_4)

For phosphate concentration, there is evidence ($p < 0.001$) of a significant interaction between the sampling location and the sampling period. Figure 2 shows that phosphate levels generally increased over time in NG but decreased over time in MB. Numerous car washing bays have been established along lakes and wetlands over the years. They are common and profitable sources of income for urban teenagers in Uganda due to their inexpensive start-up costs [48]. Wastewater from car washing bays, which contain detergent, is discharged into the water system [49]. Because of the phosphate levels in the detergent products, this increases the phosphate discharged into the surface waters and lake in the form of wastewater. Therefore, the source of phosphate in both MB and NG is attributed to the increase detergent waste that is discharged in the catchment areas.

3.3.2. Nitrate (NO_3^-)

The statistical test suggests there was no significant interaction of the nitrate concentrations between the sampling location and the sampling period ($p = 0.309$). There was no significant change in nitrate levels either for the sampling location ($p = 0.109$) or sampling period ($p = 0.369$). Increased urban agriculture in Uganda ([50–52]), particularly around the capital Kampala, has contributed to increased nutrient levels in water bodies like Lake Victoria. The concentrations of nitrate in both MB and NG are attributed to NPK 17:17:17 fertilisers. NPK 17-17-17 is among the products of highest commercialisation in the fertiliser markets of Uganda [53]. NPK 17:17:17 fertiliser typically contain nitrate nitrogen [54], which plays a vital role in providing essential nutrients to plant growth. Residents engaged in agricultural activities around MB and NG use NPK 17:17:17 fertiliser which are mainly transported by the rain runoff to the MB and NG.

3.3.3. Potassium (K)

There was no evidence that there is a significant interaction between the sampling location and sampling period ($p = 0.639$) on the concentrations of potassium. The effects of sampling location ($p = 0.079$) and sampling period ($p = 0.065$) showed no significant difference in potassium concentrations. Inadequate public toilet facilities in Ugandan markets have attributed to the increase in nutrients like potassium in the catchment areas. For example, Ggaba landing site is located on the northern shore of Lake Victoria in Murchison Bay and has a market used as the centre of the fish trade in Uganda. The landing site has inadequate toilets for people who work in the market and those who practice fishing [55,56]. This has led to people who work from this site urinating in the lake, which has increased the potassium in the lake, since urine contains potassium nutrients.

3.3.4. Sodium (Na)

The interaction between sampling location and sampling location was not significant ($p = 0.231$) for sodium concentrations. The sampling location had a statistically significant effect on nutrient concentration ($p = 0.004$), indicating that sodium levels differed significantly across the different bays. However, the sampling period did not have a statistically significant effect on the sodium concentration ($p = 0.333$). The increased consumption of table salt in Uganda has contributed significantly to sodium pollution in water bodies like Lake Victoria. Table salt consists of approximately 40–50 percent of sodium by weight [57], and with the growing population and urbanisation, many people consume large quantities. The sodium from ingested salt is excreted into the sewer systems and eventually finds its way into rivers, lakes, and other water resources. This continuous inflow of sodium has raised its levels in water bodies, particularly in urban areas where table salt consumption is higher. The higher sodium concentration observed in MB compared to NG can be attributed to more densely populated areas with greater salt consumption. Urban environments like MB see higher levels of sodium pollution due to easier access to processed and packaged foods, which are typically high in salt.

3.3.5. Ammonium (NH_4^+)

The ANCOVA test revealed no significant interaction between sampling location and sampling period for ammonium concentrations. Additionally, there was no significant difference in ammonium levels between MB and NG ($p = 0.854$) or across the sampling years ($p = 0.596$). Cattle grazing in Uganda is a common practice in the regions surrounding Lake Victoria [58], and has caused adverse impacts like increased sedimentation, degraded water quality and reduced water productivity in the lake. Cow dung and urine contain significant amounts of ammonia (NH_3), with urine being the dominant source of ammonium emissions compared to dung [59–61]. Volatilisation is the primary pathway by which ammonia is lost from cow dung and urine, contributing to the concentration of ammonium nutrients in the water bodies [60]. According to the most recent research on this by Laubach et al. [58], 19.8–22.4 percent of ammonium in cattle urine and dung can be lost through volatilisation. The remaining ammonium compounds could potentially be transported to water resources via runoff during rainfall events. With a mean pH of 8.2, this indicates there is a notable shift towards more toxic ammonia (NH_3). Therefore, cow dung and urine can be significant sources of ammonium nutrients that enter and pollute Lake Victoria through direct deposition, volatilisation and runoff.

3.3.6. Sulphate (SO_4)

Sulphate concentrations showed no significant interaction between sampling location and sampling period (0.920). Additionally, both sampling location ($p = 0.859$) and sampling period ($p = 0.434$) indicate nonsignificant changes for sulphate levels. The cosmetics market in Uganda has expanded significantly, resulting in an increase in the number of salons and consumption of cosmetics across the country [62]. Sulphates are extensively used in a number of cosmetic products [63], such as shower gels, shampoos, conditioners and facial

cleansing because of their cleaning, foaming and easy rinsing qualities [63]. Improper disposal of cosmetic products, chemicals and other waste, which can end up contaminating Lake Victoria. The COVID-19 lockdown in Uganda, however, saw salon businesses closed down, and this could be the reason to why there was a decline in sulphate nutrients in MB in the year 2021, as shown in the Figure 2. The lifting of COVID-19 restrictions, which meant the reopening of salon businesses, led to increases in sulphate nutrients in MB, and this can be seen in the year 2023. Jinja is an important agricultural centre in Uganda, and during the COVID-19 pandemic, more agricultural production was required in Uganda to address the food security challenges [64]. This led to the increases in agricultural materials like poultry manure into water resources, and this could be the reason why there was gradual increase in sulphate nutrients in NG.

3.3.7. Silica (Si)

The interaction between sampling location and sampling period was significant (0.019), suggesting that the effect of time on silica concentrations differed between bays, as shown in Figure 2. Silica is the second most abundant element in the Earth's crust, primarily in the form of silicate minerals [65]. Nama mining company is located in Nakawuka, which is in the proximity of MB, and it mines dimension stone. The crystalline silica content in dimension stones varies depending on the type of stones, for example, engineered stone containing more than 90 percent crystalline silica, about twice that is seen in granite [66]. Steel Rolling Mills Limited is located in Jinja and the company mines iron ore. The average crystalline silica in iron stone ore is 15.5 percent [67]. Weathering and erosion are the primary pathways for silica to reach MB and NG. MB may have higher concentrations of silica compared to NG, as stones contain more percentage of crystalline silica compared to iron ore.

3.3.8. Chlorine (Cl)

At the significance level of 0.004, the interaction between sampling location and sampling period was not statistically significant ($p = 0.063$). Furthermore, there was no significant change in chlorine concentrations at either sampling location ($p = 0.307$) or across the years of sampling ($p = 0.171$). Industrial wastewater discharge from chemical, petrochemical, pharmaceutical and other manufacturing industries is among the major anthropogenic sources of chloride pollution in water resources [68]. For example, the Ggaba treatment plant, which is operated by National Water and Sewage Corporation, utilises chlorine to disinfect pipes using techniques such as pipework chlorination, which ensures water quality by eliminating harmful microorganisms [69]. Discharging of waste from the disinfected pipes into MB increases the level of chlorine concentration in the catchment area. On the other hand, Nile Breweries Limited is a beer manufacturer in Uganda and is located in Jinja. Nile Breweries Limited is among the factories that discharge its wastewater directly into Lake Victoria [38], subsequently increasing the amount of nutrients like chlorine in NG.

3.3.9. Dissolved Oxygen (DO)

There was no statistically significant interactions between the two sampling location and years of sampling ($p = 0.457$) regarding the concentration of dissolved oxygen. The levels of dissolved oxygen showed no significant effect at either the sampling location or across the years of sampling. Increased nutrient pollution, particularly from phosphorus and nitrogen, can fuel the excessive growth of algae and phytoplankton and when they die off [70,71], their decomposition by bacteria uses large amounts of oxygen, which deplete dissolved oxygen levels [71,72]. Increased water temperature also reduce the ability of water to hold dissolved oxygen [73], and this is because warmer water temperature increases the metabolic rates of fish and other aquatic organisms, causing them to consume more oxygen [74–77]. Therefore, the increased oxygen demand depletes the dissolved oxygen levels in warmer water.

3.3.10. Temperature

There was a significant interaction between the sampling locations and the sampling period ($p < 0.001$), indicating that the relationship between the sampling locations and temperature varied across the years of sampling. Water temperature is a critical parameter that must be carefully managed to protect the health and functioning of aquatic ecosystems. Climate change is a major driver of increasing water temperatures in rivers, lakes and oceans around the world. As air temperatures rise because of climate change, more energy is transferred to water causing it to heat up. The temperatures in Uganda have been increasing since the 1960s, with average temperatures rising by 1.3 °C and projected to increase by 1.8 °C by the 2050s [78]. Therefore, this has impacted water temperatures in both NG and MB.

3.3.11. Total Dissolved Solids (TDS) and Total Suspended Solids (TSS)

There was no significant interaction between sampling locations and the sampling period for both total dissolved solids ($p = 0.833$) and total suspended solids ($p = 0.919$). For total dissolved solids, the concentration showed no significant change at either the sampling locations ($p = 0.957$) or during the sampling period ($p = 0.852$). Additionally, total suspended solids concentrations showed no significant difference between the sampling locations ($p = 0.733$) or across the years of sampling ($p = 0.944$). The data collected indicate that the concentration of total dissolved solids and total suspended solids in MB is higher compared to NG. Nakivubo channel is a major source of total dissolved solids and total suspended solids polluting MB [79]. The Channel carries wastewater from Kampala city, including untreated sewage from residential areas, industrial effluents, and partially treated sewage from the Bugolobi sewage treatment works. This wastewater contains high levels of suspended and dissolved solids. A study by Kabaalu [80] found high levels of total suspended solids in MB ranging from 20–80 mg/L, and this is attributed to the inflow of suspended solids from the Nakivubo channel. Similarly, a study by Angiro [81] on the total dissolved solids concentrations ranged from 47 mg/L to 370 mg/L, with the highest values observed near the channel's discharge point.

3.4. Analysis of Nutrients Concentration According to Season and Their Threshold in Water Resources

Figure 3 revealed the relationships between the concentrations of nutrients and the sampling depth in MB and NG. The nutrient concentration was also compared between the dry and wet seasons to investigate any areas of variability between either season and or location. There are well-defined nutrient thresholds for water quality, although these can vary significantly depending on the unique properties of the water body and the methods used to develop them [82]. Exceeding these thresholds can indicate potential pollution issues that need to be addressed. The thresholds of the investigated nutrients were identified, though some thresholds differed based on the organisation (e.g., World Health Organisation (WHO) and Environmental Protection Agency (EPA)) and also according to standards within different countries. Nutrients such as potassium may have a minimum required level that the nutrient should not go below and also a maximum required level.

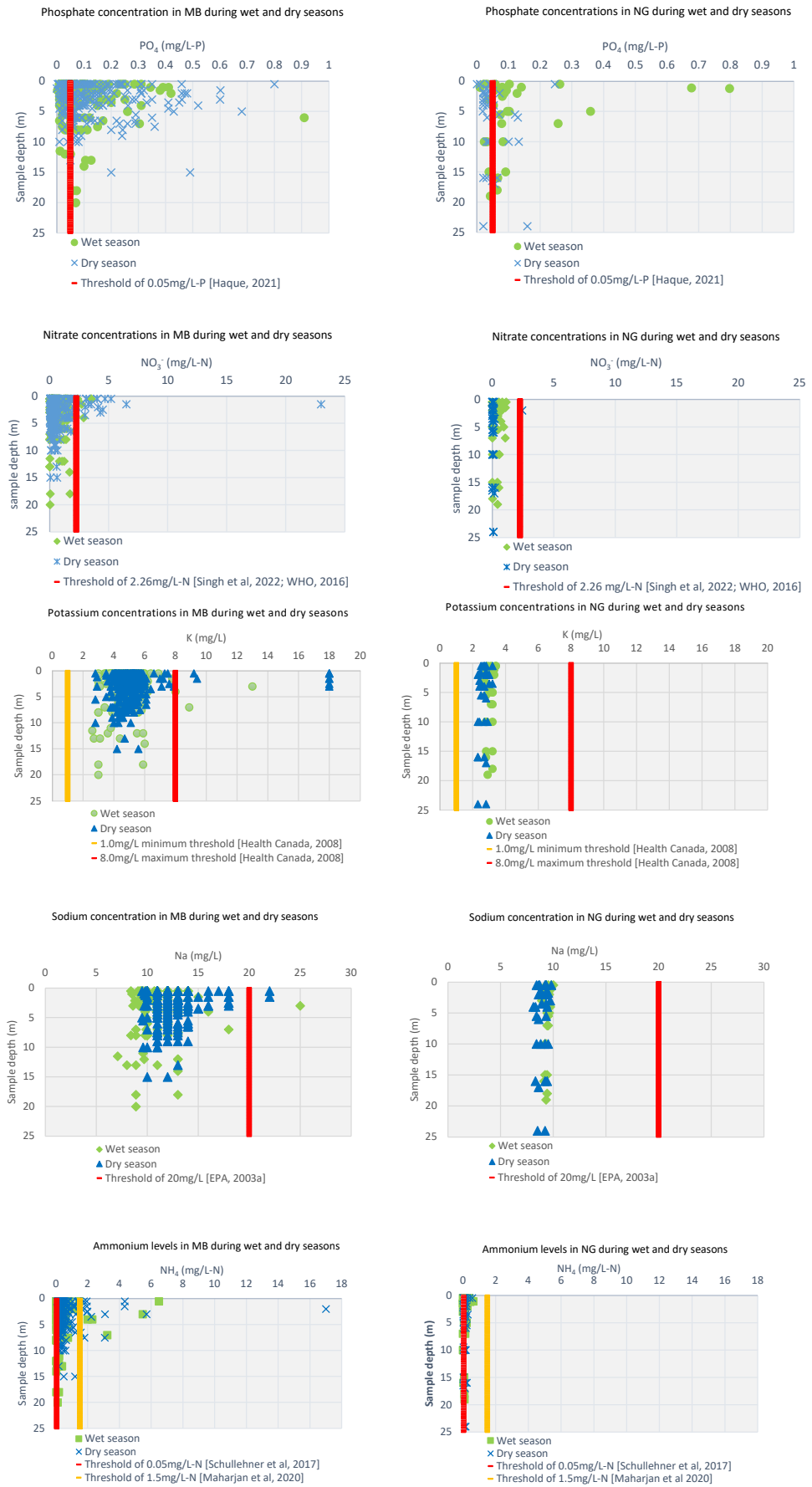


Figure 3. Cont.

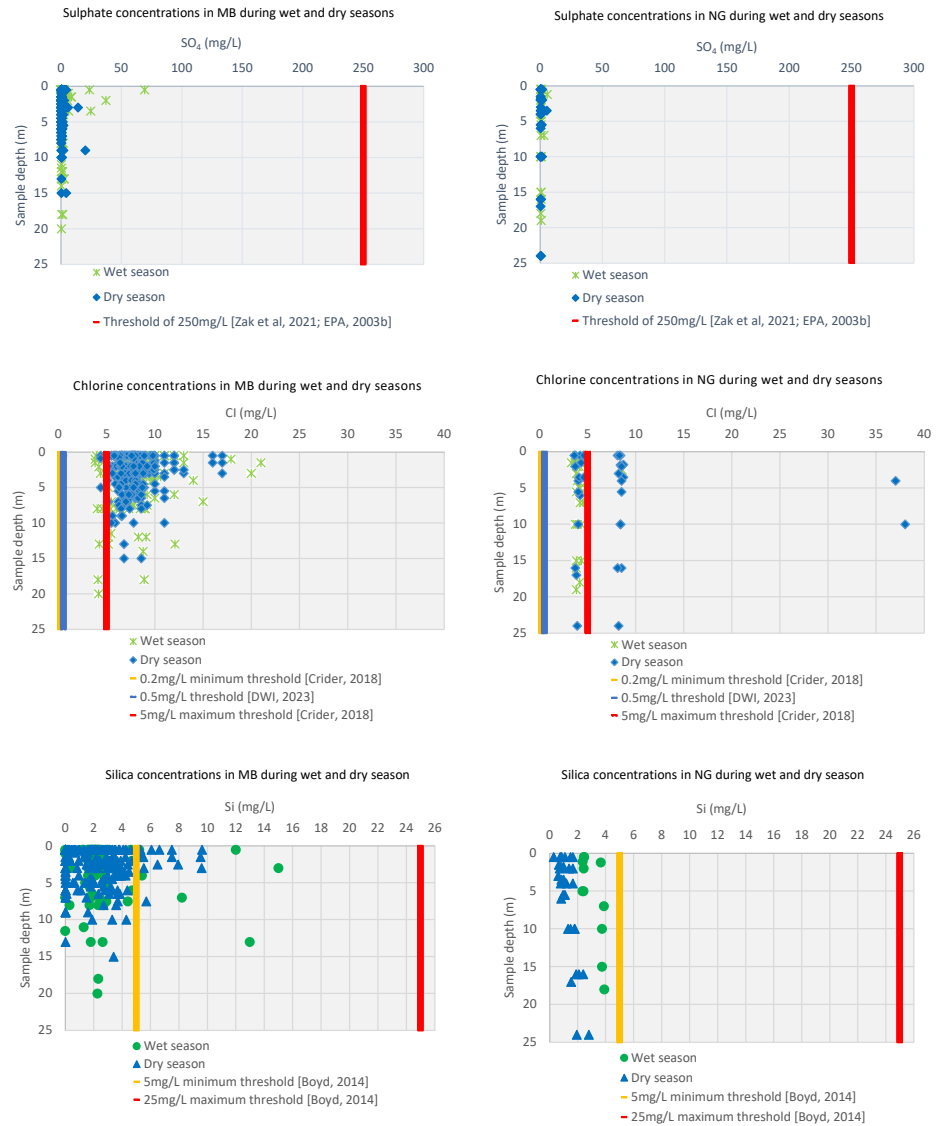


Figure 3. Cont.



Figure 3. The relationships between nutrient concentrations and other water quality variables and the sampling depth at both sampling sites [83–100].

3.5. Seasonal Nutrient Concentration and Associated Potential Implications for Exceeding the Threshold

As presented in Section 3.4, nutrient concentrations in both MB and NG exhibited seasonal fluctuations, with levels occasionally surpassing their recommended thresholds. Such exceedances are concerning because when nutrient concentrations rise above these thresholds, they can lead to potential consequences for both human health and aquatic ecosystems, as outlined in Table 5.

Table 5. Concentrations of nutrients in each bay according to the dry and wet season, as well as the potential consequences of the nutrients that have exceeded the recommended level of concentration in Lake Victoria.

Parameter	Murchison Bay	Napoleon Gulf	Performance against the Recommended Level	Potential Consequences
Phosphate (PO₄)	The average concentration of phosphate in the dry season was 0.13 mg/L-P compared to 0.10 mg/L-P during the wet season in Murchison Bay.	The average concentration of the nutrient in NG was 0.12 mg/L-P during the wet season, which was higher compared to 0.05 mg/L-P in the dry season.	According to Haque [83], the recommended limit for phosphate in a lake should not exceed 0.05 mg/L-P to maintain water quality and prevent contamination. Therefore, the average concentrations of phosphate nutrients in both MB and NG during the two seasons is above the recommended limit.	Excessive phosphate levels can stimulate the growth of algae, leading to algal blooms [83]. These blooms can reduce light penetration and lower oxygen levels, leading to the death of fish and other aquatic organisms. High phosphate levels can interfere with coagulation in water treatment plants [101] This can potentially lead to the incomplete removal of organic particles and microorganisms. This can affect the quality of water distributed for drinking.
Nitrate (NO₃)	The average concentration of nitrate nutrients was higher in the dry season (0.82 mg/L-N) than in the wet season (0.76 mg/L-N) in Murchison Bay.	The results from NG indicate that the abundant concentration of nitrate nutrients was in the wet season (0.40 mg/L-N) compared to the dry season (0.12 mg/L-N).	Maintaining nitrate levels in water below 2.26 mg/L-N is recommended to protect human health [84,85]. Therefore, the results obtained indicated that the average nitrate concentration in both the sampling sites is below the recommended limit.	High nitrate levels in drinking water can cause methemoglobinemia (blue baby syndrome), a life-threatening condition that affects the oxygen-carrying capacity of haemoglobin and can lead to cyanosis, shortness of breath, dizziness, headaches, coma and even death [102,103]. Elevated nitrate concentration in the body of a fish affects the food intake, growth rate, swimming performance, reproductive capacity and survival rate [104].
Potassium (K)	The concentrations of potassium in MB ranged from 2.60 mg/L to 13.00 mg/L in the wet season and 2.80 mg/L to 18.00 mg/L in the dry season.	In NG the concentration of potassium ranged from 2.70 to 3.40 mg/L during the wet season and 2.30 mg/L to 3.20 during the dry season.	The average potassium concentrations in drinking water generally range from 1.0 to 8.0 mg/L [86]. This indicates that the concentration of potassium in MB is above the permissible range limit.	High potassium levels in drinking water can impact individuals with kidney dysfunction, heart disease, hypertension and diabetes [105].
Sodium (Na)	The concentration of sodium in MB during the dry season ranged from 9.50 mg/L to 22.00 mg/L with an average value of 12.44 mg/L while its concentration during wet season ranged from 7.10 mg/L to 25.00 mg/L, with an average value of 12.44 mg/L.	The results of the study indicate that the concentration of sodium in NG during the dry season ranged from 8.10 mg/L to 9.80 mg/L with an average value of 8.96 mg/L though its concentration during wet season ranged from 8.90 mg/L to 10.00 mg/L, with an average value of 9.42 mg/L.	Sodium in drinking water should not exceed 20 mg/L [87].	More consumption of sodium may cause hypertension, congenital heart diseases, and kidney problems [106].
Ammonium (NH₄)	The results revealed that concentrations of ammonium in MB ranged from 0.07 mg/L-N to 17.00 mg/L-N in the dry season with an average of 0.66 mg/L-N though during the wet season it ranged from 0 to 6.48 mg/L-N, with an average of 0.27 mg/L-N.	The analysed data indicate that the concentration of ammonium in NG during the dry season ranged from 0.02 mg/L-N–0.58 mg/L-N, with an average 0.13 mg/L-N, while during the wet season it ranged 0–0.64 mg/L-N, with an average concentration of 0.16 mg/L-N.	In Demark, the standard for ammonium in drinking water is 0.05 mg/L-N [88]. The threshold proposed by the World Health Organization (WHO) guidelines for drinking water is 1.5 mg/L-N [89].	Consuming water with high ammonia levels can cause respiratory problems, skin and eye irritation, gastrointestinal issues, kidney damage and potential reproductive effects in humans [107].
Sulphate (SO₄)	The concentrations of sulphate in MB during the dry season ranged from 0.02 mg/L to 20 mg/L, with an average of 0.71 mg/L, while it ranged from 0 to 69 mg/L during the wet season, with the average of 1.72 mg/L.	In NG, the concentrations of sulphate during the dry season ranged from 0.20 mg/L to 5.30 mg/L, with an average of 0.63 mg/L, while it ranged from 0.20 mg/L to 5.65 during the wet season, with an average of 0.83 mg/L during wet season.	The recommended limit for sulphate concentration in freshwater is set from 0 to 250 mg/L [90, 91] to prevent hostile effects on both aquatic life and human health. Therefore, the concentration of the sulphate nutrients is far below the recommended limit in both catchment areas.	High sulphate levels in water bodies increase nutrient loads, promoting plant and algae growth, and depleting oxygen levels [71]. Excessive sulphate intake can cause various health issues in humans, such as diarrhoea, dehydration and gastrointestinal disorders [108].

Table 5. Cont.

Parameter	Murchison Bay	Napoleon Gulf	Performance against the Recommended Level	Potential Consequences
Chlorine (Cl)	According to the analysed data, the concentrations of chlorine in MB during the dry season ranged from 0.43 mg/L to 17.00 mg/L, with an average of 7.92 mg/L, and a range of 3.80 mg/L–21.00 mg/L, with an average of 7.96 mg/L during the wet season.	In NG, the concentration of chlorine during the dry season it ranged from 3.60 mg/L to 38 mg/L, with an average of 8.03 mg/L, and a range of 3.30 mg/L–8.60 mg/L, with an average of 4.17 mg/L.	According to the WHO and EPA, the concentration of residual chlorine in drinking water must be maintained ranging from 0.2 to 5 mg/L [92]; however, in England and Wales, the concentration of chlorine must not exceed 0.5 mg/L [93]. Therefore, the amounts of chlorine in the catchment areas of the lake were above the recommended limit.	High chlorine levels in water can cause chemical burns to fish and other aquatic species. Chlorine burns the gills and can be absorbed into the bloodstream, causing burns throughout their bodies [109,110]. High concentration of chlorine in water can cause dry, itchy skin and irritation, especially for individuals with sensitive skin [111].
Silica (Si)	The concentrations of silica nutrients in MB during the dry season ranged from 0.01 mg/L to 9.62 mg/L, with an average of 2.24 mg/L, and during the wet season it ranged from 0 to 15 mg/L.	In NG, during the dry season it ranged from 0.30 mg/L to 2.80 mg/L, with an average of 1.28 mg/L, and during the wet season it ranged from 2.34 mg/L to 3.90 mg/L, with an average of 3.04 mg/L.	The recommended level of silica in natural water usually ranges from 5 mg/L to 25 mg/L [94]; therefore, this indicates that the concentrations of silica nutrients in MB and NG were below the permissible limit.	Excessive silica nutrients can lead to the overgrowth of algae, including harmful algal blooms can decrease water quality and increase water treatment costs [112]. Harmful algal blooms can cause skin rashes in humans who come into contact with affected water bodies. When the algal blooms die and decompose, they consume large amounts of oxygen, leading to oxygen-depleted areas. This can suffocate fish and other aquatic organisms [112].
Temperature	The data revealed that temperature levels during the wet season ranged from 24.09 °C to 27.94 °C, with an average of 26.10 °C, while the temperature in the dry season ranged from 21.71 °C to 27.14 °C with an average of 25.72 °C.	The temperature in NG during the wet season ranged from 26.49 °C to 28.92 °C, with an average of 28.03 °C, during the dry season it ranged from 25.50 °C to 27.45 °C, with an average of 26.32 °C.	According Chrétien and Chapman [95], Nile perch are tolerant of a wide range of temperatures; however, temperatures above 31.5 °C are likely dangerous and potentially harmful.	High water temperatures can lead to reduced levels of oxygen, which can affect the fish by shortening their lifespan, reducing their physical sizes and reproduction rates [113].
Dissolved Oxygen (DO)	The results obtained indicate that the average amount of dissolved oxygen in MB during the dry season was 5.53 mg/L and 5.95 mg/L during the wet season.	In NG, the average amount of dissolved oxygen during the dry season was 6.14 mg/L and 8.00 mg/L in the wet season.	According to the Uganda National Bureau of Standards (UNBS) and National Environmental Standards and Regulations Enforcement Agency (NESREA), the recommended standard of DO level in surface water is 6 mg/L in Uganda and Nigeria [97]. DO below 5 mg/L is considered stressful for fish [96] and levels below 3 mg/L are too low to support most species [96].	Fish and other aquatic organisms require adequate dissolved oxygen levels to survive. Prolonged exposure to low dissolved oxygen levels (below 3 mg/L) can increase stress and lead to organism death [114,115]. Low dissolved oxygen levels can lead to changes in water colour, from light green to pea-soup green, brown, grey or black, indicating anoxic conditions [115].
Total Dissolved Solids (TDS)	The data show that the TDS level during the wet season ranged from 79.10 mg/L to 443.10 mg/L, with an average of 125 mg/L, while during the dry season it ranged from 0 to 361.20 mg/L, with an average concentration of 108.53 mg/L.	The TDS in NG during the wet season ranged from 86.80 mg/L to 97.30 mg/L, with an average of 89.06 mg/L, during the dry season it ranged from 85.40 mg/L to 91.00 mg/L, with an average of 87.81 mg/L.	According to the WHO [98], water with a TDS concentration of less than 300 mg/L is excellent for drinking while concentrations between 300 mg/L and 600mg/L is good for drinking; therefore, WHO recommends that TDS should not exceed 600 mg/L in drinking water; however, the EPA and Bureau of Indian Standards (BIS) have set an upper limit of 500 mg/L for TDS in drinking water [99,100].	Drinking water with high amount of TDS for prolonged periods may cause health conditions in humans, like cancer, kidney failure and diarrhoea [116]. Elevated TDS can lead to the near elimination of certain aquatic plant species like coontail [117] which provide cover and habitat for small fish to hide from predators, especially in clear ponds [118]. Furthermore, coontail supports aquatic insects that serve as food for fish species [118].
Total Suspended Solids (TSS)	The data revealed that the TSS level during the wet season ranged from 5.00 mg/L to 616.00 mg/L, at an average of 75.68 mg/L, while during the dry season, it ranged from 1.00 mg/L to 1770.00 mg/L, with an average concentration of 64.40 mg/L.	In NG, the concentration of TSS ranged from 1.00 mg/L to 40 mg/L, with an average of 6.43 mg/L, during the dry season it ranged from 1.00 mg/L to 64.00 mg/L with an average of 11.39 mg/L.	There was no threshold for TSS concentration in water resources was found for international organisations like WHO and EPA.	High TSS level in water resources decreases light penetration, affecting photosynthesis in aquatic plants and algae [119,120]. Excessive TSS levels affect water treatment processes, resulting in increased operational costs for drinking water and wastewater treatment plants [121]. Suspended particles can block the gills of fish and other aquatic species, causing to respiratory problems and even death [122,123].

4. Discussion

This study reveals that high toilet fees can be one of the reasons that contribute to the water pollution and nutrient contamination in Lake Victoria. Human urine contains potassium nutrients, though its concentration can vary based on factors, such as diet, hydration status and individual health conditions. According to Martin et al. [124], if urine is not diluted, its average concentration for potassium ranges from 2.2 to 2.7 g/L, though a study by Pael et al. [125] indicates that the average concentration of potassium in human urine is 1.0–2.0 g/L. The two studies differed in the average concentration of potassium in human urine; however, they both indicated that potassium is one of the nutrients that exist in human urine. In Kampala, toilet fees range from 200 to 600 Uganda shillings (USD 0.052 to 0.16) per use [126], which poses a financial burden for many, especially those living below the poverty line, where 30.1% of the population earns less than USD 1.77 per day [127]. High fees discourage the use of public toilets, leading many to resort to open urination and defecation, directly affecting water sources. The chairman at Ggaba landing site stated that, “Ggaba market has about 3000 people sharing only two toilets”. A fisher man who has been working on this landing site since 2021 revealed that, “there is a toilet fee any time you go to the toilet, each time you go to the toilet to urinate you pay 200 Uganda shillings (USD 0.052). I myself and some of my colleagues we urinate in the lake to avoid paying the toilet fee”. Studies by Liu et al. indicate that 60 percent of potassium in domestic sewage originates from urine, even though it only accounts for 1 percent of the total sewage volume. This issue is expected to worsen with increased urbanisation and population growth. Though toilet fees help fund the maintenance of sanitation facilities, they can be prohibitive for low-income communities, increasing pollution levels. Lowering fees could improve access to these facilities, reducing the amount of potassium entering Lake Victoria through urine.

According to this study, urbanisation and industrialisation have contributed to the increased nutrient concentration in Lake Victoria. The rapid and unplanned urbanisation around Lake Victoria [128], particularly in cities like Kampala, Jinja, and Entebbe, has led to increased impermeable surfaces and inadequate waste management infrastructure. This has resulted in the direct discharge of untreated sewage and nutrient-rich urban runoff into the lake or its tributaries [129,130], increasing nutrient loads, especially nitrogen and phosphorus. As shown in Section 3.3.1, that increase in detergent waste discharge directly in Lake Victoria could be one of the reasons for the increase in phosphate nutrients in the lake. Furthermore, Section 3.3.4 also indicates that the increased consumption of table salt by Ugandans has contributed to elevated sodium levels in water bodies due to sodium excretion through human urine. For industrialisation, the growth of industries around urban centres in the Lake Victoria basin has contributed to the discharge of industrial effluents containing high levels of nutrients and pollutants into the lake [129,131]. Even though the Ugandan government has set legal frameworks for managing water resources [132], but this study indicates a high concentration of nutrients to the extent that nutrients like phosphate, chlorine and silica are above the recommended international thresholds, as shown in Figure 3. This indicates that the existing measures are not enough to tackle the problem. Increasing the awareness of the public on how to manage water resources can play great role in reducing the direct discharge of waste into water resources. A study by Nalumenya et al. [132] revealed that increasing public awareness of how to manage water resources in Uganda is key to promoting sustainable water use and conservation.

The research demonstrated that excessive nutrient concentrations in Lake Victoria can lead to a decline in the fish population [133], which affects the fishing industry in Uganda. When nutrients like phosphate exceed the recommended threshold, as shown in Figure 3, this allows for excessive growth of algae and aquatic plants due to nutrient enrichment, forming dense algal blooms that deplete oxygen levels in the water. The algal bloom also blocks sunlight from reaching underwater plants causing them to die off [134]. The decomposition of this dead plant matter further reduces oxygen levels. The hypoxia (low oxygen levels) makes it difficult for fish and other aquatic organisms, like coontail, which act as their habitat, to survive. Fish death can occur when oxygen

levels drop below the threshold required for their survival [135], though different fish species have varying tolerances for low dissolved oxygen levels in water [136,137]. Nile tilapia (*Oreochromis niloticus*) is one of the most commonly fished and farmed species in Lake Victoria, and it has been found in waters with a low dissolved oxygen level of about 1.0–1.5 mg/L [137], despite the fact that the USEPA [96] recommends that dissolved oxygen levels below 3 mg/L are too low to support most species. Even if oxygen levels do not drop enough to cause direct fish death, the hypoxic conditions reduce the available fish habitat and can impact fish reproduction and growth, therefore leading to a decline in the fish population overtime. The decrease in the fish population makes it harder for fishermen to catch fish and sustain their businesses. According to UBOS [138], the fisheries sector accounted for 1.6% of Uganda's gross domestic product (GDP) in year 2019/2020. Fish exports from Uganda fell by 7992 tonnes between July 2020 and July 2021, a loss valued at around USD100 million. This decline in exports reflects reduced catches.

Nutrient concentrations in Lake Victoria vary across Uganda, Kenya, and Tanzania [16] due to different population density and more intensive agricultural and industrial activities. The northern part of Lake Victoria is more affected by the nutrient concentrations compared to any other part of the lake. The north part of the lake includes of Murchison Bay and Napoleon Gulf from Uganda and Nyanza Gulf from Kenya particularly around Kisumu. In Uganda, Murchison Bay is more highly polluted due to the high nutrient levels from urban runoff and agriculture activities. Kenya's Nyanza Gulf faces similar issues, where towns, industry, and agriculture account for over 86 percent of the nutrients and suspended sediments flowing into the Nyanza Gulf [139,140]. In Murchison Bay, the Chl-a concentration increased from 20 µg/L to 60 µg/L between the 1990s and the early 2000s [36,141], and it exceeded 100 µg/L [36,141]. Nyanza Gulf, in Kenya, experienced an increase in the Chl-a concentration from 3–5 µg/L to 40–60 µg/L between the 1960s and 2000s, with an extreme value of 650 µg/L in the Nyanza Gulf [36,142]. The southern and southwestern parts of the lake, being less industrialised and urbanised, generally have lower nutrient concentrations compared to the northern parts. Localised high nutrient levels near urban areas like Mwanza Gulf, though the Gulf has lower chlorophyll a concentrations (mean: 11–14 µg/L) compared to the northern gulfs [143]. Despite the varying nutrient concentrations in Lake Victoria across Uganda, Kenya, and Tanzania, all the three regions contribute to the lake's pollution. In order to mitigate this issue, the three countries need to combine the best options to create guidelines that will limit the discharging of untreated water into water resources and the inappropriate disposal of waste in and around water resources [132]. This requires strong collaboration among the national governments and local authorities to monitor and implement the laws to achieve a common goal [132].

According to this and previous studies, the concentrations of nutrients in Lake Victoria has increased overtime. Kabenge et al. [129] examined concentrations of nitrate and phosphate in MB between 1990 and 2011. The maximum concentration of nitrate grew from 0.084 mg/L in 1990 to 0.412 mg/L in 2011, whereas that of phosphate increased from 0.04 in 1990 to 0.58 mg/L in 2011 [129]. In addition, a study by Okello and Kurmayer [144] indicates a maximum concentration of ammonium in MB of 0.24 mg/L. Nutrients in NG have also risen, though less severely compared to MB. The maximum concentrations of nitrate in NG were 0.18 mg/L and 0.02 mg/L for ammonium [144]. As demonstrated in Table 1, the maximum concentrations of nutrients, such as nitrate, phosphate and ammonium, have increased compared to prior studies, and Section 3.3 discusses potential nutrition sources for MB and NG. The ongoing trend of increasing nutrient concentrations in Lake Victoria not only reduces the water quality but also poses a threat to human beings and water species, as shown in Table 5. Despite the overall trend of increasing nutrient concentrations in MB and NG, certain years have shown a decline in nutrient levels due to improvements in wastewater management and favourable climatic conditions, such as reduced rainfall leading to less runoff [129]. In 2018–2019, the concentrations of chlorophyll-a in Lake Victoria's nearshore and off-shore surface waters were 10.3 µg/L and 2.8 µg/L, respectively, which are lower than those measured in the 1990s (71 µg/L and 14 µg/L) [145].

5. Conclusions

Human activities in Uganda have led to the high nutrient concentrations in Lake Victoria. The study conducted revealed that the concentrations of nutrients (phosphate, nitrate, potassium, ammonium, sodium, sulphate, silica and chlorine) in both the dry and wet seasons over the five years (2016–2023) of sampling. The concentrations of the nutrients were significantly higher in MB compared to NG. When nutrient levels exceed the recommended thresholds, they become pollutants in the water resource, and they can affect the water quality, human health, and aquatic species. Aquatic species like fish are more likely to survive in NG compared to MG due to the high average level of dissolved oxygen in NG compared to MG for the dry season in both, as shown in Table 5.

The main key outcomes obtained from the study can be summarised as follows:

- The results of the analysis demonstrate that more often there were excessive concentrations of nutrients (such as phosphate, chlorine and silica) that may have a negative impact on the water quality Murchison Bay compared Napoleon Gulf;
- The study found that the dry season had higher average concentrations of nutrients (e.g., phosphate, nitrate, potassium, sodium and ammonium) in MB compared to the wet season, possibly due to the reduced water flow and nutrient dilution;
- The analysed results reveal that the wet season had higher average concentrations of nutrients (e.g., phosphate, nitrate, potassium, sodium, sulphate and silica) in NG than in the dry season, possibly due to increased runoff from agricultural land and urban areas, which carries more nutrients into the water;
- The study demonstrates that the human activities (such as urinating in water, car washing bays and poor pharmaceutical disposal) contributed more to the nutrient concentrations in Lake Victoria compared to industrialisation. However further research is required to investigate the direct impact of each specific nutrient.

The study suggests that the Ugandan government should regulate toilet fees so that they are affordable for any member of the public. It is recommended to increase the awareness of the public on how and why they should manage water resources in their societies. Furthermore, maintaining a consistent and adequate sampling rate, with equal sampling efforts in both Murchison Bay and Napoleon Gulf, is vital for generating accurate and comparable data on water quality.

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