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Water Quality of Lake Barombi Mbo, A Volcanic Crater Lake and Associated Point Sources

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A B S T R A C T

Lake Barombi Mbo is the main source of water for half a million people. Recurrent cases of Typhoid fever among users necessitated quality assessment of the source waters. We aimed to assess the water chemistry, coliform load and trophic status of this natural resource. Water samples were collected at sites within the lake and point sources. Physicochemical parameters were analysed using standard methods and means tested for significance using RTANOVA and Spearman rank correlation. Coliform load was determined and *Salmonella-Shigella* media used for the presence of *Salmonella typhi*. Most physicochemical parameters were within the WHO (2008) standards for fresh- recreational water except for $N-NH_4^-$ and bicarbonate ions. Annually, the lake receives 9610, 286.3, 189.2 and 26487 tons of HCO_3^-, $N-NH_4^+$, NO_3^- and SO_4^{2-} respectively with low release through the outlet. The lake was eutrophic, promoting macroalgae blooms. There is faecal contamination of water from the lake and all inlets as indicated by coliform counts >1100 CFU, and *Salmonella typhi* was present in significant numbers. This attests to anthropogenic influences on an ecosystem that is expected to be pristine. The results are significant for management of this and other watersheds in urban and peri urban areas susceptible to anthropogenic influences.

Introduction

Water supports life on earth and is one of the essential natural resources for existence and development of life (Rajagopal *et al*., 2010). The growing human population harnesses freshwater from streams, springs, rivers and increasingly, lakes. Humans frequently depend on lakes for many goods and services such as drinking water, waste removal, fisheries, agricultural irrigation, industrial activity, recreation and transport. Lakes are superb habitats for the study of ecosystem dynamics, which is the interactions between biological, chemical and physical processes in the ecosystem (Hairston and Fussmann, 2002). Although lakes contain less than 0.01% of all the water on the Earth's surface, they hold >98% of the liquid surface freshwater available for human use.The quality of water

in lake ecosystems is influenced by watershed processes; the geological, chemical and biological processes that occur onthe land and streams that lie uphill. The movement ofchemicals, sediments, detritus, and of many organisms, is typically unidirectional from the watershed to the lake. In consequence a lake and its watershed are often considered a single ecosystem (Likens, 1985).Watershed processes determine the kinds of materials that enter the lake, which in turn reflects these through changes in water quality (Dong *et al*., 2010). Thus where lake watersheds are prone to anthropogenic activities the potential for alteration of water quality increase drastically. Such activities typically include deforestation, agricultural activities, waste and sewage disposal, deliberate fish poisoning etc.These activities alter lake water quality through sedimentation, sewage contamination, agrochemical contamination etc., and the result is typically eutrophication, toxic algae blooms and contamination by enteric bacteria, rendering the water unfit for direct human consumption (Biradar *et al.*, 2014). The microbiological and physic chemical alteration of the quality of water is likely to arise from a variety of sources including application of agrochemicals and organic wastes, infiltration of effluents from sewage treatment plants, pits, lagoons and ponds used for storage (Aydin, 2007). In assessing the quality of water therefore, qualitative and quantitative indices are applied. Qualitative indices will include colour, odour and taste, and perhaps the general hygiene around the catchment. Quantitative indices provide definitive data on the quality of water and include characterization for algae community structure, enteric bacteria assessment, nutrients composition and chemical assessment; physical assessments such as pH, total dissolved solids and conductivity of the water are also necessary.

These factors have major influenceon quality of water.

In most of Africa South of the Sahara, portable water is typically sourced from rivers and streams. One exception is the water supply scheme in Kumba, a metropolis in South West Cameroon with a population of about half a million people, which depends on Lake BarombiMbo, a crater lake of volcanic origin which is also a Ramsar site. Lake BarombiMbo measures 2.5 Km across and 110 m deep, and in 2006 was designated a RAMSAR site by the government of Cameroon. It is located at 4°4´28N, 9°23´23E, and forms part of a protected reserve established in 1940 by order No. 17 of 1940 with a view to protecting existing flora and fauna in the area. It serves as a fishing ground, touristic site, transportation of agricultural and forest produce, and is the main source of water supply to the metropolis of Kumba.The lake is animated by five inlets whose flow balances the anthropogenic abstraction and outflow through a small outlet, and as such there is very little fluctuation in water levels.

However little is known about the water quality of the lake. According to (Giresse, 1991) quantitative water chemistry assessment was carried out in 1991 with very little work on bacteria evaluation. In the year 2010 a water pollution crisis occurred, but no follow-up studies on the underlying causes exists, and as the water continues to be abstracted for consumption there is increased risks to the human population. The purpose of this study was to assess the quality of water through physico-chemical and microbiological assessment. We hypothesized that the water source is unfit for drinking, and the treatment procedures from source to taps are barely effective.

Materials and Methods

Description of the study area

Lake Barombi Mbo is located at 4˚4´28N, 9˚23´23Eatan altitude of 301m asl. It is about 60 km NNE of the 4100 m high active Mt. Cameroon (Giresse *et al*., 1994) (Figure 1). It forms part of the *Cameroon Volcanic chain*, and is the largest *volcanic lake* in West and Central Africa. It is *radiocarbon-dated* at about 1 million years old (Giresse *et al*., 1994; Balgah and Kimengsi, 2011). The lake is animated by five streams, subsequently referred to as point sources in this paper. Fifteen species of fish have been recorded from the lake, 12 of which are endemic. The lake also has an endemic species of *sponge* (*Corvospongillathysi*), and an endemic species of *shrimp* **(**Caridina *sp.*).It provides portable water for the entire Kumbametropolis and its environs (Duker and Borre, 2001).

The Climate of the region is equatorial, and the SW Monsoon winds bring rain into the region from March-April to November. The dry season ranges from December to February. Typically rainfall averages 3,000 to 4,000 mm per year (Giresse *et al*., 1991).The mean annual temperature approximates 28 °C or even less as the altitude increases, with an annual humidity ranging from 70-84 %. The soil is covered by a 2-3 m thick fersialitic soil characterised by a common hydromorphic soils having bluish-gray colour.

Identification of study sites and samples collection

Sampling sites were identified during a reconnaissance survey in February 2014. Selection of sites took into consideration the different types of land uses and also the different point sources entering the lake.

Two sets of sampling sites were selected: Point Sources represent the inlet streams into the lake. Within the lake, sampling sites were also established. Details of the sampling sites and their characteristics are presented (Table 1).

Collection, Handling of Samples

Water samples

Three sets of surface water were collected in 0.5 L plastic bottles for chemical and bacteriological analyses from five Lake Sites (LS1 to LS5), one Outlet (LS6) and five Point Sources (PS1 to PS5). For bacterial samples, two additional samples were collected from a tap in town for comparison. Before collection, each container was rinsed several times with the surface water. Samples for bacterial analyses were stored at 0°C and analysed within six hours.

Samples Analyses

Physicochemical and nutrient analyses of water

Analyses for nutrients were done at the Plant and Soil laboratory in the University of Dschang and the following were analysed: Bicarbonate (HCO_3^-) (mg/l), Electrical conductivity (EC), Turbidity (NT), Nitrogen-Nitrate (N-NO_3^-), Sulphate (SO_4^2), Zinc (Zn), Calcium (Ca), Magnesium (Mg), Iron (Fe), Potassium (K), Sodium (Na), and Soluble Phosphorus (P Soluble) using standard methods (APHA 2005). Salinity and Total Dissolved Solid (TDS) were calculated from conductivity using the conversion factor described by Dohrman (2011) as used in Fonge *et al.*(2012).

Salinity = (conductivity) $^{1.0878}$ * 0.4665
TDS = conductivity µS/cm * 0.674

Total coliform count and *Salmonella* analysis

Total coliform count was carried out to assess levels of coliforms in the water. A set of samples was subjected to a presumptive test in the Life Sciences Laboratory of the University of Buea. Three sets of test tubes each containing lactose broth of increasing strength were inoculated with water samples and incubated for 24 hours at 35°C. The presence of cloudiness in the sample was indicative of the presence of coliforms. From the number of positive test-tubes in the presumptive test, the Most Probable Number (MPN) of coliforms was determined by referring to standard tables as described in Florida Lake Watch (2003).For bacteria isolation and characterisation *Shigella Salmonella* (SS) medium was used to isolate *Salmonella* and *Shigella* species (Florida Lakewatch, 2003).

Trophic status of the lake

The trophic status index (TSI) was determined based on phosphorus concentrations according to Carlson (1977) (Table 2):

TSI - P = 14.42 * Ln [TP] + 4.15 (in ug/L) (where TP = soluble phosphates concentration, Ln = natural logarithm).

A second trophic status index, the Euglenophycean Index based on phytoplankton composition, was also determined. For determination of Euglenophycean Index, three slides were prepared for each sample for quantitative and qualitative analysis. A complete phytoplankton biodiversity assessment is the subject of a separate study; for the current study, counts of species in divisions Chlorophyta, Cyanophyta and Euglenophyta were made using an Olympus BH-2 light microscope at magnification of 1000x. For abundance, cells were enumerated under a light microscope. Identification was done according to Nguetsop *et al*. (2007) and Nwankwo and Onyema (2003).

The Euglenophycean Index was calculated for each site as follows:

$$\text{Euglenophycean Index (EI)} = \frac{\text{Number of Species in Euglenophyta}}{\text{Number of species in both Chlorophyta and cyanophyta}}$$

When EI < 1, the site is eutrophic, and if EI > 1 the site is oligotrophic

Budgeting annual inputs and outputs of nutrients and other chemical compounds

The width and depth of the point sources were measured in 9 replicates, and the flow rate determined in three replicates. The concentrations were converted from mg/l to mg/m^3 by multiplying with a factor of 1000. The flow rate was calculated as follows:

$$\text{Flow rate} = \left(m^3/s\right) = \text{Stream width (m)} * \text{Depth (m)} * \text{speed} \left(m/s\right)$$

The nutrients and compounds released per year were calculated as follows:

Release (g/yr) = (Conc. (m3) * Flow rate (m/s) * 31536000)/1000

$$\text{Release}\left(\frac{g}{yr}\right) = \frac{(\text{Concentration (m}^3) * \text{Flow rate}\left(m^3/s\right) * 31536000}{1000}$$

Where 31536000 is a conversion factor, the number of seconds in a year; 1000 converts concentrations from mg to g. Results were subsequently converted to tons per year.

Data Analysis

Calculation of relevant indices was done as explained in the methods. Descriptive statistics was used to produce figures and tables. The means of the physicochemical

parameters were separated Rank-Transformed Anova with Tukey HSD test at α = 0.05, following negative tests for normality. These analyses were done at α=0.05 using Minitab version 16 statistical package (Minitab Inc., USA). Kruskal-Wallis test was carried out to compare bacterial contamination of water within the lake and the tap water. Spearman Rank correlation was done between physico-chemical characteristics of the point sources and lake sites to determine the relationships between the sites.

Results and Discussion

Physical characteristics of the water samples

Results of physical characteristics of the lake water and water from associated point sources are presented in Figure 2. The water was neutral-to-basic with significant differences (p<0.001) in pH between specific sites, but with no clear pattern between lake sites and point sources. The most basic site was PS1 with a pH of 8.13 while the rest of the sites had a pH between 7.0 and 7.9.Conductivity of water samples was below 0.3 mS cm^2, which is characteristic of fresh water. However, water from point sources had higher conductivity than water within the lake and this was significant (p<0.001). This pattern was consistent with the concentration of dissolved solutes (TDS) in the samples but was not reflected in the salinity which ranges between 0.02 and 0.03 psu and did not vary across sites (p = 0.064). Turbidity was significantly higher (p<0.001) in specific sites such as PS1 but there was no clear pattern between lake sites and point sources. Temperature of the lake was significantly higher than that of the point sources (P<001). Except for site LS1 at 24°C, temperature of sites within the lake ranged between 27.25 to 28.07°C compared to a range of 24.13 to 24.38°C for the point sources.

Chemical characteristics of the water samples

Concentrations of nutrients are presented in Figure 3. Concentrations of Nitrogen ammonium ranged from 1.4 to 2.7 mg/l. These concentrations differed significantly (p < 0.05) between specific sites but there was no clear trend between point sources and lake sites. The highest concentration (2.7 mg/l) in PS3 coincides with equally high concentrations in LS3 (2.25 g/l) and LS6 (2.03 g/l). Consistent with ammonium concentrations, nitrate concentrations were significantly higher in PS3 (1.8 g/l) with the least concentration in PS2 (0.33 g/l). Nitrate concentrations appear to fluctuate more in the point sources compared to the lake sites. Concentrations of sulphates ranged from 67.7 mg/l in site LS5 to 299.25 mg/l in site PS2. These differences were significant (p<0.05). Concentrations of magnesium were highest in Site PS3 (7.23 g/l) with the least in LS4 (0.55g/l). Just like sulphates, Calcium concentrations were highest in PS2 (17.45 mg/l) but equally high concentrations were found in LS2 and LS3 (11.45 mg/l). Bicarbonates were identified in all sites and ranged from 58.4 mg/l in PS5 to 321.1 mg/l in PS1.The point sources generally had higher concentrations of bicarbonate ions, for example 221.1 mg/l in PS1 and 109.8 mg/l in PS3. Concentrations of potassium (p = 0.76) and sodium (p = 0.07) were statistically similar across sites. Phosphate concentrations (data not shown) in both input sources and the lake sites were very low.

Table 3 presents correlations between the parameters in both point sources and lake sites. Sulphate concentrations in lake sites

correlate positively with pH of water in the point sources, which in turn correlates negatively with lake water temperature. Turbidity of point sources seems to be related to increased sulphate concentrations (ρ = 0.552, p = 0.012). Bicarbonate concentrations in point sources correlate positively with lake Mg concentration (ρ = 0.547, p = 0.013). Point sources contribute significant quantities of Mg to the lake (ρ = 0.839, p = 0.000). Concentrations of Mg in the lake also correlate positively with Mg concentrations in the point sources (ρ = 0.803, p = 0.000). Salinity of lake water correlates positively with that of point sources (ρ = 0.554, p = 0.011).

Comparing the water physicochemical parameters of Lake Barombi Mbo with international standards

When compared with international standards, pH values fell within the WHO (2008) permissible range of 6.5-8.5 mg/l for drinking water (WHO, 2008). Electrical conductivity was very far below the WHO (2008) permissible limit of 1000 uS/cm^2. Ammonium Nitrate concentrations were higher than WHO standards of 0.5 mg/l. Nitrate concentrations were within acceptable WHO (2008) limits of 45mg/l, likewise sulphates, which were below 250 mg/l. Concentrations of bicarbonates were far higher than the acceptable limits (5 mg/l), but concentrations of Sodium, Magnesium and Calcium were within the permissible limits.

Water quality indicators of pollution in Lake Barombi

Assessment of Euglenophytes, Cyanophytes and Chlorophytes for the Euglenophycean Index showed that there were 26 pollution indicator species in the lake and 22 in the point sources. Of these the most abundant were *Microcystis aeruginosa* (Cyanophyta),

Trachelomonas caudata (Euglenophyta) and *Euglena mutabilis* (Euglenophyta).A complete spectrum of phytoplankton community structure is the subject of a separate study; for the current study, counts of Chlorophyta, Euglenophyta and Cyanophyta were used to calculate the Euglenophycean Index presented in Table 4. The tropic status (TSI) of the point sources showed that the water bodies were colonised mostly by eutrophic species; the Euglenophycean Index shows that PS4 and PS 5 were the main eutrophic sites. Thus the point sources PS4, PS5 and all lake sites were eutrophic. This eutrophication is further evidenced by floating macroalgae blooms at LS3 (Figure 4).

Microbiological profile

Coliform bacteria were present in all sites except the outlet (LS6), with extremely high numbers in all the Point Sources (>1100 CFU/100ml) compared to lake sites (Table 5).*Salmonella typhi* was also present in all the Point sources and in the lake sites. No coliform or *Salmonella* bacteria were identified in the tap water. All the sites were associated to poor water quality containing coliform bacteria and high correspondence with *Salmonella typhi*.

Synthesis

Figure 5 synthesises the results of the research. It presents inputs per year from all sources, and outputs from the outlet. The quantity of outputs is a function of the size of the streams. Point sources 4 and 5 account for most of the inputs into the lake. Each year PS5 accounts for 272.6 tons of N-NH_4^+, 177.2 tonsNO_3^-, 25.4tons $SO_4^{2-}$and 490.3tons of K. This is followed closely by PS4 which accounts for 10.5tons N-NH_4^+, 10.3 tons NO_3^-, 779.5tons SO_4^2 and 25.1tons of K annually.

Table.1 Coordinates (Universal Transverse Mercator) of all Sampling points and sites

STUDY SITES	COORDINATES		Description
Point Source 1 (PS1)	Latitude	545360	Point Source 1 is a small, approximated 40cm wide stream that passes through a small cocoa farm before emptying into the lake
	Longitude	516184	
	Elevation	327	
Point Source 2 (PS2)	Latitude	544959	Point Source 2 is about 60cm wide and is found within sampling plot one of the terrestrial ecosystems
	Longitude	516329	
	Elevation	322	
Point Source 3 (PS3)	Latitude	544341	Point Source 3 is about 120 cm wide and also flows through a small cocoa farm
	Longitude	516393	
	Elevation	336	
Point Source 4 (PS4)	Latitude	543534	It flows through the village, and has a cloudy appearance. About 120cm wide. It carries all the organic debris and wastes from the small village into the lake
	Longitude	516109	
	Elevation	308	
Point Source 5 (PS5)	Latitude	543779	Point Source 5 flows through the largest cocoa farms in the BarombiMbo neighbourhood before emptying into the lake. It is about 640 cm wide
	Longitude	515975	
	Elevation	318	
Lake Site 1 (LS1)			Lake water hits here before being discharged through the outlet.
Lake Site 2 (LS2)	Latitude	544606	Lake Site 2 was located at the centre of the lake.
	Longitude	515033	
	Elevation	314	
Lake Site 3 (LS3)	Latitude	543705	Lake Site 3 is located beside the BarombiMbo Village and it is the main region where point sources 4 and 5 discharge into the lake.
	Longitude	516106	
	Elevation	314	
Lake Site 4 (LS4)	Latitude	543983	There are no point sources close to this site

	Longitude	514398	
	Elevation	315	
Lake Site 5 (LS5)	**Latitude**	543920	
	Longitude	516337	There are no point sources close to this site
	Elevation	305	
Lake Site 6 (Outlet) (LS6)	**Latitude**	545391	
	Longitude	514125	This is the point at which water exits the lake and it is about 168 cm wide
	Elevation	298	

Table.2 Trophic status of the lake based on

	Trophic Status Index and water quality
<30	Oligotrophic; clear water; high DO throughout the year in the entire hypolimnion
30 – 40	Oligotrophic; clear water; possible periods of limited hypolimnetic anoxia (DO =0)
41 – 50	Moderately clear water; increasing chance of hypolimnetic anoxia in summer; fully supportive of all swimmable/aesthetic uses
51 – 60	Mildly eutrophic; decreased transparency; anoxic hypolimnion; macrophyte problems; warm-water fisheries only; supportive of all swimmable/aesthetic uses but "threatened"
61 – 70	Blue-green algae dominance; scums possible; extensive macrophyte problems
71 – 80	Heavy algal blooms possible throughout summer; dense macrophyte beds; hypereutrophic
>80	Algal scums; summer fish kills; few macrophytes due to algal shading; rough fish dominance

Table.3 Correlation between physico-chemical parameters of water samples from point sources and those from the lake sites

		pH	Conductivity	Turbidity	Bicarbonates	N-NH4-	N-NO3-	Ca	Mg	K	Na	Sulphate	Carbonates	TDS	Salinity
Lake Sites	pH	-0.167	-0.388	-0.068	-0.283	-0.149	0.592	-0.341	0.236	0.312	-0.324	-0.200	-0.130	-0.388	-0.079
		0.481	0.091	0.774	0.227	0.530	0.006	0.141	0.317	0.181	0.163	0.398	0.584	0.091	0.741
	Conductivity	0.300	0.214	0.413	0.368	0.485	0.065	0.203	0.457	0.265	0.309	0.330	0.564	0.214	0.554
		0.198	0.366	0.070	0.110	0.030	0.787	0.390	0.043	0.259	0.185	0.155	0.010	0.366	0.011
	Nitrates	0.189	0.137	0.136	0.034	-0.424	-0.103	-0.134	-0.198	0.271	-0.474	-0.317	-0.169	0.137	0.195
		0.425	0.564	0.566	0.887	0.063	0.665	0.575	0.402	0.247	0.035	0.174	0.477	0.564	0.410
	Calcium	0.002	0.186	-0.034	0.268	0.329	-0.079	0.566	0.633	-0.091	0.011	0.706	-0.115	0.186	-0.185
		0.992	0.433	0.887	0.253	0.156	0.740	0.009	0.003	0.701	0.963	0.001	0.628	0.433	0.434
	Mg	0.339	0.462	0.296	0.547	0.448	-0.121	0.727	0.839	0.266	0.118	0.803	0.139	0.462	0.020
		0.144	0.040	0.205	0.013	0.048	0.613	0.000	0.000	0.258	0.622	0.000	0.559	0.040	0.934
	Sulphates	0.533	0.370	0.552	0.309	0.256	-0.065	-0.006	-0.035	0.093	0.140	-0.063	0.626	0.370	0.481
		0.016	0.108	0.012	0.185	0.276	0.787	0.980	0.882	0.697	0.556	0.790	0.003	0.108	0.032
	Temperature	-0.575	-0.361	-0.616	-0.388	-0.233	0.016	-0.027	-0.109	0.366	-0.254	0.054	-0.736	-0.361	-0.430
		0.008	0.118	0.004	0.091	0.322	0.946	0.909	0.648	0.113	0.280	0.822	0.000	0.118	0.059
	TDS	0.300	0.214	0.413	0.368	0.485	0.065	0.203	0.457	-0.265	0.309	0.330	0.564	0.214	0.554
		0.198	0.366	0.070	0.110	0.030	0.787	0.390	0.043	0.259	0.185	0.155	0.010	0.366	0.011
	Salinity	0.301	0.214	0.413	0.369	0.485	0.064	0.203	0.456	-0.265	0.310	0.330	0.564	0.214	0.555
		0.197	0.365	0.070	0.110	0.030	0.789	0.390	0.043	0.258	0.184	0.155	0.010	0.365	0.011

Point Sources (column grouping header)

Table.4 Trophic Status of Lake BarombiMbo

Sites	EI	TSI(TP)	% oligotrophic	% mesotrophic	% eutrophic	Total indicators species
PS1	1.50	37.40	22.20	0.00	33.30	9.00
PS2	2.50	60.60	28.60	0.00	57.10	7.00
PS3	1.33	37.40	15.40	7.70	46.20	13.00
PS4	0.40	106.40	12.50	5.00	47.50	40.00
PS5	0.23	112.20	14.30	2.90	34.30	35.00
LS1	0.12	17.80	10.00	4.00	36.00	50.00
LS2	0.40	37.40	35.30	0.00	23.50	17.00
LS3	0.17	110.50	11.00	3.10	34.40	64.00
LS4	0.18	37.40	12.20	2.40	29.30	41.00
LS5	0.11	100.90	14.60	2.10	35.40	48.00
Outlet	0.00	57.30	15.00	0.00	60.00	20.00
Mean		**60.22**	**16.35**	**1.93**	**36.43**	**40.00**

EI = Euglenophycean Index. When EI < 1, the site is eutrophic; when >1, the site is oligotrophic

Table.5 Incidence of coliform bacteria and Salmonella typhi in the Point sources

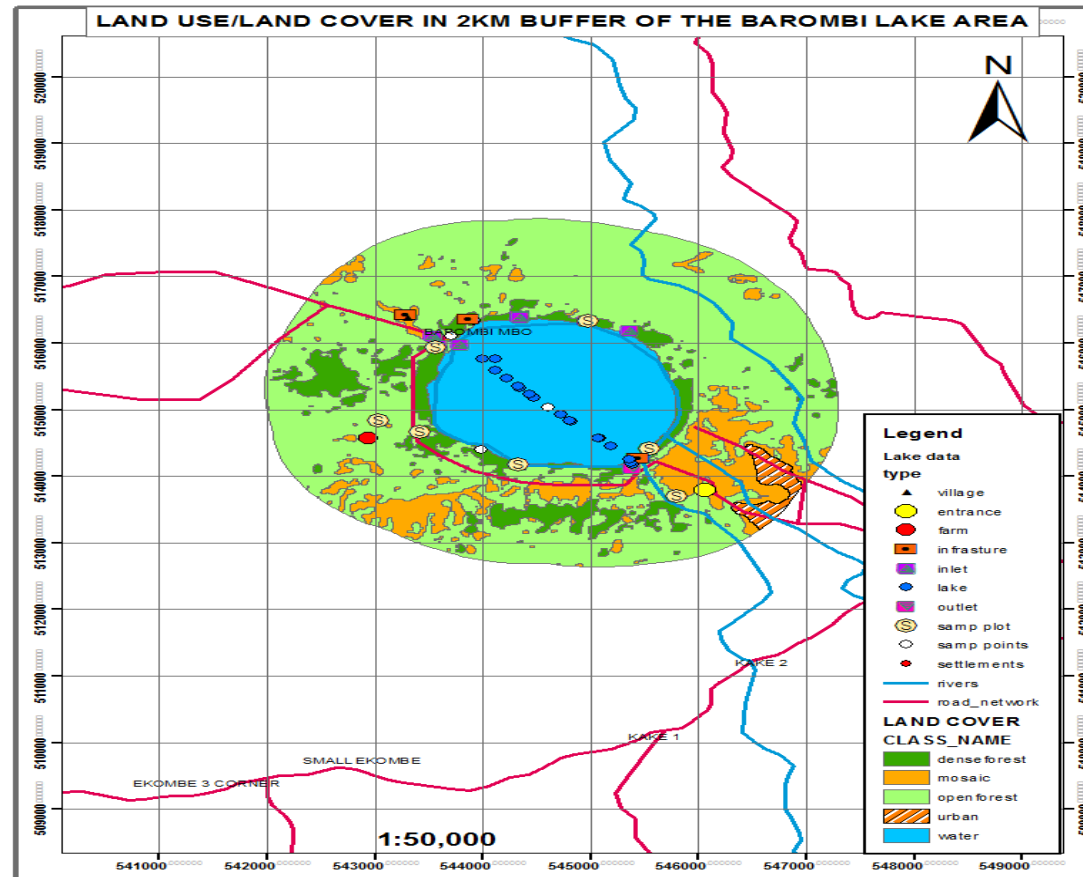|	Replicate 1		Replicate 2	
Sites	**CFU/100ml**	*Salmonella typhi*	**CFU/100ml**	*Salmonella typhi*
PS1	> 1100	Present	1100	Present
PS2	1100	Present	1100	Present
PS3	>1100	Present	1100	Present
PS4	>1100	Present	>1100	Present
PS5	>1100	Present	1100	Present
LS1	93	Present	0	Absent
LS2	150	Absent	4	Present
LS3	23	Present	75	Present
LS4	150	Absent	93	Absent
LS5	28	Present	9	Absent
LS6	23	Absent	>1100	Absent
Tap	0	Absent	0	Absent

Fig.1 Location of Lake BarombiMbo

Fig.2 Physical characteristics of water from the sampling sites. Solid bars portray sites within the lake, and clear bars portray point sources. Bars represent means. Means separated through Ranked Transformed ANOVA (RTANOVA) with Tukey HSD test at α = 0.05.Bars with the same letter are not statistically different.
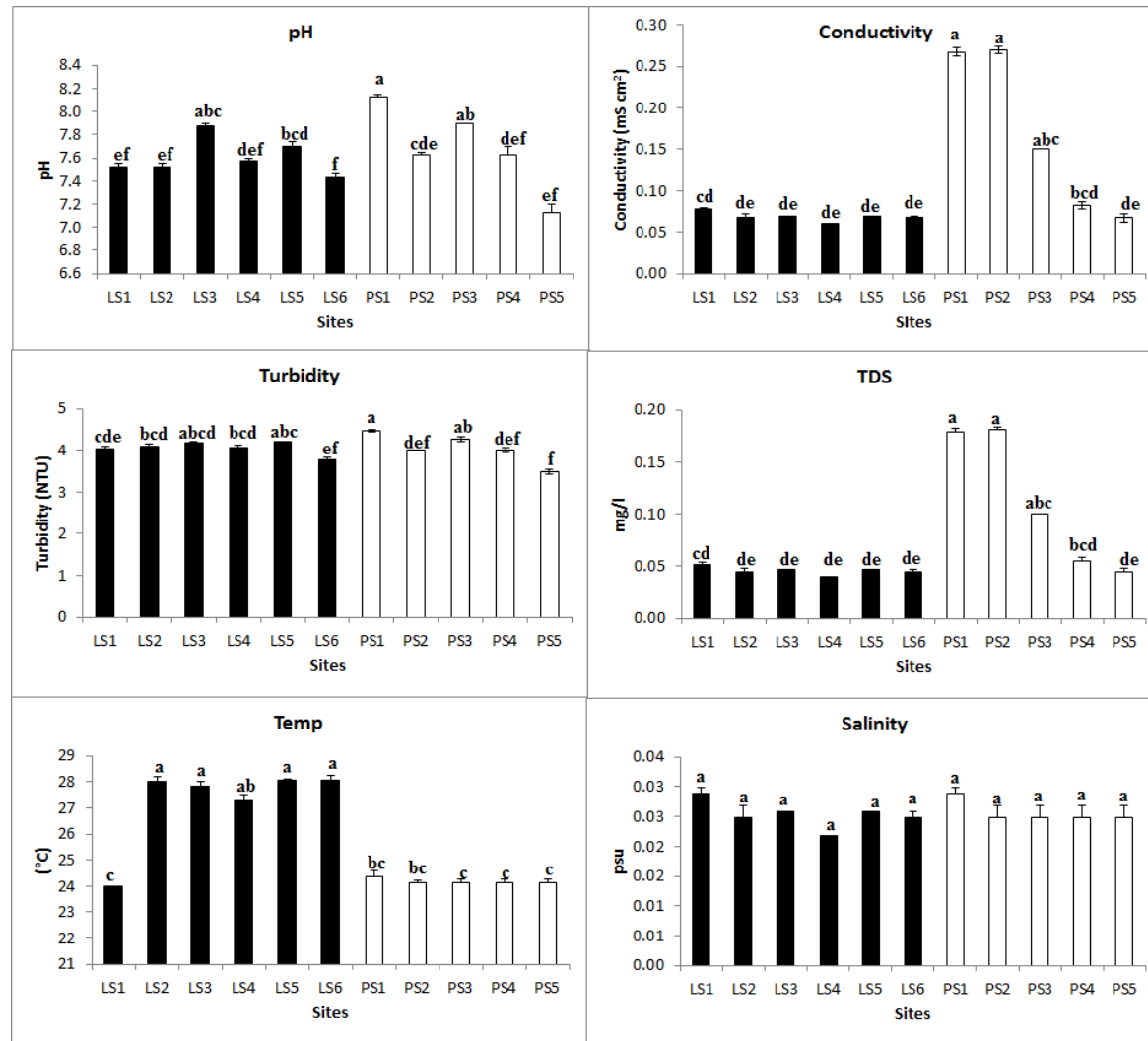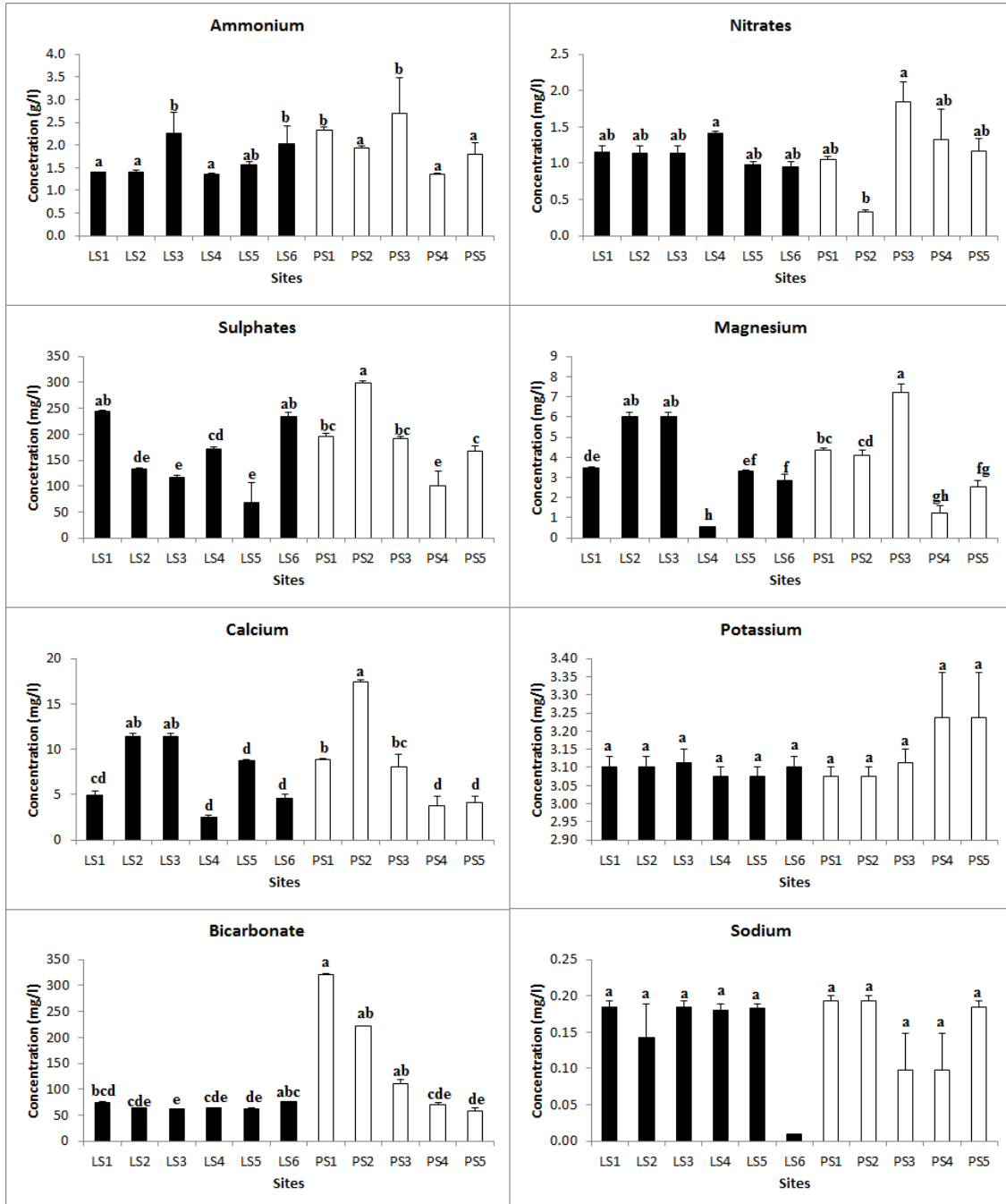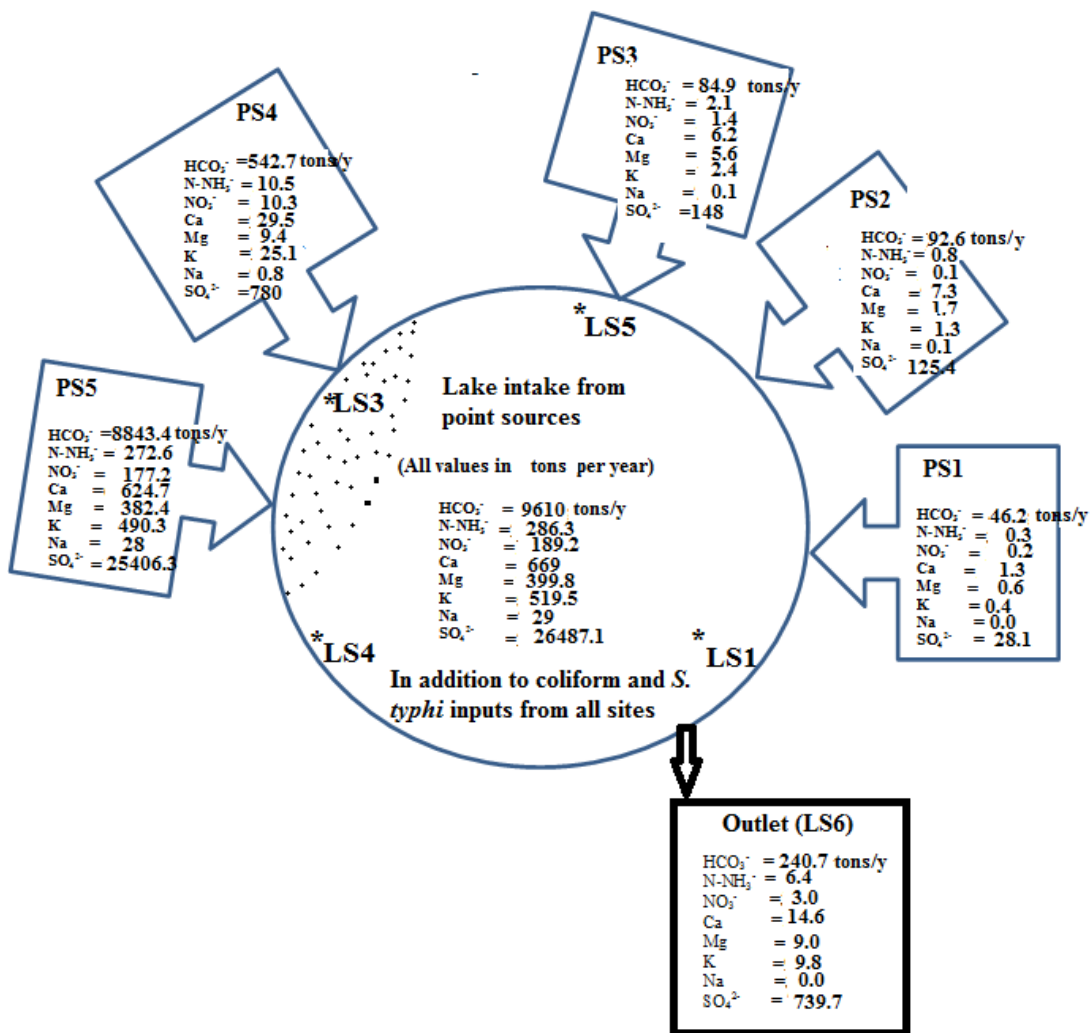
Fig.3 Chemical characteristics of water from the sampling sites. Solid bars portray sites within the lake, and clear bars portray point sources. Bars represent means. Means separated through Ranked Transformed ANOVA (RTANOVA) with Tukey HSD test at $\alpha = 0.05$. Bars with the same letter are not statistically different.

Fig.4 Floating macroalgae on lake

Fig.5 Synthesis of research results. All concentrations in tons/yr and do not include direct inputs into the lake by birds and other animals. We used mean flow rates, and did not account for direct inputs into the lake by animals, and output through anthropogenic abstraction.

These two sites are closely associated with LS3 in which blooms of macroalgae are common, and they drain sections of the watershed with high agricultural activities. The sites PS1, PS2 and PS3 contributed much less to the annual input (Figure 5). The outlet (LS6) drains 6.4tons $N-NH_4^+$,3 tons NO_3^-, and 9.8tons of K and 739.7 tons SO_4^{2-}. Concentrations of phosphates in both the input waters and the outlet (data not shown) were insignificant.

Physical characteristics of the water in both the lake and point sources are strikingly similar. The conductivity was characteristic of freshwater, with the neutral pH required for portable water. Within the lake, water temperature was significantly high, compared to the point sources, perhaps because of lack of canopy cover over the lake. Point sources on the other hand flow through forested landscapes and the close canopy probably accounts for the lower water temperature. Point sources contribute to the nutrient and chemical characteristics of the lake, as reflected in the ammonium, nitrates, sulphates, and magnesium and bicarbonate concentrations. These varied significantly between lake and point sources. At first glance the lack of a clear correlation between physico-chemical parameters of point sources and lake sites may suggest that point sources do not influence the massive lake. However, this is deceptive. As shown in Figure 5, annual inputs of nutrients are exceedingly high.

As water empties into the lake it brings with it nutrients and other matter, and all of these modify the water in the lake. Although a complete budget could not be derived, there is a great possibility of the lake being an overall sink of nutrients. Chemical characteristics of water are a function of several factors, top among which are the hydrology, the landscape through which the water flows and associated land uses. It has been shown for example, that the ionic composition of water reflects the weathering processes in the rock strata from which the river originates and through which it flows (Sarin *et al*., 1992). Lake BarombiMbo is of volcanic origin, while the surrounding landscape is rich in carbonates. This explains the presence of bicarbonates in the lake waters in spite of its volcanic origin; these come from the point sources which had significantly high concentrations in PS4 and PS5. This is shown in magnesium concentrations in point sources which correlated positively with that in lake sites, suggesting that the predominant carbonates in the surrounding rocks are those of magnesium and calcium.

Other nutrients and chemicals emanate from anthropogenic land uses. Fonge *et al*. (In Prep.) have comprehensively assessed the land uses around the lake. For the purposes of this paper, it suffices that farming activities around the lake make use of large quantities of agrochemicals which eventually find their way into the point sources through leaching, consistent with findings by other authors (Agrawal *et al*., 2010). These point sources in turn transport the nutrients into the lake. In turn, nutrients drive algae growth (Thornber *et al*. 2008). Phosphate and nitrate ions are limiting factors of algae growth (Elser *et al*., 2007). The Trophic Status Index (60.22) shows that the sites are mildly eutrophic. A phytoplankton diversity assessment should show the early stages of blooms. However, these are rare for two reasons: firstly, the point sources are perennial, some of them fast-flowing and this reduces resident times of the nutrients.

Thus much more nutrients are released into the lake than can be measured in real time. Secondly, once within the lake there is a

diluting effect – LakeBarombiMbo measures 2.5 km across and 110 m deep, thus it has a high dilution potential. One of the clearest physical indications of eutrophication in Lake BarombiMbois the macroalgae blooms at LS3. This site is close to the village, and two streams (PS4 and PS5) discharge here, bringing with them nutrient- and-potentially sewage-rich water from the village and the macroalgae blooms are thus indicative of this enrichment (Teichberg *et al*., 2010).

The presence of coliform bacteria in all samples is a clear indication of faecal contamination. According to USEPA (1986) the maximum limit of *Escherichia coli* in freshwater fit for use is 235 CFU/100ml in a single sample. Several sources could account for enteric bacteria counts, but all are of faecal origin e.g. human, birds, animals etc. (Pandey *et al*., 2014). Thus as the feeder streams (point sources to the lake) meander over land, there is contamination with sewage which is then transferred into the lake.

Indeed, evidence of *E. coli* multiplication in soil and subsequent contamination of water sources during high water events or floods has been reported (Solo-Gabriele *et al*., 2000; Ouattara *et al*., 2011) thus a single faecal contamination event has a potentially long resident time and high contamination potential. Of greater concern is the presence of *Salmonella typhi*, which has a potential to cause epidemics. Indeed, typhoid fever is endemic in the Kumba metropolis, but our control samples from tap water showed that the treatment procedures of the water supply company (CAMWATER) are effective; however should high flow overwhelm the treatment ponds for example in the rainy season, or if there is a slight breach of water treatment protocol, there is a high risk of *Escherichia coli* and *Salmonella typhi* contamination of the portable water system.

This has serious implications for public health, and poses challenges to management of watersheds and catchment in urban and peri urban areas in Africa as a whole. Although Lake BarombiMbo is part of the BarombiMbo National Park and is a Ramsar site, our studies reveal intensive anthropogenic activities have severely compromised the quality of water within the lake.

Ensuring quality and safety of portable water from this source requires a comprehensive strategy that begins with enforcing the laws creating and governing national parks, and implementing protocols that maintain Ramsar sites pristine. Only when the integrity of the source waters is ensured can we be assured of safe and portable water from our catchments. Our results have important implications for management of other watershed and catchments in urban and peri urban areas subject to anthropogenic activities.

In conclusion, the quality of water in Lake BarombiMbo is strongly influenced by point sources, which are in turn subject to anthropogenic influences

- The water is eutrophic, and this drives visible macroalgae blooms
- There is sewage contamination which is evidenced by high *E. coli* counts, and the presence of *Salmonella typhi* renders the water dangerous for human health
- However, when treated, the water is fit for drinking

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