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Limnological Survey of the Alkaline, Saline Crater Lakes of Western Uganda

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Abstract

Eight alkaline, saline crater lakes in western Uganda were surveyed between 26th February and 3rd March, 2014 with an aim of providing information on the physico-chemical features of these less known unique habitats and provide a basis for comparison with similar environments in other parts of the world. Lakes considered for this study included; Katwe, Kikorongo, Murumuli, Nyamunuka, Munyange, Bunyampaka, Bagusa and Maseche. Surface and Bottom measurements of physic-chemical parameters were measured in-situ from at least three geo-referenced points. Water samples for alkalinity, nutrients and detailed ionic analysis were taken from each of the points. In the laboratory, collected water samples were analysed following APHA standard operating procedures. All the studied lakes were alkaline and saline in nature as reported in the previous studies except Lake Kikorongo which was found to be fresh with a salinity of zero in this present study. With the exception of Lake Murumuli which was found to be a Carbonate-chloride lake, the rest of the sampled lakes are carbonate-sulphate lakes which is contrary to earlier studies which reported lakes like Katwe and Kikorongo to be Carbonate-chloride lakes.

Keywords: Alkaline, saline, carbonate-chloride, carbonate-sulphate, lakes

Introduction

The Western part of Uganda is richly endowed with crater lakes many of which are both alkaline and saline. They are small unique water bodies occurring in basin associated with the Western Rift valley. These lakes being small, alkaline and saline in nature this makes them have very unique physical and chemical characteristics in comparison to the big fresh water systems like Lake Victoria, Edward, Albert, Kyoga and George. Lakes Katwe, Munyanyange, Nyamunuka, Bagusa, Murumuri, Maseche, Bunyampaka and Kikorongo, all of which belong to the Katwe-Kikorongo volcanic field in western Uganda have been considered for this study. Lake Katwe with an average area of 2.5km^2 is the largest among these lakes (Nixon, Morton *et al.*, 1971: Kirabira, Kasedde *et al.*, 2013). This area has got volcanic soils, exhibits a relatively hot and dry climate and experiences a bimodal rainfall pattern with March – May and September – November being the rain seasons. This area has been reported to receive a mean annual rainfall range of 60 – 70cm with a mean monthly temperatures ranging between 19.0±2.8°C and 28.0±3.2°C. The dominant vegetation is mainly savannah grassland and dry woodland mosaic (Mungoma, 1990). The majority of these lakes are alkaline in nature and exhibit considerable temporal variations in volume and surface area. The total depth of the lakes have been reported to range between <1 – 6m (Kirabira, Kasedde *et al.*, 2013). Stable alkaline conditions in previously studied alkaline systems have been attributed to a unique combination of climate, geological and topographical conditions (Grant, 2006). These lakes have been categorized by earlier studies into three group; carbonate-chloride, sulphate-chloride or chloride lakes depending on the dominant anion(s) (Mungoma, 1990; Camargo, Durán *et al.*, 2005) while Matagi (2004) in a biodiversity assessment of the flamingo lakes of East Africa reported highly alkaline, hypersaline environments to be referred to as soda lakes (Matagi, 2004). Soda lakes have been described as the earth's most stable high pH environments (Grant, 2006). These lakes were reported to have a pH above 9.6 (Matagi, 2004; Grant, 2006). These lakes have been reported to be associated with low Mg^{2+}, Ca^{2+} geology with very high evaporation rates often exceeding their water inflows (Grant, 2006). Other areas other than the East African Rift Valley where such environments have been reported to occur include arid and semi-arid areas of tropical and / or subtropical rain-shadow deserts like in North America and continental interiors of Asia (Grant, 2006). The ionic composition and concentration in these lakes plays an integral role in determining their limnochemical characteristics and resource exploitation by the surrounding communities.

In Uganda, it is only lakes Katwe and Bunyampaka which are commercially exploited for common salt (NaCl) by the local communities (Matagi, 2004). The majority of these other alkaline, saline lakes have not been put to use.

In the past these lakes attracted a lot of attention because of their unique physico-chemical characteristics. In comparison to fresh water systems and other inland water bodies, the limnology and hydrobiology of saline systems have not been given as much attention in the recent studies (Stenger-Kovács, Lengyel *et al*., 2014). Despite the vast research done on these lakes which dates back from Beadle (1932, 1974), Holmes & Harwood (1932), von Knorring & DuBois (1961), Arad & Morton (1969), Kilham (1971a, b), Melack & Kilham (1972), Hecky and Kilham (1973), Melack (1976, 1978), Melack *et al.,* (1982) and so on, none of these research focused on the limnology of these lakes.

It is therefore the aim of this present study to conduct a limnological survey in selected alkaline, saline crater lakes in Western Uganda to provide information on the physico-chemical features of these less known unique habitats and provide a basis for comparison with similar environments in other parts of the world.

Materials and Methods

Study Area

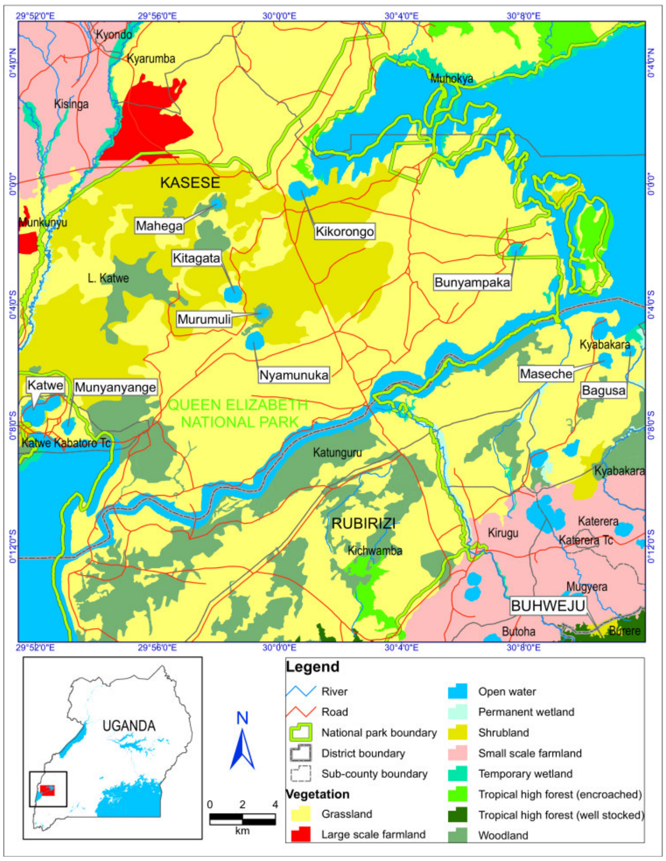

Figure 1; Map showing the selected Alkaline saline crater lakes of Western Uganda considered in this study

Lakes	Coordinates		Altitude	lake Surface Area	Average Depth (mean±SD)
	Long. E	Lat. N	(H a.s.l)	(Km2)	(M)
Katwe	029.87033˚E	00.13217˚S	897	2.45	2.1±0.7
Munyanyange	029.88591˚E	00.13513˚S	915		0.2±0.0
Nyamunuka	029.98743˚E	00.09344˚S	929		0.2±0.0
Murumuri	029.99186˚E	00.07323˚S	887		0.2±0.0
Bunyampaka	030.12819˚E	00.03765˚S	893	0.43	0.20±0.1
Bagusa	030.17958˚E	00.09793˚S	884		1.9±0.5
Maseche	030.19019˚E	00.09355˚S	918		1.3±0.2
Kikorongo	030.01228˚E	00.01190˚S	939	1.03	2.3±0.3

Table 1: Main geomorphology and hydrological characteristics of the studied lakes

General assessment of the lake environments

Data collection in this study was done between the 26th of February and 3rd of March, 2014, a period towards the end of the dry season in this region. A Global Positioning System (GPS) unit (GARMIN 12XL) was used to take GPS coordinates and the Altitude / elevation above sea level (H. a.s.l) of the different points of sample collection at each of the sampled lake. Visual observation of water color, number of fresh water inflows, and percent vegetation cover were made at each of the studied lake. Fringing vegetation in the littoral zone around each of the studied lake was characterized and the major plant species identified where possible.

Determination of physico-chemical parameters

At each lake, selected physical and chemical parameters (depth, temperature (T°C), dissolved oxygen concentration (DO), pH, Conductivity (Cond) and salinity) were measured at the Lake Surface and bottom *in situ*. Where lakes were too shallow, measurement were done at the lakes surface. Water temperature, dissolved oxygen concentration and conductivity were measured using a YSI oxygen/temperature/conductivity meter (Model YSI 550A), pH was determined using an OAKTON pH Tester 30, while salinity was measured with a refractometer. From each of the selected sampling point, Depth was determined using a portable depth finder (Hondex PS-7). The depth finder was lowered just below the water surface, while pointing to the lake bottom, the button was pushed and the depth reading was taken from the backlit screen in meters.

Surface water samples for chemical and nutrient characteristics of each of the studied lakes were collected using a Van Dorn water sampler from geo-referenced sampling points and stored in pre-rinsed Nalgene bottles for analysis in the laboratory. In the field all water samples in pre-rinsed Nalgene bottles were kept in a cooler box containing dry ice and later transferred to the National Fisheries Resource Research Institute (NaFIRRI) laboratory in Jinja. In the laboratory the collected water samples were analysed for the following parameters: alkalinity, bicarbonate (HCO_3), carbonate (CO_3), Sulphate (SO_4), Silicates (SiO_2), Chloride (Cl^-), Fluoride (F), Sodium (Na), Magnesium (Mg), Calcium (Ca), Potassium (K), and Hydrogen Sulphide (H_2S), Sodium, Magnesium, Calcium, Potassium, Chloride (Cl), Fluoride (F), and silcon following APHA 1975 standard Operating procedures.

Determination of Nutrients characteristics

Water samples for dissolved nutrients; soluble reactive phosphorus (SRP), ammonia-nitrogen ($NH_{3-}N$) and nitrite-nitrogen ($NO_{2-}N$) were, filtered through 47mm pore Whatman GF/C filter papers and analysed by spectrophotometric methods following procedures by Stantoin *et al.,* 1977. Water samples were also analysed for total suspended solids (TSS).

Results and Discussion

Lakes Munyanyange, Murumuri and Nyamunuka were reported by the locals to be seasonal lakes and sometimes evaporate to dryness during the dry seasons. Lakes Katwe, Bunyampaka, Bagusa and Maseche are permanent lakes with very high variations in water volumes between the dry and wet seasons reported by the locals (Table 2). Lakes Katwe, Bunyampaka, and Maseche waters were found to be pea-nut soup green in color (figure 3) while lakes Nyamunuka and Murumuri waters were dark green in color. Lakes Kikorongo and Munyanyange waters were greenish in color. Lake Bagusa waters were pinkish along the shore and reddish brown offshore (figure 2).

Figure 2; *Cyprus lavigatus* with the Pinkish waters near the shores of lake Bagusa which turns reddish brown towards the middle of the lake.

Figure 3: Pea-nut soup green waters from Lake Katwe

Lakes Katwe and Munyanyange had the lowest vegetation cover, estimated to be 35% and 45% respectively. This was followed by Lake Bunyampaka with an estimated vegetation cover of 60%. The rest of the other studied lakes had a vegetation cover estimates of 75% and above (Table 2). Lakes Katwe, Bagusa and Maseche were found to have freshwater wetlands surrounding them in some parts. *Cyperus lavigatus*, savannah woodland dominated by Acacia woodland and *Euphorbia candelabra* were the dominant vegetation surrounding these lakes.

Table 2; Selected environmental characteristics of the selected alkaline, saline Lakes of Western Uganda

Lake	**General environment characteristics**			
	Seasonality	**Waters**	**% Vegetation cover**	**Fringing vegetation**
Katwe	Permanent but experience variations in water volume	Thick, slimy &Peanut soup green in color	35	Acacia woodland, *Euphorbia candelabra*, savanna grassland and *Cyperus lavigatus* on the shoreline
Munyanyange	Seasonal, sometimes evaporates to dryness in dry season	Slimy & green in color	45	Savannah grassland, scattered thorny shrubs, *Euphobia candelabra,Cyperus lavigatus*
Nyamunuka	Seasonal, sometimes evaporates to dryness in dry season	Thick slimy &Dark green in color	80	Savannah grassland Woodland and scattered shrubs
Murumuli	Seasonal, sometimes evaporates to dryness in dry season	Thick slimy &Dark green in color	90	Acacia woodland
Bunyampaka	Permanent but experience variations in water volume	Thick slimy &Peanut soup green	60	Woodland dominated by *Euphorbia candelabra*. Other plant species include: *Acacia siberiana*, wild palms, *Caparis tomentosa*. Shoreline has wetland dominated with *Cyperus lavigatus* and wild palms.
Bagusa	Permanent but experience variations in water volume	Thick, slimy, Pinkish on shore and Reddish-brown offshore	80	Grassland, woodland, wild palms. Shoreline dominated by *Cyperus lavigatus*
Maseche	Permanent but experience variations in water volume	Thick slimy &Peanut soup green in color	75	Grassland, woodland, wild palms. Shoreline dominated by *Cyperus lavigatus*
Kikorongo	Permanent but experience variations in water volume	greenish in color	80	Grassland, shrubs and woodland.

Physical characteristics of selected alkaline, saline lakes

Table 3; Mean±SD of *in-situ* measured of selected physical characteristics of the study alkaline, saline crater lakes of Western Uganda

Lake	Mean ±SD					
	Depth (m)	D.O (mgl^{-1})	pH(-)	Temp. (^oC)	Salinity(mgl^{-1})	Cond ($mscm^{-1}$)
Katwe	2.1±0.7	2.6±0.2	9.9±0.1	27.9±0.3	180±67.8	104.5±6.4
Munyanyange	0.2±0.1	1.7±0.4	10.8±0.4	34.4±2.4	101.0±7.1	59.7±8.2
Nyamunuka	0.2±0.2	2.6±0.3	11.5±1.0	30.5±3.1	205.0±15.3	10.5±0.6
Murumuri	0.2±0.0	1.7±0.5	11.1±1.3	32.0±0.8	162.8±34.2	106.3±3.5
Bunyampaka	0.20±0.1	2.20±0.6	9.58±0.1	30.33±1.5	199.50±16.4	103.90±4.3
Bagusa	1.9±0.5	3.2±0.8	10.5±0.4	32.1±2.0	199.5±16.4	103.9±4.3
Maseche	1.3±0.2	2.9±0.4	10.9±0.4	30.0±0.7	92.3±7.6	71.2±1.3
Kikorongo	2.3±0.3	6.0±1.0	10.4±0.0	28.9±0.4	0.0±0.0	18.6±0.1

With the exception of Kikorongo whose average depth was above 2m, the rest of the sampled lakes where found to have an average depth less than 2m. The highest measured dissolved oxygen (DO) was 6.0±1.0mg/l measured in Lake Kikorongo, followed by lakes Bagusa and Maseche which had D.O levels of 3.2±0.8 and 2.9±0.4mg/l respectively. In all the sampled lakes the pH was high above neutral ranging between 9.58±0.1 and 11.5±1.0, measured in lakes Bunyampaka and Nyamunuka respectively. The highest measured temperatures were 34.4±2.4^{o}C followed by 32.1±2.0^{o}C and 32.0±0.8^{o}C measured in lakes Munyanyange, Bagusa and Murumuri respectively. The lowest measured temperatures were 27.9±0.3^{o}C and 28.9±0.4^{o}C measured in lakes Katwe and Kikorongo respectively. Of all the sampled lakes it was only Lake Kikorongo which had fresh waters. The rest of the sampled lakes were found to be hypersaline with salinities ranging between 92.3±7.6mg/l and 205.0±15.3mg/l measured in lakes Maseche and Nyamunuka respectively. The conductivity in all the studied lakes ranged between 10.5±0.6ms/cm and 106.3±3.5ms/cm which were the lowest and highest conductivities recorded in lakes Nyamunuka and Murumuri respectively (Table 3).

Chemical composition of selected chemical parameters in the Alkaline, saline crater lakes

Lakes Katwe (110205.0±7.1mg/l), Nyamunuka (101254.5±6.4mg/l), and Maseche (76909.1±7.0mg/l) had the highest alkalinities while lakes Kikorongo (12534.4±1.6mg/l) and Munyanyange (12767.2±329.3) had the lowest alkalinities. All the studied lakes were found to have carbonate and bicarbonates as the dominant anions with lakes Nyamunuka and Kikorongo having the highest and lowest carbonate concentrations respectively. Calcium was found to be the dominant cation in all the studied lakes. Lakes Bunyampaka, Katwe and Maseche had the highest sodium concentrations while lakes Murumuli, Bunyampaka and Katwe respectively had the highest Chloride concentration (table 4).

Table 4; Mean ±SD of selected chemical parameters and ionic composition of the waters of the different lakes considered in this study.

	Mean±SD of the concentration of the different chemical parameters in each lake							
Parameter	Bagusa	Bunyampaka	Katwe	Murumuli	Nyamunuka	Munyanyange	Kikorongo	Maseche
Alkalinity (mgL^{-1})	66161.7±3.5	65391.7±200.3	110205.0±7.1	66050.5±71.4	101254.5±6.4	12767.2±329.3	12534.4±1.6	76909.1±7.0
Calcium (mgL^{-1})	147.7±17.2	674.5±77.1	1275.7±1.4	368.5±0.7	677.5±0.7	124.0±5.7	111.0±1.4	631.3±6.9
Carbonates (mgL^{-1})	46398.3±142.6	59151.0±8.5	31905.0±7.1	37250.5±0.7	67804.0±5.7	8315.2±21.4	8333.5±0.5	43628.0±7.1
Chloride (mgL^{-1})	164.3±8.5	203.1±35.9	202.3±0.0	1140.0±0.7	102.0±2.1	134.0±8.5	8.4±0.5	183.4±4.6
Bicarbonates (mgL^{-1})	19518.3±319.4	6090.8±20.0	78302.0±2.8	28753.5±4.9	34451.0±1.4	4650.0±70.7	4205.5±7.8	33241.2±56.6
Sulphates (mgL^{-1})	293.0±7.3	243.9±20.6	244.9±0.6	143.0±4.2	181.7±0.3	194.0±14.1	154.0±28.3	233.9±3.2
Sodium (mgL^{-1})	84.5±4.7	135.9±1.4	134.6±2.1	67.8±0.2	92.6±0.7	89.9±9.4	62.2±1.4	106.6±1.9
Magnesium (mgL^{-1})	33.8±0.1	176.4±45.8	557.3±2.8	114.5±7.1	246.5±0.7	32.1±4.1	27.4±0.4	226.4±2.0
Potassium (mgL^{-1})	43.1±1.6	78.6±3.7	65.1±3.5	31.0±1.4	48.6±0.1	45.4±7.0	30.2±0.3	56.7±1.0
Hydrogen sulphide (mgL^{-1})	15.0±0.2	1.2±0.1	13.8±1.4	4.3±0.7	7.4±0.2	1.6±0.1	0.4±0.1	7.7±0.6
Total silica (mgL^{-1})	21.8±1.1	10.6±3.5	28.8±1.5	16.2±0.7	19.3±0.2	10.0±0.3	11.3±0.1	19.9±1.0
Fluoride (mgL^{-1})	0.4±0.0	0.7±0.0	0.8±0.1	0.3±0.0	0.4±0.1	0.3±0.1	0.3±0.1	0.9±0.4

Table 5; Mean±sd of selected nutrients concentrations in the selected Alkaline, saline lakes considered in this study

	Mean ± SD for Nutrients and TSS				
Lake	**NH_3-N mgl^{-1}**	**NO_2-N mgl^{-1}**	**NO_3-N mgl^{-1}**	**SRP mgl^{-1}**	**TSS mgl^{-1}**
Katwe	8.03±0.28	1.48±0.05	0.19±0.04	64.93±2.91	281.00±30.29
Bunyampaka	7.78±2.55	1.68±0.10	0.29±0.11	32.90±13.68	3103.00±2122.09
Maseche	7.20±1.44	1.30±0.10	0.17±0.03	32.47±0.61	8462.85±5782.53
Munyanyange	6.53±0.68	1.83±0.15	0.24±0.01	15.53±1.76	1984.32±176.88
Bagusa	13.45±1.89	1.98±0.13	0.47±0.04	12.23±1.34	5241.86±1305.56
Murumuri	6.13±0.03	1.31±0.27	0.23±0.04	14.15±7.99	35175.23±93.96
Kikorongo	0.04±0.01	0.15±0.07	0.21±0.01	9.40±0.71	90.03±10.20
Nyamunuka	7.7±1.21	1.7±0.11	0.23±0.04	82.01±0.91	91833.33±186.23

Lake Kikorongo had the lowest concentrations of NH_3-N, NO_2-N, NO_3-N, SRP and TSS. Among the sampled Lakes, Bagusa had the highest NH_3-N, NO_2-N, and NO_3-N concentrations while Lake Nyamunuka had the highest SRP and TSS (Table 5 above).

Discussion

General Environment characteristics of selected Alkaline, saline lakes

In this study, communities confirmed Lake Munyanyange and Murumuri in addition to Lake Nyamunuka to evaporate to dryness during the extreme dry seasons. These lakes having no major inflow and the intense solar heating they experience are the main reason why these lakes evaporate to dryness in the extreme dry seasons. Although soda lakes are characterized by high evaporation rates, the presence of many fresh water inflows around Lakes Katwe, Bunyampaka, Bagusa and Maseche ensures that these lakes do not evaporate to dryness even in the dry season hence making them permanent lakes (Musinguzi and Katikiro, 2000). The high variations in the volume of these lakes can be attributed to the very high evaporation rates experienced in saline lakes (Jones and Grant, 1999). Melack (1978) reported Lake Nyamunuka to have evaporated to dryness for a period of two weeks in May 1971. This could have been mainly because lake Nyamunuka has few and very small fresh water inflows which are not enough to maintain the water in the lakes during the dry season.

The peanut soup green, dark green and greenish color in lakes Katwe, Bunyampaka and Maseche, Nyamunuka and Murumuri, Kikorongo and Munyanyange respectively observed in this study might be attributed to the cyanobacteria and algal blooms which have been reported in alkaline, saline lakes (Mungoma, 1990; Jones and Grant, 1999; Matagi, 2004). Lakes Kikorongo and Maseche waters were reported to be peanut soup green in color while Lake Bagusa waters were reported to be brown in color in the earlier limnologicals studies done on the lakes (Mungoma, 1990). East African Saline lakes have been reported to have unique cynobacteria community (Hadgembes, 2006). With the exception of Lake Kikorongo whose waters were not thick and slimy, the waters in the rest of the other sampled lakes were found to be thick and slimy. Previous studies by Matagi (2004) attributed the thickness and slimy nature of the waters in alkaline, saline the high algal abundance and high evaporation rates in hypersaline lakes which leave behind lots of organic matter (Jones and Grant, 1999; Grant, 2006).

Lakes Katwe, Munyanyange and Bunyampaka are experience severe impacts of overgrazing and deforestation. Deforestation and overgrazing have been reported to be among the major drivers of reduced vegetation in the hypersaline rift valley lakes in Tanzania and Ethiopia (Matagi, 2004). A lot of vegetation has been cleared around lakes Katwe and Bunyampaka by salt miners who use in re-enforcing salt crystallization pans during their construction. It is also used to cover the extracted salt as a way of protecting it from rain during storage while waiting for the buyers. The high vegetation cover in the other studied lakes (Murumuri, Nyamunuka, Bagusa, Maseche and Kikorongo) could be because the lakes are found in Queen Elizabeth National park (QENP) where there are protected from encroachment by Uganda Wild Life Authority (UWA). The freshwater wetlands around Lakes Katwe, Bagusa and Maseche are maintained by ground water and seasonal streams flowing from highlands surrounding these lakes (Grant, 2006). Musinguzi *et al* (2000) reported lakes Katwe, Munyanyange and Nyamunuka to be surrounded by pure strands of *Cyperus lavigatus*. Salinity has been reported to have a significant impact on the emergent vegetation in the littoral zones of saline lakes (William and Fawn, 2009). This explains why *Cyperus lavigatus* a species that is adapted to such saline environments was found to be surrounding many of the lakes in this study. In a biodiversity assessment of the flamingo lakes of East African, savannah woodland, bush land and shrub land were reported to be the dominant vegetation in the alkaline rift valley lakes of East Africa. *Euphorbia candelabra* was reported in most highland forests surrounding these lakes while *Cyperus lavigatus* dominated the surrounding wetland vegetation (Matagi, 2004). *Cyperus lavigatus* and *Cyperus rotundus* are among plants reported to be tolerant to difficult conditions in arid and semi-arid areas (Alsherif, Ayesh *et al*., 2012). This region having hot and dry climate with high evaporation rates (Mungoma, 1990), it is mainly the plants like *Ciperus lavigattus*, and *Euphobia candelabra* with ability to survive in such harsh conditions that abound to be the dominant vegetation.

Physical characteristics of selected alkaline, saline lakes

The studied lakes being shallow can be attributed to the mode of their formation. All these studied lakes were formed by water filling a series of shallow depressions which were formed by tectonic activities during the formation of the great East African rift valley (Matagi, 2004; Grant, 2006). Endorheic, saline have been described to be typically small (<50ha) and shallow (<1m) (Stenger-Kovács, Lengyel *et al*., 2014). Previous limnological studies of alkaline, saline lakes in Uganda reported these lakes to be shallow with only lakes Kikorongo and Mahega being the only lakes reported to have a depth exceeding 5m (Mungoma, 1990). This remains true as per the findings of this present study.

With the exception of Lake Kikorongo, the rest of the sampled lakes had very low dissolved oxygen (DO) levels (<3.5mg/l). The low DO could be explained by the high decomposition rates of dead algae since these lakes are reported to be amongst the most productive aquatic systems in the world (Grant, 2006). Earlier studies have reported dissolved oxygen levels (less 1mg/l) to be very low in these alkaline, saline crater lakes (Mungoma, 1990). Alkaline, saline lakes have been reported to generally have high pH above 9.6 (Matagi, 2004; Grant, 2006). Study finding from this study are in agreement with the past studies, with the current studied lakes having pH ranging between 9.58±0.1 and 11.5±1.0. With the very high evaporation rates experienced in these lakes, the dissolved minerals are concentrated into alkalis, with pH ranging from 8.5 in dilute lakes to around 12 in highly concentrated lakes (Grant, 2006). Other East African Alkaline, saline lakes like Nakuru (10.5), Elimenteita (9.4), Manyara (10.2), Reshitani (9.2) and Big Momela (10.4) have been reported to have similarly high pH ranges (Melack and Kilham 1974).

The highest and lowest measured temperatures of 34.4±2.4^{o}C and 27.9±0.3^{o}C measured in lakes Munyanyange and Katwe respectively were higher than the reported the reported mean monthly temperatures of this region 19.0±2.8°C and 28.0±3.2°C from previous studies by Mungoma (1990). This could be because the survey was carried out in the dry season with high atmospheric temperatures. This area experiences a hot and dry climate compared to the surrounding highlands (Mungoma, 1990). Such climates are characterized by high atmospheric temperature. These alkaline saline lakes being small and shallow with no major out flow, there are very sensitive to weather and climate changes. Small changes have been reported to cause large and sometimes irreversible changes in the nature of saline lakes (Hammer, 1990). Shallow closed-basin saline lakes of Northern Great Plains have been reported to be very sensitive to changes in precipitation and evaporation (Evans and Prepas, 1996). Like the shallow closed-basin saline lakes of the Northern Great Plains, the alkaline saline lakes of Uganda are closed with no major outflow. This implies that they are also very sensitive to weather and climate variations.

Lake Kikorongo was found to be fresh with a salinity of 0.0±0.0mgl^{-1}. This is contrary to previous literature which reported lake Kikorongo to be saline (Mungoma, 1990; Hadgembes, 2006). The rest of studied lakes were hypersaline. With the exception of Lake Maseche whose salinity was slightly below 100mgl^{-1}, the rest of the sampled lakes had their salinities above 100mgl^{-1} (Table 3). Such hypersaline lakes with high pH above 10 have been referred to as soda lakes (Matagi, 2004). These lakes have been reported to be experiencing temporal variations in salinities as high as 50mg/l (Mungoma, 1990). Lake Kikorongo has been reported to receive fresh water from floods coming from the neighboring Lake George during the rain seasons (Hecky and Kilham, 1973; Mungoma, 1990). This together with precipitation which has been reported to affect salinity in closed lakes (Saros and Fritz, 2000), could be responsible for the reduction in salinity observed in lake Kikorongo. From studies of potential effect of climate change on ion chemistry and phytoplankton communities in prairie saline lakes, precipitation and evaporation were reported among the factors affecting salinity in these lakes (Evans and Prepas, 1996). Evans *et al.,* (1996) also reported local difference in surface and ground water to have an effect on brine concentration and composition in closed saline lakes. This together with addition waters received by Lake Kikorongo from precipitation might be some of the factors responsible for the reduction in salinity levels in this lake.

Conductivity has been reported as a useful indicator for the levels of available inorganic constituents in water and play an important role in determining the availability of aquatic organisms in certain environments (Gupta and Mrinal, 2013). The observed high conductivity in these lakes under the current study is due to the high concentration of inorganic ions in these lakes.

Chemical characteristics of selected alkaline, saline lakes

The low alkalinities, salinities and conductivities in Lake Munyanyange can be attributed to it being a seasonal lake and had just received its waters from rain only a few days ago at the time of sampling. It usually requires some residence time for the lake waters to infiltrate down to the salt rich parent rock which leads to diffusion of salts from the parent rock to the lake waters. As the rain waters spend more time in the lake, the salinity, alkalinity and conductivity increase. The low alkalinity, salinity and conductivity in Lake Kikorongo can be explained by dilutions with fresh water which is reported to come from the neighboring Lake George when it floods during the rainy season (Mungoma, 1990).

In this present study, all lakes were found to have carbonates as the dominant anions, followed by sulphates. This is in agreement with earlier studies where carbonates were reported to be the major dissolved anions in soda lakes of East Africa (Jones and Grant, 1999). Modern and Holocene carbonate sedimentology of two saline volcanic maar lakes in Southern Australia reported carbonates to be among the common components in sediments of modern salt lakes (Last and De Deckker, 1990). The high carbonate concentrations in these lakes waters might be caused by incoming waters into these lakes dissolving the carbonates from the sediments of these lakes. Jones and Grant (1999) reported the high concentration carbonates as major dissolved anions to be caused by evaporative concentration. Contrary to the current study findings, previous studies by Mungoma (1990) reported lakes Katwe and Kikorongo to have more chlorides than carbonates. Chloride concentrations in lake Katwe might have reduced due to the excessive salt extraction while for Kikorongo it might be the dilution cause by rains and the reported floods from lakes George (Hecky and Kilham, 1973; Mungoma, 1990). With the exception of SiO2 and F which are lower, all the other chemical compounds considered in this current study are higher than those reported earlier studies by Mungoma in the 1990s. The high concentration of nitrogenous compounds including NH3-N, NO2-N, and NO3-N in these lakes (table 5) can be attributed to the high algal biomass found in these lakes where upon decay and subsequent nitrification lots of nitrogenous compound like nitrates are released in these highly productive lakes. Lake Kikorongo having the lowest concentrations of NH3-N, NO2-N, NO3-N, SRP and TSS can be attributed it being the least productive among the different studied lakes. . Total phosphorous concentrations were reported to be frequently highly in saline lakes in the Canadian prairies. The high phosphorous concentration was associated with the conservation of phosphorous in these lakes (Evans, Arts et al., 1996). In the same way, phosphorous might be conserved in these saline crater lakes of western Uganda like it is in the phosphorous–rich saline lakes of the Canadian prairies since these lakes are also found in areas experiencing high evaporation rates exceeding precipitation rates and in closed drainage basins (Jones and Grant, 1999) as is the case for Canadian prairies saline lakes.

Conclusions

All the studied lakes were alkaline and saline in nature as reported in the previous studies except Lake Kikorongo which was found to be fresh with a salinity of zero in this present study. With the exception of Lake Murumuli which was found to be a Carbonate-chloride lake, the rest of the sampled lakes are carbonate-sulphate lakes which is contrary to earlier studies which reported lakes like Katwe and Kikorongo to be Carbonate-chloride lakes.

Climate change and human activities such as rock salt extraction, water diversion to salt pans, deforestation, and livestock grazing are threatening the ecological status of these lakes more especially those outside the protected areas like Katwe and Munyanyange. Could the observed increment in water temperatures in the study lakes and a reduction in salinity more especially in Lake Kikorongo be a sign of climate change? For this to be confirmed, it requires routine and continuous monitoring in these lakes. Although the majority of these lakes are found in Queen Elizabeth National Park (QENP) which is a protected area, there is need to offer additional protection to these unique systems if these systems are to be protected from human induced climate change. Alkaline saline lakes in Carpathian Basin which are under ex.lege Protection (by law) (Stenger-Kovács, Lengyel *et al*., 2014) can be useful examples.

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