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# Lake Sedimentary Environments and Roles of Accumulating Organic Matter in Biogeochemical Cycling Processes and Contaminants Loading Are Invasions of Water Hyacinth in Lake Victoria from 1989 a Concern?

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Additional information is available at the end of the chapter

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## Abstract

Sediments accumulated in lake basins consist of various organic and inorganic materials, mostly utilized as proxies for climatic changes and as historical records of the lake connectivity to terrestrial ecosystems and anthropogenic activities. In-lake production, aerial wet and dry deposition and transported materials in running water are the main sources of lake deposits, which may be permanently deposited as bottom sediments or remobilized through erosive forces and turbulence, resuspension, tunneling by organisms, and pore-water exchanges with the overlying water mass. Examination of the sediment biodiversity, quality, composition, and stratigraphy is part of the approaches in understanding ecological and climatic changes and other anthropogenic impacts in lakes. There are no detailed studies on the spatial distribution of sediment characteristics within the Nyanza Gulf, especially after the establishment of water hyacinth. The first observations on the nature of the bottom of Lake Victoria were made during 1927–1928 survey, with subsequent detailed geochemical core studies concentrated in the main lake. Roles of sediment organic matter are explained, and data from surficial sediments collected, from about 32 sampling sites between 1994 and 2012, are used to characterize the sediments. Lastly, the potential influences from increased urbanization, eutrophication, presence of water hyacinth (*Eichhornia crassipes*), and associated floating macrophytes since 1989 and current cage aquaculture in *L. Victoria* are explored.

**Keywords:** Lake Victoria, sedimentary environments, sediments, organic matter, contaminants, organic carbon, depositional basins

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## 1. Introduction

Lakes are important land features forming linkages with the hydrological systems at local and transboundary scales, while providing water sources, supporting fisheries, and providing livelihoods to many surrounding communities and different ecosystem services. Small and large lake depositional basins continuously accumulate dissolved or particulate inorganic and organic materials produced within the lake water column (autochthonous) or transported from the catchment area (allochthonous). However, besides lake production, human developments and urbanization around surface waters (lakes and rivers) are also a source of various solid and nutrient-rich materials depositing and accumulating on the lake sediments. When autochthonous matter is dominant, lake sediments may be either carbonate-rich or silica-rich due to the accumulation of siliceous diatoms, or they may be mostly organic. In the latter case, the organic carbon content may reach 20–25%, but in peat bogs it may be even higher [1, 2]. Particulate matter scavenges chemical species (organic and inorganic pollutants) and, with other geochemical barriers, influences their mobility in the secondary environments. Therefore, understanding the sediment-chemical species associations has given more insights to the chemical element availability for metabolic processes and toxicity under certain environmental conditions. Knowledge of lake bottom dynamics and sedimentological processes is essential in matters related to geographical distribution and potential ecological effects of contaminants and in many practical issues, such as choice of adequate dumping sites for dredging deposits and choice of sampling sites from aquatic pollution control. Sediment accumulation areas prevail where fine materials, medium silt with grain size less than 0.006 mm, can be deposited continuously; sediment transportation zones appear where there is discontinuous deposition of fine particles/aggregates, and sand erosion zones prevail where there is no deposition of fine materials [3]. The sediments within areas of transportation, for natural reasons, are generally very variable (from sand to loose mud); areas of erosion are most frequent in shallow waters and characterized by hard or consolidated deposits (from bare rocks, gravel, and sand to glacial clays), and the deposits from areas of accumulation are always comparatively loose, with high water and organic contents and sometimes with a high content of pollutants [3]. The Lake Victoria (Kenya) gulf waters are eutrophic, and it is continuously fed by several large and small rivers which traverse the fertile agricultural highland areas and transport high levels of eroded materials. Information from sedimentological studies in *L. Victoria* exists but is inadequate due to lack of new studies. The chapter examines the significance of sediment organic matter (SOM) in freshwater aquatic environments, besides other sediment factors, and uses the spatial concentration of total organic carbon determined in surficial sediments of Lake Victoria (Kenya) to explore whether water hyacinth invasion has any significant influence on SOM. It also gives an opportunity to reflect on the potential environmental impacts which can possibly emanate from the new cage aquaculture developments in most of the shallow African inland lakes, such as *L. Victoria* which has a huge potential for cage culture.

### 1.1. Lake Victoria

Lake Victoria, the world's second largest freshwater lake (68,800 km<sup>2</sup> in surface area and mean depth of 35 m) supports the world's largest inland fishery and is a transboundary ecosystem with the Nyanza Gulf, on the extreme eastern edge forming the Kenya portion (**Figure 1**). The gulf connects to the open lake via Rusinga Channel. River water inflows

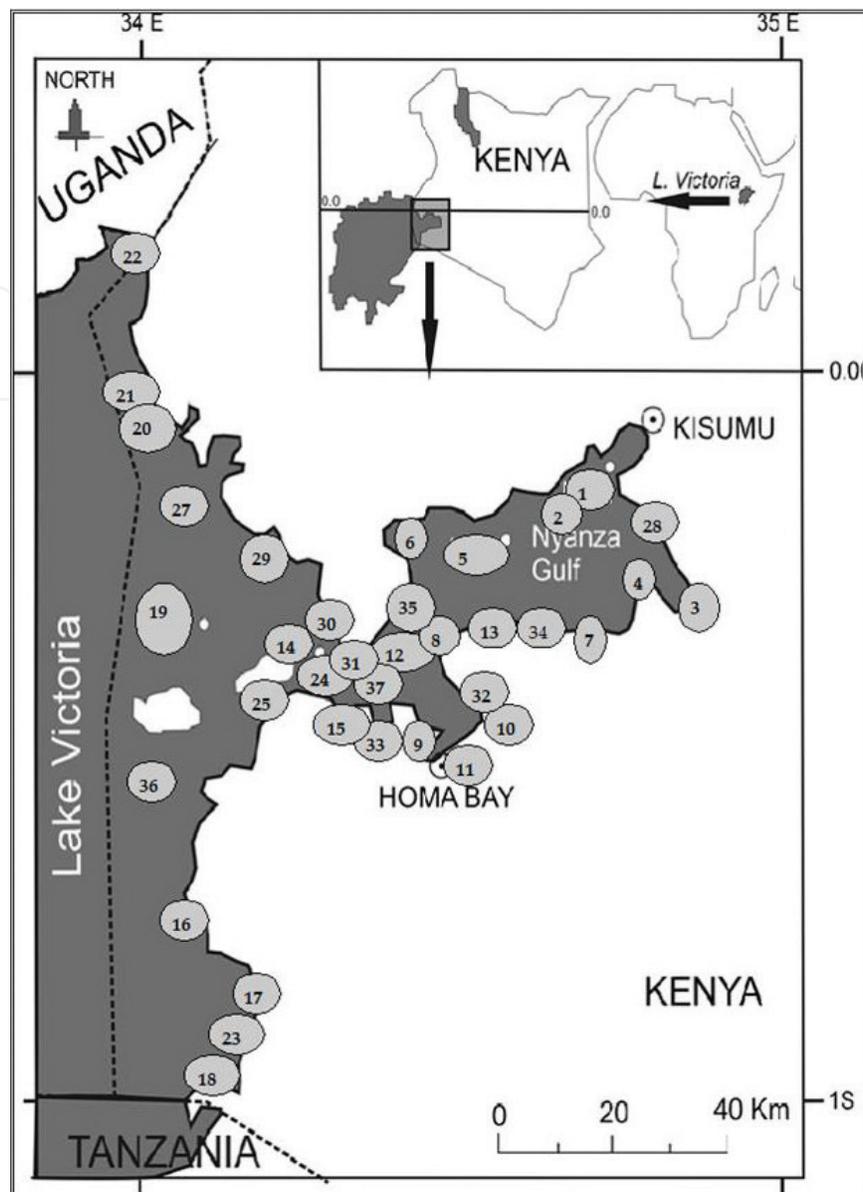


Figure 1. The map of Lake Victoria (Kenya) showing sampling sites.

account for about 20% of the total water inputs into the main lake. The catchment area and the drainage basin are covered by grassland savanna, wetland vegetation, agricultural crops, and forested highland and mountain areas. It is characterized by high tropical temperatures and heavy rainfall in the highlands, described in a long (April–June) and short (October–December) wet season and a dry season. The lake hydrology, physicochemical environment, and changes in primary production of the lake and gulf areas are well-described by various authors [4–13].

Morphometric characteristics from early investigations in L. Victoria and its main gulf areas are provided by Crul [10]. Seismic reflection profiles confirm the origin of the lake as a result of regional tilting and provide an estimated age of 400,000 years for the lake basin [14]. The Nyanza Gulf deepens towards the western direction, as shown by bathymetric map after Kendall [15] and Scholz [16]. Some information on the lake bottom and sediments in the Nyanza Gulf is provided by Mothersill [17] and Mothersill et al. [18].

Nyanza Gulf, a relatively shallow gulf compared to the main lake basin, is composed of numerous inner bays and receives inflowing water from several major rivers. This makes it a distinctly important habitat for several fish species, which are known to breed in the various vegetated bays and river-mouth areas. The gulf is greatly influenced by catchment activities through river inflows and nearby urban human activities. Besides this, an invasive water weed, the water hyacinth, is commonly found in the whole lakeshores and bays. The plant was first reported from Lake Victoria in 1989, and it began to increase in the early 1990s, until it infested some 200 km<sup>2</sup> by 1998 [19]. Its early spread and nourishment were thought to be triggered by nutrient enrichment, and the plant floating mats have persisted up to today.

## 2. Sources of organic matter sources in lake sediments

Lake basins are receptors of different types of dissolved and suspended materials transported by inflowing water, above lake precipitation, and blowing wind. In-lake productivity processes also contribute a significant amount of organic matter and mineral elements, which enter the lake biogeochemical cycles.

Organic matter in aquatic ecosystems ranges from dissolved organic compounds to large aggregates of particulate organic matter and from living to dead materials [20]. Nearly all of the organic carbon in natural waters is in the form of dissolved organic carbon (DOC), colloidal organic carbon (COC), and dead particulate organic carbon (POC). Metabolism of the organic matter and interactions of this material chemically and biologically are, to a significant extent, governed by the size and chemical composition of the organic matter [20]. The productivity of aquatic macrophytes of the wetland and littoral land-water interface zones constitute a major source of organic matter input for a majority of the lakes of the world [20]. A central role in the underwater light climate is played by dissolved organic matter which is present in all aquatic ecosystems. Chromophoric dissolved organic matter (CDOM) originates from the degradation process of organic materials, usually macrophytes and planktons. Recently, using fluorometer data, Alexander and Imberger [21] characterized phytoplankton patchiness in the Nyanza Gulf as indicators of phytoplankton diversity and CDOM, while Loiselle et al. [22] determined the spatial dynamics of CDOM of three major bays on the Kenyan and Ugandan shores of Lake Victoria and developed a model to estimate its flow from these bays to the lake.

Lake sediments are comprised mainly of clastic material (sediment of clay, silt, and sand sizes), organic debris, chemical precipitates, or combinations of these. The relative abundance of each depends upon the nature of the local drainage basin, the climate, and the relative age of a lake. Sediments are deposited at different rates in different aquatic environments. Deposition rates vary from site to site, but typical values for the rate at which sediments accumulate in freshwater lake sediments are 1 mm/year (or 1 m per 1000 years). When a watershed drains into a lake, accumulated sediments have the potential to yield information about historic rates of sedimentation that can be used to evaluate the effectiveness of previous erosion control measures [23].

The active lake sediment layer (top layer) forms the exchange zone between sediments and overlying water column. It plays an important role in the biological system; however, it can become anoxic in deeper areas, hence influencing the chemical equilibria and transformations.

Degradation of decaying organic matter and organic rich waste discharges can lead to decreases in DO concentrations as a result of the increased microbial activity (respiration). In severe cases of reduced oxygen concentrations (whether natural or man-made), anaerobic conditions can occur (i.e. 0 mg l<sup>-1</sup> of oxygen), particularly close to the sediment–water interface as a result of decaying, sedimenting material. Dissolved oxygen levels influence the redox potentials (Eh) and different chemical processes in the aquatic habitats and the distribution of fish species. This is explained by Njiru et al., [24] who explored the impacts of hypoxic conditions to the fishery in Lake Victoria, where, from acoustic data, Nile perch catches increased with increase in DO concentrations and no fish were caught when DO was below 2.5 mg/L<sup>-1</sup>.

Organic matter constitutes a minor but important fraction of lake sediments. It is made-up of a complex mixture of lipids, carbohydrates, proteins, and other biochemicals contained in the tissues of living benthic micro-organisms and contributed from the detritus of organisms formerly living in the lake and its watershed. Humic substances are diagenetically formed from these biochemical starting materials and constitute the major part of the complex mixture of organic materials [25]. Some natural organic compounds significantly affect the quality of water for certain uses, especially those which depend on organoleptic properties (taste and smell). During chlorination for drinking water disinfection, humic and fulvic acids act as precursor substances in the formation of trihalomethanes such as chloroform. In addition, substances included in aquatic humus determine the speciation of heavy metals and some other pollutants because of their high complexing ability. As a result, humic substances affect the toxicity and mobility of metal complexes [2]. Therefore, measurement of the concentrations of these substances can be important for determining anthropogenic impacts on water bodies. Humus is formed by the chemical and biochemical decomposition of vegetative residues and from the synthetic activity of micro-organisms. It is operationally separated into fulvic and humic acid fractions, each being an aggregate of many organic compounds of different masses. Fulvic acid has molecular masses mostly in the range 300–5000, whereas the dominant masses in humic acid exceed 5000. The relative content of fulvic acid in the dissolved humic substances present in freshwaters is between 60 and 90%. Humic and fulvic acids are fairly stable (i.e. their BOD is low). However, these substances are chemically oxidizable and, therefore, can readily affect the results of COD determinations [2].

Organic matter also forms part of the palaeolimnological record preserved in lake sediments. The different types of biota populating a lake and its watershed produce organic matter having distinctive biochemical compositions. Changes in the community structure of these biota create variations in the amounts and types of organic matter deposited at different times in the history of a lake. Organic matter is consequently a dynamic biogeochemical component of sediments [25].

### **2.1. Roles of lake sediment organic matter**

The most important determinants of chemical-sediment association are composition or grain-size distribution, pH, salinity, DO<sub>2</sub>, mineralogical content (clay mineral composition, hydrous iron-manganese oxides, carbonate contents), organic matter, and redox potential.

Concentrations of some inorganic and organic contaminants (PAH, PCBs, OCs, Hg, and alkylated metal forms) can become increasingly high and important sources of exposure, with transfers

along lake food chains in the long term. Contaminated sediments are therefore a concern to lake managers of surface lake waters receiving significant amounts of anthropogenic wastes, hence the development and use of sediment quality guidelines in protecting the aquatic fauna and flora. Managing contaminated sediment in place requires a complete chemical, biological, and physical understanding of the fate and mobility of contaminants. Most of them adsorb onto suspended and deposited particles at the bottom, where they form important secondary sources. Soils and sediments are important “sinks” for such contaminants because of their enormous quantities and their abilities to pick up, or sorb, large amounts of a wide variety of contaminants. It is essential to understand the mechanism by which the contaminant is sorbed to soil and sediment [26]. Compared to other natural environmental substrates, sediments have a greater capacity to bind Hg more than 90% of total Hg in sediment-water system which is sorbed or held in sediments [27].

Stable isotope signatures ( $^{613}\text{C}$  and  $^{815}\text{N}$ ) of organic matter in lake sediment cores have been used as indicators of historic lacustrine productivity [28, 29] and past nitrogen sources [28, 30], respectively. Total carbon (TC) to total nitrogen (TN) ratios of OM can be used to assess the relative contributions of higher plants versus phytoplankton to sediments [31–34]. In *L. Victoria* (Tanzania), the potential to discriminate between input sources of organic material into lakes using stable isotope signals in sediment and suspended particulate matter was demonstrated, where stable C and N ratios showed that inshore areas in bays without pronounced fluvial input were dominated by autochthonous planktonic organic matter; conversely, for bays receiving significant fluvial inflows, the composition of organic matter depended on the extent of preservation of shoreline vegetation [35].

Sediment metabolism (e.g. measured as sediment oxygen uptake) is highly varied and depends on the individual characteristics of a lake. Profundal sediments may have a high organic carbon content (up to 25%) and are more homogenous compared with littoral sediments, with a resultant high sediment metabolism [36]. Organic matter degradation is influenced by the presence of benthic fauna, which enhance the oxidation of the sediments and organic matter cycling by increasing oxygen supply during respiratory pumping [37]. Benthic animals and microbes depend on organic matter for their nutrition. Because many components of organic matter are relatively easily oxidized forms of reduced carbon, the dissolved oxygen concentration of sediment porewater is controlled largely by the availability of oxidizable organic matter below the sediment–water interface [25]. Organic matter so resuspended is re-exposed to oxidation in the water column. Resuspension is usually greater in large, well-mixed lakes than in small lakes. Bioturbation, or biological mixing, of surface sediments also prolongs the exposure of organic matter to oxidation and adds to this the degradation due to the nutritional needs of benthic fauna [25].

## 2.2. Chemical adsorption to sediments and soil

Sorption to soils and sediments is probably the most influential factor on the transport and fate of organic contaminants in the environment. The extent of the sorption to soil and sediment affects not only the contaminant level in an ecosystem but the movement and fate of the contaminant as well. For example, in a hydrogeologic system, the increased sorption of a contaminant to soil and sediment reduces its level in the adjacent water column and thus

decreases its exposure and transport to other parts of the ecosystem, such as fish and plankton [26]. The way in which contaminants are sorbed into soil or sediment varies with the nature of the contaminant and the makeup of the soil and sediment [38, 39]. The composition of soil and sediment includes both mineral matter and organic matter as the primary constituents. Under relatively dry conditions, the soil/sediment mineral matter acts as an adsorbent, where the sorbed organic compounds are held on the surface of the mineral grains. The soil/sediment organic matter (SOM) acts as an absorbent or a partition medium, where the sorbed organic compounds dissolve (partition) into the matrix of the entire SOM. The soil or sediment, then, is characterized as a dual-function sorbent, in which the mineral matter sorbs the contaminant by adsorption, while the SOM sorbs the contaminant by a partition process [40–42]. Because so many environmental contaminants are transported by groundwater and surface water, it is important to understand the unique function of the soil organic matter within these aquatic systems and how the partition processes affect the fate of common environmental contaminants.

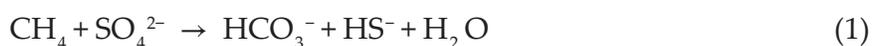
The organic carbon partitioning coefficient,  $K_{oc}$ , data of both carbon tetrachloride (CT) and 1,2-dichlorobenzene on most normal soils from shallow depths are shown to be quite invariant, suggesting that soil organic matter at such depths from diverse geographic sources maintains a comparable polar-to-nonpolar balance and possibly a comparable composition [26]. However, soil samples are genuinely different from bed-sediment samples in terms of their  $K_{oc}$  values. The average  $K_{oc}$  values for nonpolar solutes on bed sediments are about twice those on soils, suggesting that sediment organic matter is in general less polar in nature than soil organic matter. This unique geochemical disparity has not been documented until now [26]. The observed difference in  $K_{oc}$  between the soil and bed-sediment samples must be taken into account in future studies. Because it has now been shown that  $K_{oc}$  values for soils are largely consistent worldwide, just as  $K_{oc}$  values for sediments are largely consistent worldwide,  $K_{oc}$  values can be used to assess the sorption of nonpolar contaminants to the organic matter of different soils/sediments. This finding should result in considerable savings in cost and time for contamination studies [26].

Although suspended sediment as a whole can be examined as a transport mechanism for trace metals, additional insight can be gained from a knowledge of the particle-size distribution. The most significant factor controlling sediment capacity for retaining trace metals is grain size, according to Jenne et al. [43]. The correlation between decreasing grain size and increasing trace-metal concentrations is significant. This correlation is a result of factors, both physical and chemical, that most notably are related to the large surface area per unit weight of fine particles (such as clays) compared to larger particles. According to Horowitz [44] the increase commonly is more than a hundredfold.

A recent view of the role of clays as metal concentrators implies that clays function as substrates for the precipitation and flocculation of organic matter and secondary minerals such as hydrous iron and manganese oxides. Those secondary minerals, in turn, become substrates for the accumulation of trace metals rather than the clays themselves, according to Jenne [45]. There is some debate whether accumulation takes place by organics and secondary minerals or whether there is direct physical and chemical interaction with the clays. However, there is general agreement that the largest concentrations of metals are present with the clays and that the following clay minerals have a decreasing order of association with trace metals: montmorillonite > vermiculite > illite, chlorite > kaolinite.

### 2.3. Methane production

Besides methane emissions from wetland areas [46], freshwater anoxic areas are notably important sources. Freshwater bacteria are at the hub of biogeochemical cycles and control water quality in lakes [47]. Methane is oxidized in lakes by a group of bacteria that convert methane and oxygen to cellular material and carbon dioxide [48]. In deeper lakes, methane oxidation occurred mainly within a narrow zone at the boundary of the seasonally mixed layer and the permanently anoxic monimolimnion [49]. Reduction of carbon dioxide and the decomposition of organic sediment material contribute to methanogenesis. Methanogenic bacteria directly reduce the dissolved carbon dioxide near and in the sediments. Simultaneously, methane is formed from organic matter by acetate fermentation. Only three key functional groups of micro-organisms of limited diversity regulate the fluxes of methane on earth, namely, the aerobic methanotrophic bacteria, the methanogenic archaea, and their close relatives, the anaerobic methanotrophic archaea [50]. The anaerobic methanotrophic archaea appear to gain energy exclusively from the anaerobic oxidation of methane, with sulphate as the final electron acceptor according to the net reaction:



A great deal of biogeochemical research has focused on the causes and effects of the variation in global fluxes of methane throughout earth's history, but the underlying microbial processes and their key agents remain poorly understood [50]. This is a disturbing knowledge gap because 85% of the annual global methane production and about 60% of its consumption are based on microbial processes [50]. Furthermore, wetland ecosystems are vulnerable due to increasing demand for agricultural lands, yet they act as important filters and C sinks. Nutrient concentration gradients were observed between the deep and seasonally stratifying main lake basin and the large, shallow river-influenced Nyanza Gulf, which are connected by the relatively deep and narrow Rusinga Channel [51]. Since the gulf as a whole is P limited, continued P input to this semi-closed part of the lake will result in increased algal blooms and increased eutrophication and therefore negatively affecting the water quality [52, 53]. Increased availability of nutrients in the water helps sustain the healthy water hyacinth, the persistent alien-invasive floating macrophyte species in the Nyanza Gulf. Increased eutrophication [11, 12, 54] process and changes in productivity have been recorded in the lake from several studies and coupled with increased allochthonous material, there is a potentially higher probability of continued degradation of the lake environment.

### 3. Studies on sedimentary environments in Nyanza Gulf of Lake Victoria (Kenya)

More detailed observations on the sedimentary environments on diatom records and sediment bottom structures in Lake Victoria were made by Stager et al. [55–59] and Scholz et al. [16], with more insights on sediment chronology, accumulation rates, and stratigraphic patterns of biogenic silica accumulation in deepwater cores in the main lake basin determined by Verschuren et al. [60]. Mfundisi [61] analyzed the impact of wetland drainage on soil and plant carbon

pools in Yala Swamp. In the developing countries, wetlands are a source of great support to the rural communities, which derive a significant proportion of their livelihood from these areas [62]. However, land cover changes and degradation are often associated with increasing demand for agriculturally fertile soils in the drainage basins. P washed down from the catchments has been identified in the basin and finds its way into the lake especially in areas where macrophytes have been cleared. Upon decomposition of the vegetation matter, the nutrients are released to the bottom mat and sludge [63]. Several studies in lake sediments have tried to explore their potential as sources of labile phosphorus nutrient [64–66] and eutrophication. Other authors have tried to utilize stable isotopes of C and N to understand different sources of OM and processes operating in the C and N cycles [67–69].

### 3.1. Why study sedimentary organic matter

Sedimentary records are valuable indicators of the short- and long-term in-lake ecosystems. Long-term effects of anthropogenic activities are better understood when linked to the slower sedimentary processes, especially in large deeper basins. However, such efforts are hampered by the lack of expensive C analysers in most laboratories. The use of the inexpensive and rapid LOI method allows generation of useful information on sediment organic matter contents and is a widely accepted method. Several sediment studies apply this approach [70] in trying to find relationships between organic matter and organic carbon determined from dry combustion. Apart from comprehensive palaeolimnological research efforts made possible by new sediment cores collected in 1995 and 1996 and (eutrophication related changes in the pelagic phytoplankton community of *L. Victoria* as archived in the offshore (in the deepest parts of the lake basin) sedimentary record of biogenic silica, no other detailed information on the spatial distribution of the surficial sediment organic matter on the extreme eastern gulf (*L. Victoria*, Kenya) has been provided. Information gathered in two separate surveys is used to show the spatial distribution of some of the surficial sediment characteristics.

### 3.2. The physicochemical environment of Nyanza Gulf of Lake Victoria (Kenya)

In the gulf, most of the sampling sites are nearshore zones of less than 10 m deep (sites of greater 10 m are LS\_37 of 11.0 m and LS\_14 of 13.8 m), when compared to the deeper sites sampled in the main lake (except for the shallow river-mouth areas in the northern area). Surficial sediments in the gulf were observed to consist of dark/gray to brown fine mud and slightly sandy to sandy muds. Observed sediment characteristics are shown in **Table 1** for each site.

**Table 2** shows the mean and range values of the sampled water depth, surface water turbidity, transparency, and chlorophyll-a concentrations. Surface water conditions during the survey and previously collected data are shown in **Figures 2–4**. Although all the three parameters were not determined during all the surveys, available data show a similar trend in water transparency and surface water turbidity. The lake water turbidity showed a high spatial variation during all the sampling surveys. The range values of surface water turbidity were 6.08 NTU to 561 NTU (a maximum value omitted in the graph, at site LS\_21 during May 2000). In February 2001 and January–February 2004, surface water turbidity values ranged from 6.45 NTU to 74.8 NTU and 5.08 NTU to 56.6 NTU, respectively.

Gulf sites	Nearshore/offshore zones	LS_1 (brownish muddy sediment); LS_2, LS_5, LS_6, LS_8, LS_34, LS_13, LS_37, LS_30, LS_31, LS_15, LS_9, LS_32, LS_33, LS_24, LS_14, (dark/gray fine muddy sediment, with large and small empty shell remains)
	Off river-mouth zones	LS_4, LS_7, LS_10, LS_3, LS_28 (sandy brown/gray muddy sediment with empty shell remains)
Open lake sites	Off river-mouth zones	LS_23 (slightly sandy brown muddy sediment); LS_22 (fine dark brown sandy muddy sediment); LS_21 (fine brown muddy sediment with small to slightly larger bivalve shells); LS_20 (muddy sediment with discrete fine sandy particles with small to slightly larger bivalve shells)
	Nearshore/offshore zones	LS_18, LS_16, LS_17, LS_25 (dark/gray fine muddy sediment); LS_36 and LS_19 (fine greenish watery muddy sediment signs of algal deposits)

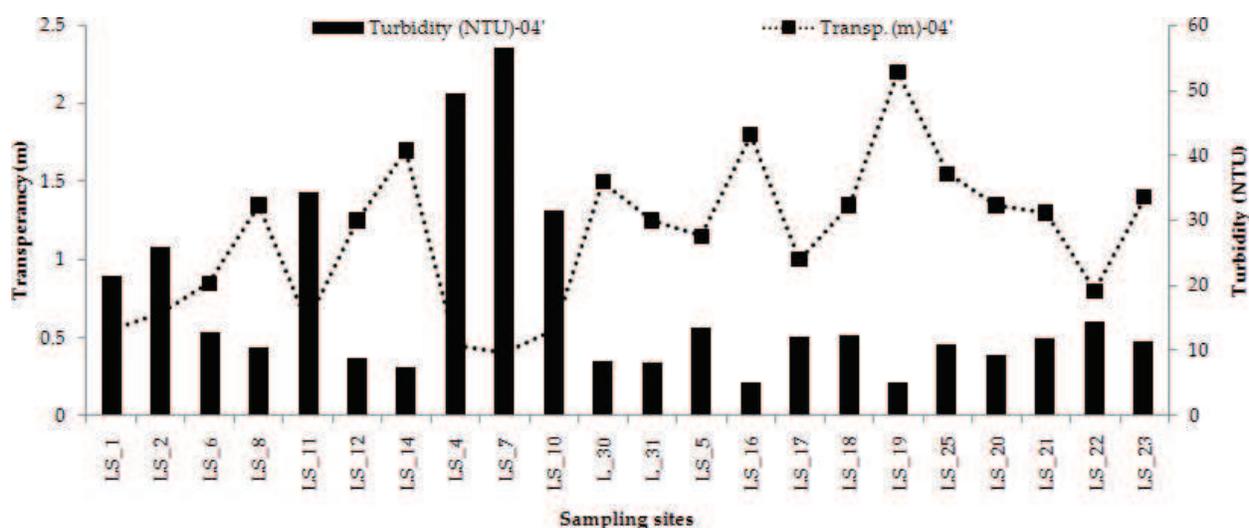
**Table 1.** Visual descriptions of collected surficial sediments during June–July 2012 survey.

	Mean ( $\pm$ SD)	n	Min. value	Max. value
<b>June–July 2012</b>				
Water depth (m)	9.1 (11.3)	30	0.87	54
Transparency (m)	0.88 (0.85)	24	0.2	3.2
<b>January–February 2004</b>				
Water depth (m)	8.2 (7.4)	25	2.5	40
Transparency (m)	1.1 (0.5)	25	0.4	2.2
Turbidity (NTU)	17.98 (15.32)	26	3.0	56.6
Chlorophyll-a ( $\mu\text{g l}^{-1}$ )	10.68 (3.73)	25	6.01	22.73
<b>July 2003</b>				
Water depth (m)	8.6 (7.5)	25	2.5	40
Transparency (m)	0.99 (0.58)	25	0.35	2.85
Chlorophyll-a ( $\mu\text{g l}^{-1}$ )	20.62 (10.69)	23	8.0	48.02
<b>August 2001</b>				
Water depth (m)	6.4 (4.0)	24	1.9	18
Transparency (m)	0.96 (0.49)	24	0.3	2.60
Chlorophyll-a ( $\mu\text{g l}^{-1}$ )	16.2 (8.9)	24	5.5	38.5
<b>February 2001</b>				
Water depth (m)	7.2 (3.4)	19	2.3	12.6
Transparency (m)	0.89 (0.35)	19	0.45	1.6
Turbidity (NTU)	19.16 (16.5)	19	6.45	74.8

	Mean ( $\pm$ SD)	n	Min. value	Max. value
<b>December 2000</b>				
Water depth (m)	6.7 (3.5)	21	2.4	14.8
Transparency (m)	0.92 (0.43)	21	0.2	1.86
<b>September 2000</b>				
Water depth (m)	8.0 (6.1)	19	2.5	26.0
Transparency (m)	0.99 (0.43)	19	0.4	2.0
Chlorophyll-a ( $\mu\text{g l}^{-1}$ )	7.70 (3.21)	19	1.26	13.08
<b>May 2000</b>				
Water depth (m)	5.6 (3.6)	20	2	14
Transparency (m)	0.83 (0.35)	19	0.32	1.5
Turbidity (NTU)	49.9 (122.2)	20	4.86	561

**Table 2.** Changes in recorded mean and range values of the sampled water depth, surface water turbidity, transparency, and chlorophyll-a concentrations in *L. Victoria* (Kenya).

Water transparency values also followed a similar trend as the turbidity in each sampling site. In May 2000, September 2000, December 2000, February 2001, August 2001, July 2003 January–February 2004, and June–July 2012, the values ranged from 0.32 m to 1.5 m, 0.2 to 1.86 m, 0.45 m to 1.6 m, 0.3 m to 2.6 m, 0.35 m to 2.85 m, 0.4 m to 2.2 m, and 0.2 m to 3.2 m). In most of the sites, the values were below 1.5 m (the maximum values were recorded at deeper sites in the open lake).



**Figure 2.** Water turbidity and transparency variations during January–February 2004 survey.

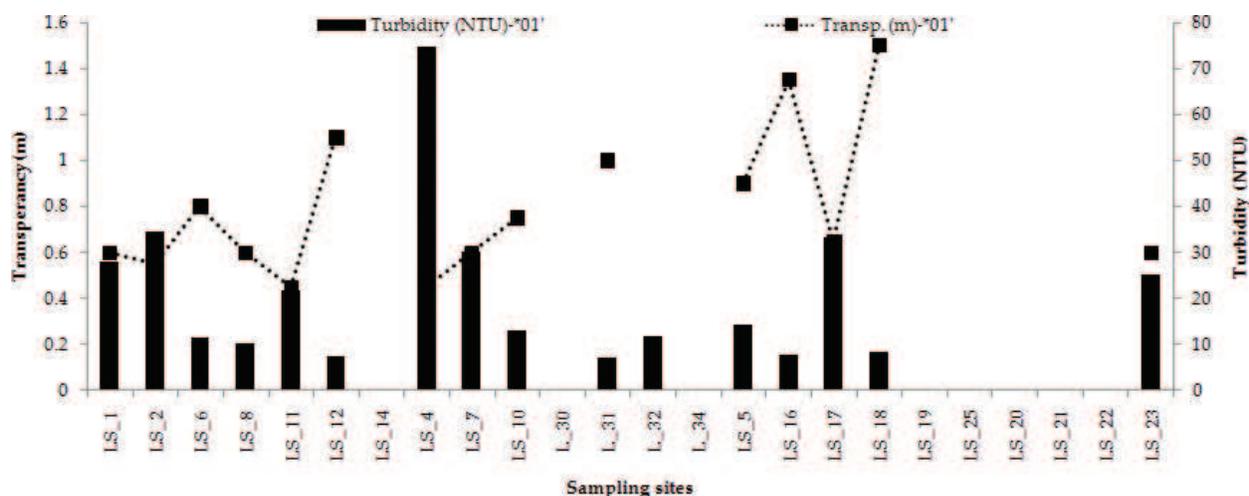


Figure 3. Water turbidity and transparency variations during February 2001 survey.

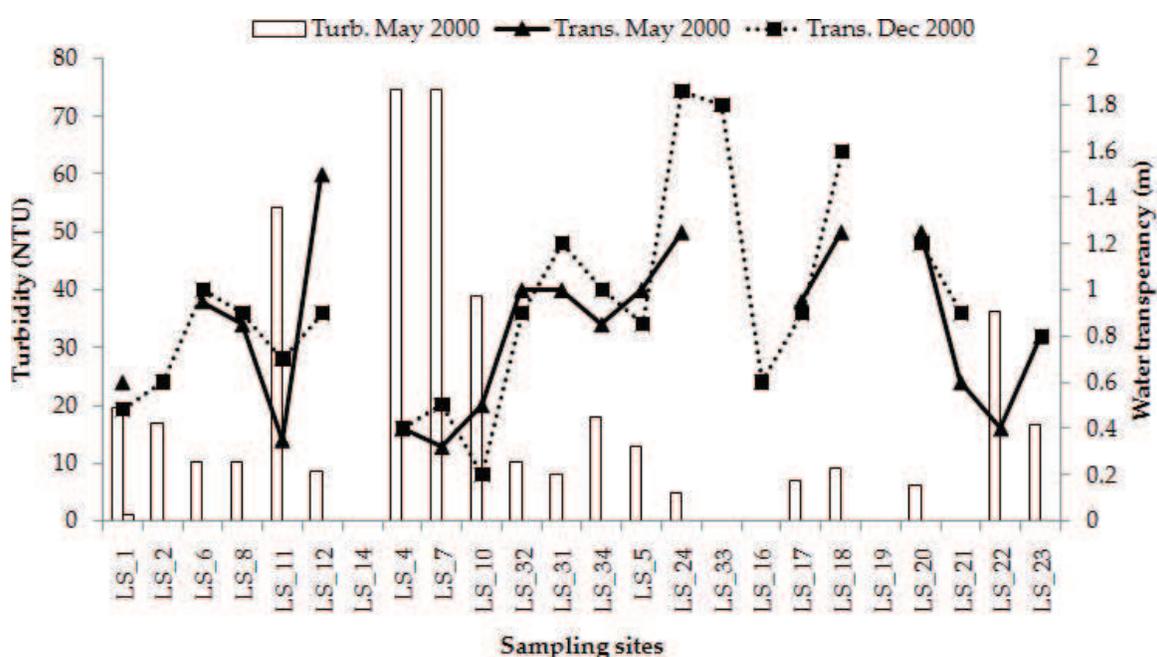


Figure 4. Surface water turbidity and transparency variations during May 2000 and December 2000 surveys.

Changes in spatial variations in chlorophyll-a concentrations have been reported previously, but only a few measurements were available from the various survey data discussed (Figure 5). In September 2000, August 2001, July 2003, and January–February 2012, the values ranged from  $3.48 \mu\text{g l}^{-1}$  to  $13.08 \mu\text{g l}^{-1}$ ,  $5.4 \mu\text{g l}^{-1}$  to  $38.5 \mu\text{g l}^{-1}$ ,  $8.95 \mu\text{g l}^{-1}$  to  $48.02 \mu\text{g l}^{-1}$ , and  $6.01 \mu\text{g l}^{-1}$  to  $22.73 \mu\text{g l}^{-1}$ , respectively. Although the values showed high spatial variability, relatively higher concentrations were evident in the gulf waters during May 2000 and July 2003. However, most of the chlorophyll-a concentrations showed insignificant and negatively correlated with water depth and water transparency. Significant correlations of the chlorophyll-a concentration with water transparency were observed during February 2001 ( $r = -0.679$ ,  $p < 0.01$ ,  $n = 19$ ). Similarly, in January–February 2004, the concentrations of chlorophyll-a were negatively and significantly correlated with surface water turbidity ( $r = -0.770$ ,  $p < 0.01$ ,  $n = 26$ ).

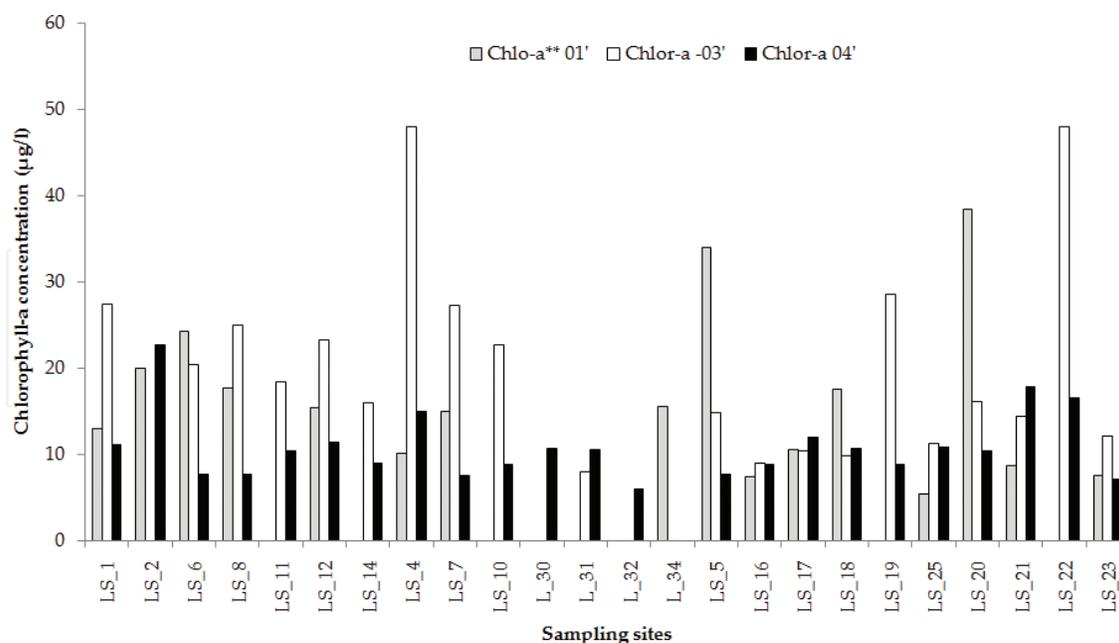


Figure 5. Chlorophyll-a concentration variations during August 2001\*\*, July 2003, and January–February 2004 surveys.

The months of May 2000, December 2000, and June–July 2012 fall within the wet season, whereas the rest of the sampling surveys were conducted during the drier season experienced around the lake basin. Calculated correlations showed strong positive correlations between water transparency and water depth with a significant Pearson  $r$  coefficient ( $p < 0.01$  level) of 0.817 (2012 survey,  $n = 24$ ); 0.717 (2004 survey,  $n = 26$ ); 0.828 (2003 survey,  $n = 25$ ); 0.792 (August 2001,  $n = 24$ ); 0.478 ( $p < 0.05$ ; February 2001,  $n = 19$ ); 0.496 ( $p < 0.05$ , December 2000,  $n = 21$ ); 0.631 (September 2000,  $n = 19$ ), and 0.541 ( $p < 0.05$ , May 2000,  $n = 20$ ).

The surficial sediments were characterized by a relatively high water content, with over 89% of the samples containing water contents of greater than 75%. The values ranged from a minimum of 27.34% to a maximum value of 91.55%. Sediment organic matter contents (1 hour drying values) were more variable (Figure 6) and ranged from 1.90% to 33.47%. Lake sites with notably low sediment-water contents were LS\_20, LS\_21, and LS\_23, whereas lower contents (less than 20%) of organic matter were found in sites LS\_20; LS\_23; LS\_34, LS\_13, LS\_1, and LS\_32; LS\_11; LS\_17; LS\_14; LS\_22; and LS\_9 and LS\_10.

The overall mean ( $\pm$  standard deviation) carbonate content (Figure 7) was  $2.26 \pm 1.48\%$  ( $n = 29$ ). Surficial sediment mean carbonate contents ranged from  $0.21 \pm 0.01\%$  to  $8.09 \pm 0.36\%$  for all the stations in 2012. The distribution of calcium carbonate contents in surficial sediments (Figure 10) shows a relatively low range when compared to values obtained in 2003/2004 which ranged from 0.5% to 21.8% ( $n = 29$ ), with a mean (standard deviation) of  $8.9 \pm 6.6\%$ . The differences are mainly attributed to the method of determination used. Current sediment carbonate concentrations are based on the gravimetric method as opposed to the wet digestion method used for the data of 2003/2004. Shell remains in surficial sediments seem to contribute to the variable concentrations found, although most of the samples contained relatively low amounts. These values are lower when compared to bottom sediments from more calcareous formations, although the contributions of other possible biochemical sources have also not been assessed.

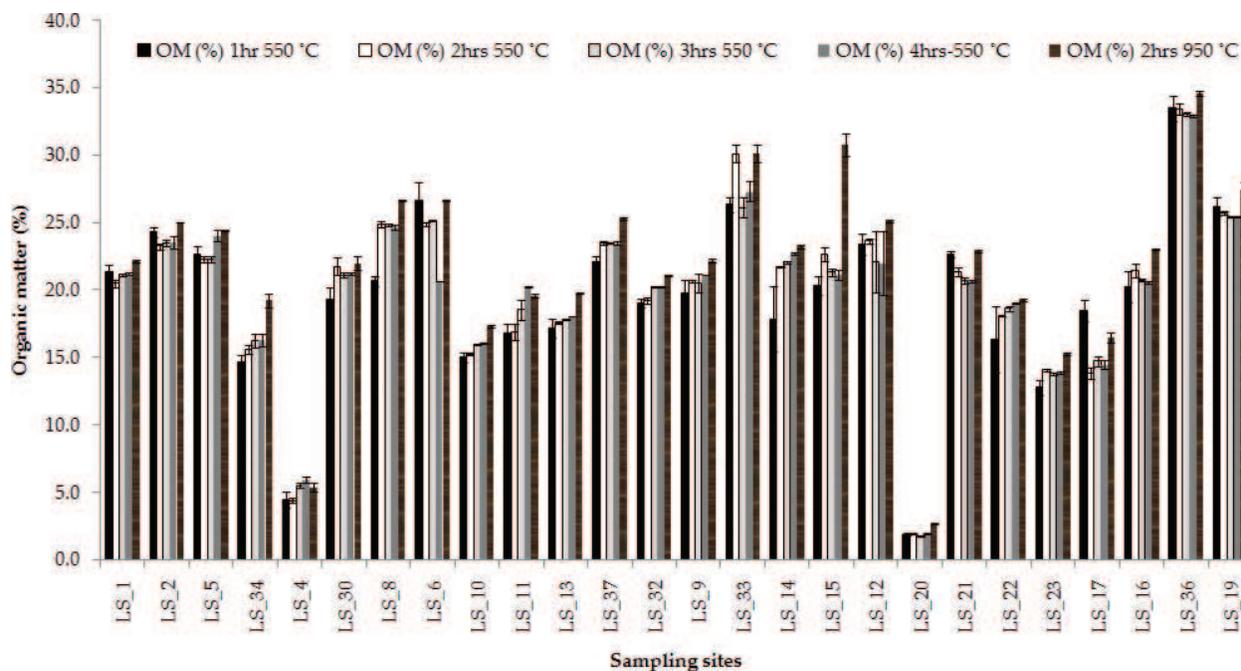


Figure 6. Mean ( $\pm$ SD) sediment organic matter variations at different drying durations and temperature using 2012 survey sediment samples.

Relationships between some of the sediment characteristics determined are shown in **Figures 8** and **9**. The organic matter content shows a strong positive correlation with water content and water depth at 0.01 level of significance (two-tailed test). Calculated bulk density values (**Figure 9a** and **b**) were within a narrow range from  $0.0205 \text{ gcm}^{-3}$  to  $0.0875 \text{ gcm}^{-3}$ , with higher values in sediments of relatively low percentage of OM and water contents. The sediment bulk density relationship with the sediment OM and water contents was best described by an exponential relationship ( $r^2 = 0.900$  and  $r^2 = 0.630$ ), with a strong negative correlation coefficient. The water content of surface sediments varies from about 30–50% in minerogenic deposits from areas of erosion to approximately 95–99% in highly organic sediments [3]. Part of the sediment

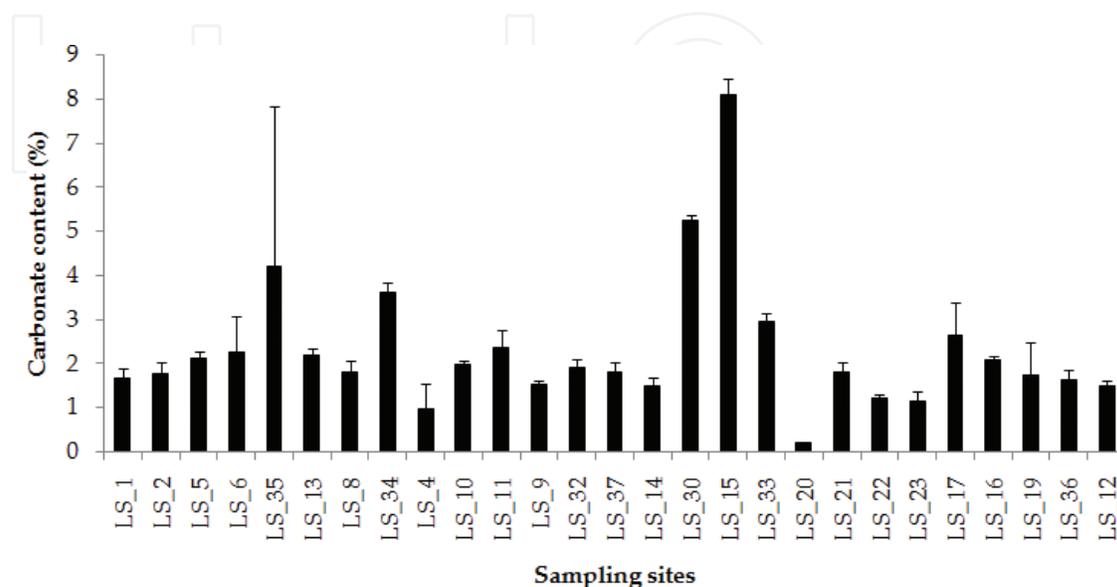


Figure 7. Mean ( $\pm$ SD) sediment carbonate content variations during June 2012 survey in *L. Victoria* (Kenya).

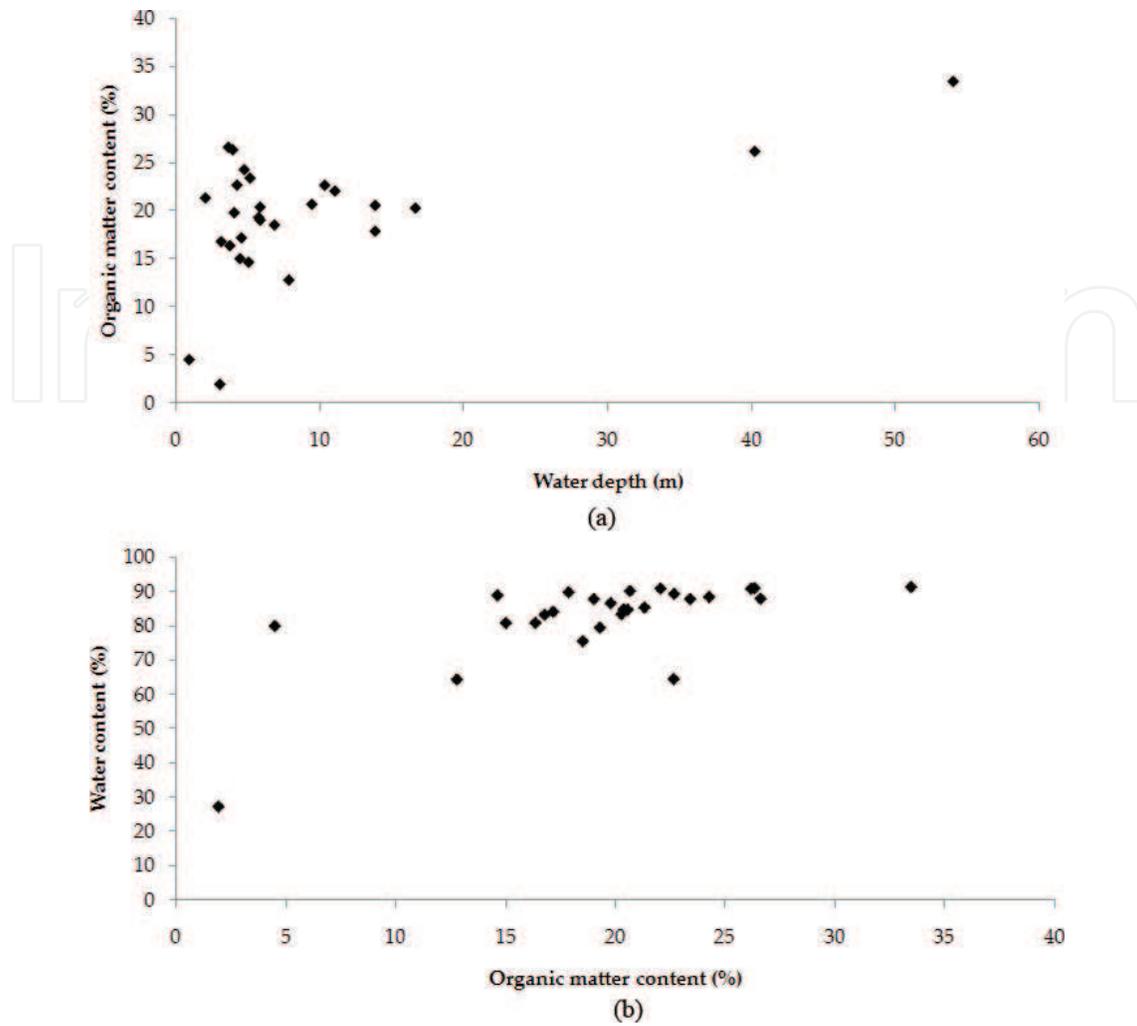


Figure 8. (a) The relationship between surficial sediment organic matter and water depth ( $r = 0.533$ ,  $n = 27$ ). (b) the relationship between surficial sediment organic matter and water content ( $r = 0.661$ ,  $r^2 = 0.437$ ;  $n = 27$ ).

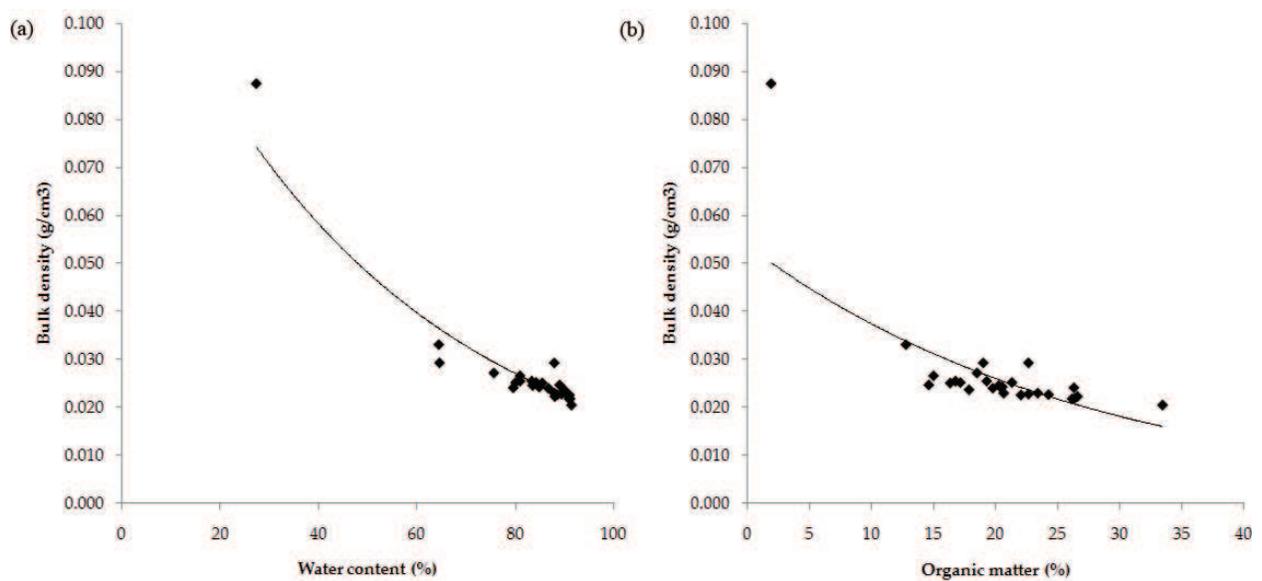
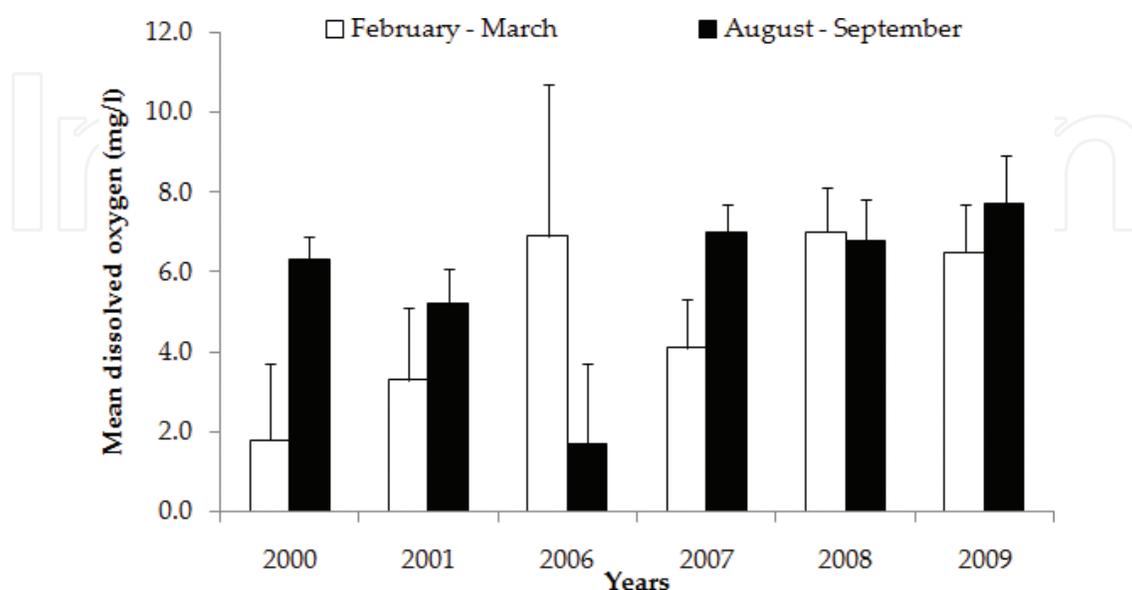


Figure 9. (a) Relationship between the sediment-water content and bulk density. (b) Relationship between the sediment organic matter content and bulk density.

water is bound to crystals in chemical structures or forms film tightly adsorbed to sediment particles, and the rest constitutes the mobile medium, which surrounds the sediment particles and takes part in exchange processes between the particulate and dissolved phases, as well as in exchange processes between sediments and lake water [3].

Surface and bottom lake water temperature show about 2°C range (surface 23.9°C to 25.9°C, bottom 23.0°C to 25.2°C) and a difference of about 0.9°C to 0.7°C. There are no large variations of the gulf water temperature when compared to the whole lake surface and > 50 m depth mean temperatures reported in 2009 ([13],  $25.88 \pm 0.86^\circ\text{C}$  surface and  $24.89 \pm 0.23^\circ\text{C}$  > 50 m) and 1927 ([71],  $24.69 \pm 0.71^\circ\text{C}$  surface and  $23.32 \pm 0.29^\circ\text{C}$  > 50 m). Studies from main lake [72] show that between 1927 and 2008 the lake's temperature increased by 0.99°C at the surface and by 1.34°C at depths >50 m, with the rate of warming increasing most rapidly between 2000 and 2008 in the whole lake. In February 2000 there were marked thermal discontinuities in the water column at a number of deep stations, with marked oxyclines at depths ranging from 30 to 50 m and with all stations being anoxic from 50 m downwards [72]. In contrast, in February 2007 the lake's temperature had risen, especially at the bottom, and both the thermal discontinuities and oxyclines were much reduced, only one station recording a dissolved oxygen concentration of  $<2.0 \text{ mg l}^{-1}$  at 50 m [72].

Lake waters are more towards neutral alkaline (pH values of 7.59–8.51) and of high oxygenation levels in the surface layers, and sometimes appreciable oxygen levels occur even in deeper waters (above  $3.45 \text{ mg l}^{-1}$  in 2012). In July 2003, the dissolved oxygen in bottom water stations was above  $2 \text{ mg l}^{-1}$  in all stations. However, in some instances, very low to anoxic conditions have been reported in deep sites. Sitoki et al. [13] reported mean dissolved oxygen of  $2.55 \text{ mg l}^{-1}$  at stations of greater than 40 m depth (**Figure 10**) from lakewide surveys in 2000 and 2001 (February to March) and  $5.75 \text{ mg l}^{-1}$  (August to September). But less deoxygenation of lakewide bottom was reported at the same stations in February–March and August–September of 2006 to 2009 surveys with mean DO concentrations of  $6.13 \text{ mg l}^{-1}$  and  $5.80 \text{ mg l}^{-1}$ , respectively.



**Figure 10.** Mean dissolved oxygen concentration ( $\text{mg l}^{-1}$ ) at greater than 40 m lake water depth during February–march and August–September lakewide surveys in different years (values adapted from Sitoki et al.) [13].

In Lake Victoria, thermal stratification, leading to hypoxia, was observed in the late 1920s [4]. Hypoxia conditions were restricted to the deeper waters (>60 m) and for shorter periods during the rainy season [6]. Lake Victoria has three phases of thermal stratification; moderate stratification occurs between September and December, stable stratification in January to March/April, and deep strong mixing in June to July [6, 73]. Stratification of the water column isolates the bottom water from exchange with oxygen-rich surface water and the atmosphere, while decomposition of organic matter in the isolated bottom water consumes dissolved oxygen [24]. For lakes, factors affecting vertical water mixing such as wind and temperature can lower DO in bottom waters to anoxic levels. Increase in deepwater temperatures, increases thermal stratification stability [74]. Thermal stability makes the lake less able to mix effectively and promotes low oxygen conditions in deepwaters during stratification period between September and April [73].

Low dissolved oxygen or hypoxic conditions can be due to natural causes such as algal respiration, seasonal flooding, stratification, and anthropogenic causes. Low dissolved oxygen environments vary in temporal frequency, seasonality, and persistence [75–77]. Hypoxia occurs naturally in habitats characterized by low mixing or light limited, heavily vegetated swamps and backwaters that circulate poorly, stratify, and have large loads of terrestrial organic matter [78, 79]. Levels of hypoxia are mainly determined by primary productivity, depth, and temperature of the aquatic body [77]. Increasing and widespread deepwater anoxia in Lake Victoria might put at risk the entire fishery [80]. In Lake Victoria, severe hypoxic conditions (<1.0 mg l<sup>-1</sup>) now persists at depths below 40–50 m which cover about 35% of the lake's total bottom area [81]. Water hyacinth is notably a persistent floating macrophyte in Lake Victoria. Shading of the water by the hyacinth curtailed photosynthesis, while microbial breakdown of decaying plant material used the available oxygen. The waters below water hyacinth recorded DO as low as 0.1 mg l<sup>-1</sup> making it inhabitable to most fish [82]. Additionally, the weed affected the distribution of fish by blocking migratory routes of those escaping low DO and predation [83]. However, studies by Njiru et al. [82] found the hyacinth to have led to recovery of the native species which were more hypoxia tolerant such as catfishes, lungfish, and tilapia. Hypoxia is physiologically stressful for fish, shellfish, and invertebrates with prolonged exposure to anoxia being fatal to most aquatic fauna [76, 84]. Njiru et al. [24] explored the impacts of hypoxia on the fishery of Lake Victoria. Hypoxia exposure can prompt both lethal and sublethal effects in fishes, leading to reduced feeding, reproductive, growth, metabolism, and slower reaction time. These effects vary across fish species [84] but also depend on the frequency, intensity, and duration of the hypoxic events [76]. In shallower lake areas, with permanent cover of macrophytes, especially large extensive floating water hyacinth, deoxygenated waters may influence the distribution of low oxygen-intolerant fish species in the lake.

### **3.3. Sources of organic matter in Lake Victoria sediments**

Sediments accumulated in lake basins consist of various organic and inorganic materials mostly utilized as proxies for climatic changes and as historical records of the lake. The gulf's bottom deposits are mainly a combination of the several externally transported materials, surface runoffs, and shoreline-eroded materials and slowly settling suspended loads. An equally important source is the autochthonous organic matter which is aerielly derived materials. The first observations on the nature of the bottom of Lake Victoria were made by Graham and

Worthington during their survey in 1927–1928 [71]. They stated that nearly all the bottom of the lake was covered with a fine greenish-black mud which was almost entirely composed of the dead shells of diatoms [10]. First palaeolimnological records of bottom sediments in the northern part of the main Lake Victoria (outside the Nyanza Gulf) were provided by Kendall [15]. Scholz et al. [16] study revealed that fine-grained late-Pleistocene and late-Holocene sediments having a maximum open-basin thickness of about 8 metres overlie older desiccated lake sediments, alluvial materials, Precambrian crystalline, and tertiary volcanic rocks depending on the position in the lake. The distribution of these sediments mimics bathymetry. Thicker sediment layers may be found near bathymetric heights and inshore waters. Analyses of the composition of oven-dried samples of mud revealed 24–64% silica, 4–25% carbon, 1.5–4.8% iron, 0.6–2.2% nitrogen, 0.5–2% sulfur, 0.04% phosphate, 0.3% Ca, 0.07% Mg, 0.05% K, and 0.03% Na [10]. Talbot and Livingstone [85] used geochemical analysis of organic matter in sediment cores from Pilkington bay, Ugandan area of *L. Victoria* in 1971 (depth of 32 m and 66 m) to provide a history of lake level fluctuations. The core sediments were characterized by moderate to low organic contents and very low hydrogen index. Very low HI from sediments rich in algal remains indicates severe degradation of the organic material. At 6.9 m and 9.8 m downcore Ibis core 1, the TOC values were 18.6 and 2.6%, respectively [85]. Similarly, at 7.3 m and 10.3 m downcore Ibis core 3, the TOC values were 7.9 and 2.1%, respectively [85]. TOC and HI both decline as an exposure surface is approached, mainly due to the selective removal of unstable components by bacterial respiration and inorganic oxidation. The carbon isotopic composition of the organic matter shows significant variations through the core  $\delta^{13}\text{C}_{\text{org}}$  values were  $> -20\text{‰}$  at and below the discontinuity surfaces and  $< -20\text{‰}$  above the upper shell bed. According to Talbot and Livingstone [84], variations in the carbon isotopic composition of the bulk organic matter may reflect mainly changes in the relative contributions from different plant communities, which are also related to changes in the lake. Although all aquatic algae and many vascular plants have carbon isotopic compositions in the range from  $-22\text{‰}$  to  $-30\text{‰}$ , plants using the  $\text{C}_4$  photosynthetic pathway have range from  $-9\text{‰}$  to  $-16\text{‰}$  [86, 87]. Variations in the bulk organic matter isotopic composition of organic matter in Lake Victoria are likely principal to reflect varying contributions from plant communities with different proportions of  $\text{C}_3$  and  $\text{C}_4$  plants. In particular a sediment dominated by inputs of aquatic algae or forest trees is likely to have a  $\delta^{13}\text{C}$  between  $-20\text{‰}$  and  $-30\text{‰}$ , while substantial inputs from  $\text{C}_4$  graminoid plants from either marshes or terrestrial grassland will tend to produce a  $\delta^{13}\text{C}_{\text{org}}$  between  $-10\text{‰}$  and  $-15\text{‰}$ . Characterization of stable isotope signatures of various organisms from the lake shows varied values, but the information is limited spatially. Studies on sources of carbon in the *L. Victoria* ecosystem reported mean ( $\pm$ SD) values of stable C isotope values for organisms collected at deep site and littoral site in Napoleon Gulf in 1995 [69] for  $\delta^{13}\text{C}$  were gastropods ( $-19.0 \pm 1.7$ ), bivalves ( $-18.0 \pm 0.7$ ), *Rastrineobola argentea* ( $-16.9 \pm 0.8$ ), and *Lates niloticus* ( $-18.9 \pm 0.2$ ). The  $\delta^{13}\text{C}$  of plants ranged from  $-8.8\text{‰}$  to  $-24.6\text{‰}$ , while in fishes the values ranged from  $-18.6\text{‰}$  to  $-24.5\text{‰}$ , suggesting assimilation of mostly  $\text{C}_3$  sources for the fishes [67]. According to Gichuki et al. [68], aquatic macrophytes from wetland ecosystems in Nyanza Gulf had  $\delta^{13}\text{C}$  isotopic ratios ranging from  $-8.92$  to  $-29.18$ , and for the dominant macrophytes, they observed most enriched  $\delta^{13}\text{C}$  values for *Cyperus papyrus* and most depleted  $\delta^{13}\text{C}$  values for *Eichhornia crassipes*. Fractionation of carbon isotopes during photosynthesis is a key parameter for understanding organic carbon isotope signatures in aquatic ecosystems. Photosynthetic fractionation of carbon isotopes can occur at the diffusion, dissolution, and

carboxylation step [88]. During photosynthesis, plants preferentially acquire the lighter carbon isotope,  $^{12}\text{C}$ . Consequently, plant organic matter has a lighter isotope ratio than the source inorganic carbon [88]. More recently, on the Tanzanian portion of the lake, Machiwa [35] demonstrated the potential to discriminate between input sources of organic material into lakes using stable isotope signals in sediment and suspended particulate matter. Variations in  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , and C/N ratios in SPM and sediments in inshore areas were due to differences in the proportions and sources of autochthonous or allochthonous matter. Watershed characteristics, such as urbanization, and lake characteristics, such as algal blooms, also immensely influenced the stable isotope signal of the organic matter in sediments [35]. Although this study did not incorporate isotopic studies, it clearly shows that interpretation of such information demands more spatial and temporal information on isotopic patterns to understand within lake variations in allochthonous inputs, considering the high seasonal variability in a tropical type of climate experienced in the lake region.

Short cores from the open lake document a shift in lake conditions beginning in the 1930s that progressed to the major ecosystem collapse of the early 1980s [14]. The coincidence of the shift in sediment properties in the 1930s with the beginning of rapid expansion of human population and agricultural activity suggests cause and effect. It is conceivable that the lake experienced similar conditions due to natural causes between about 9800 and 7500 years ago [14]. From core studies, deep rift lake basins [89], with anoxic depths below 250 m, contains thick sequence of biologically undisturbed, finely laminated muds and silts. Similar low oxygen conditions to anoxic conditions reported in deep sites of Lake Victoria a relatively shallow basin can possibly promote accumulation of significant amounts of organic matter after deposition, depending on type of sedimenting materials, the extents of bioturbation processes, and redox conditions. There are no experimental studies on downward flux measurements of particulate carbon in the gulf areas. In shallower areas, downward fluxes of particulate organic matter may be highly variable, and the remobilization of deposited sediments through resuspension caused by physical mixing processes may contribute to variations in sediment composition and low-sediment organic matter.

Understanding sources, dispersion pathways, and sinks of sedimentary materials can improve our understanding of various geochemical cycles in the lake. In aquatic environments dissolved phosphate is consumed during growth of phytoplankton and is regenerated during bacterial decomposition of organic matter. The regenerated phosphate may be released to the overlying water, reprecipitated within the sediment as authigenic phase or adsorbed by other constituents of sediment [90]. Development of anoxia in sediments will lead to reduction of iron oxides and release of sequestered P. Adsorption on oxidized surface sediment affects the flux of phosphate from the sediment to the overlying water [91].

Besides the sediment physical factors, iron-manganese oxides, clay minerals, organic matter, and reactive Fe are among the sedimentary geochemical factors controlling chemical partitioning and bioavailability. Linnik and Zubenko [92] showed that the release of heavy metals from bottom sediments was promoted, for example, by a deficit in dissolved oxygen, a decrease in pH and redox potential (Eh), and an increase in mineralization and in dissolved organic matter concentration. Compared with other natural environmental substrates, sediments have a greater capacity to bind Hg. More than 90% of the total Hg in sediment-water system is

sorbed or held in sediments [27]. Sediments therefore serve as useful long-term records of the material influx and provide historical records for evaluating past and other ecological changes occurring in the lake. However, very few studies have been concentrated in the gulf, as the best depositional basins for provision of long-term records are in the main lake. Therefore, continuous provision of data on the sedimentary environment is valuable in understanding processes within these areas and their influences on the above water quality, considering the fact that the area receives significant inputs from the inflowing rivers and nearby human activities.

The six coring stations, representative of the main lake depositional basin, were located at a water depth range between 48 and 68 m [60], but none was located in the Nyanza Gulf, where the depths are below 60 m. Accumulation of fine-grained Holocene sediments in offshore regions of Lake Victoria is restricted to the deep east-central basin floor [16, 59]. However, surficial sediment deposits the deep gulf, and open stations contain similar organic rich muds. Verschuren et al. [60] noted that with increasing distance from the depositional centre, progressively thinner sheets of Holocene sediments occur, for example, about 5.4 m at station V95-1G and 3.6 m at V96-1MC (eastern central basin), reflecting bottom dynamics that become less and less favorable for undisturbed sediment accumulation. According to Verschuren et al. [60], in the transect of stations examined, greater physical biological sediment mixing at shallower depths is evident in the lack of flocculent surface muds in cores V96-1MC and V96-8MC (western central basin). In these shallow sites, organic matter decreases from 32% at the top of the short sediment core surface, to 23% at bottom of core compared to a change of 14% (top of core) to 10% (end of core). The deepest site short cores at 58 m and 68 m water depth had a sub-oxic sediment–water interface ( $0.0 \text{ mg l}^{-1}$  to  $0.7 \text{ mg l}^{-1}$ ), with high and near constant organic matter contents along the sediment core (35–38% near top surface of the core and 33–35% end of core). The core closer to the extreme western side of the open lake portion of the Nyanza Gulf contained 27% (top) and 25% (end of core).

### 3.4. Sedimentation and nutrients in Lake Victoria

Rivers contribute a significant load of suspended materials annually into the lake. Although it is not possible to provide current rates of resuspended loads, the inputs of organic matter into the depositional areas seem significant from the productive water column (autochthonous sources). Johnson [92] summarized published sedimentation rates for several lakes. There is surprisingly little difference between the sedimentation rates observed in tectonic versus glacial lakes, even though the relief, and hence, the sediment supply rate per unit area of drainage basin should be higher around tectonic lakes. Verschuren et al. [60] established average recent sedimentation accumulation rates of  $0.032 \pm 0.001$  to  $0.028 \pm 0.001 \text{ g cm}^{-2} \text{ yr}^{-1}$  from  $^{210}\text{Pb}$  dating of sediment cores in deep depositional sites in the main lake. The rates are lower but comparable with other variable rates reported for other temperate lakes [93]. Variable sedimentation rates are reported in different types of lakes, but the mean values reported by Verschuren et al. [60] for the lake appear to fall within the low end values for other lakes. In L. Erie, sedimentation rates [94, 95] estimated from 35 stations varied from less than  $20 \text{ mg cm}^{-2} \text{ yr}^{-1}$  to greater than  $1000 \text{ mg cm}^{-2} \text{ yr}^{-1}$  with an average of  $230 \text{ mg cm}^{-2} \text{ yr}^{-1}$ .

Although soil types and land uses vary in different drainage basins, the surrounding gulf areas are under the same typical tropical wet climate. Lindenschmidt et al. [96] in a neighbouring rural

catchment of *L. Victoria* found out that less loading will occur from riverine systems that have lower discharges, consist of nonagricultural land, and have low basin slope. Soil erosion and leaching in this tropical region increase dramatically as slope incline increases. A sediment core was taken 55 m water depth off western Kenya (core at station 103) and the diatom and chemical stratigraphy analyzed [9]. The dry weight sedimentation rate increased after 1960 to  $90 \text{ gm}^{-2} \text{ yr.}^{-1}$  from  $57 \text{ gm}^{-2} \text{ yr.}^{-1}$  before then. There is an interpretable sequence which begins with increasing production of *Cyclostephanos* concurrent with an increase in C and N deposition early in the century [9]. These trends continued until the decade of the 1960s when P and biogenic Si deposition began a rapid increase. By the late 1960s, *Melosira* spp. was nearly gone largely replaced in the diatom community by *Nitzschia*. By the late 1970s, modern rates of C, N, P, and Si deposition were established as was the modern diatom community [9]. The increased deposition rates of N beginning in the 1920s and P beginning in the 1950s were likely results of watershed and airshed disturbance [9]. Primary production was extremely high as lake level rose in its first 500 years, nourished by the high input of nutrients from the flooded landscape [14].

Concentrations of P in the gulf lake water (2000–2002) were found to be different from those in the main lake with phosphorus fractions, soluble reactive P, and total P being significantly higher in the main lake than in the gulf [53]. Well-oxygenated conditions in the gulf keep the  $\text{PO}_4\text{-P}$  strongly bound to mineral particles, whereas in the main lake, where deeper depths allows for development of anoxia, it is released into solution [53]. In 2005 and 2006, an assessment of the potential for sediments to contribute to the water column P concentrations in Lake Victoria showed that sediment total TP, apatite phosphorus, inorganic phosphorus, and organic phosphorus increased in sediments along the gulf towards the main lake, while the non-apatite inorganic phosphorus (NAIP) increases were less defined [65]. The longitudinal gradient of sediment TP and its fractions in Nyanza Gulf is a result of high rates of terrigenous input and resuspension and transport of the light, phosphorus-rich inorganic and organic matter towards the main lake [64]. The non-apatite inorganic P concentration on the western end of the gulf is exceptionally high,  $>1500 \text{ mgkg}^{-1}$  [66]. Total P in the sediment ranged from 812.7 to  $1738 \text{ mgkg}^{-1}$  dry weight and was highest in the Rusinga Channel, the exchange zone between the gulf and the main lake. In the gulf and the Rusinga Channel, the less bioavailable apatite phosphorus dominated, whereas in the deeper main lake, organic P was the major fraction illustrating the importance of anaerobic release of P from sediments and acceleration of internal P loading in the main lake [65].

Chemical processes within the sediments play an important role in the P fluxes within and from sediments. In aquatic environment dissolved phosphate is consumed during growth of phytoplankton and is regenerated during bacterial decomposition of organic matter [91]. Much of the regeneration takes place in the water, but in relatively shallow environments such as lakes, estuaries, and continental shelves, sediments may play an important role in the regeneration of phosphate [97]. The regenerated phosphate may be released to the overlying water, reprecipitated within the sediment as authigenic phase or adsorbed by other constituents of sediment. Adsorption on metal oxides in the sediment has been identified as one of the principal reactions involving phosphate [90]. Mortimer [98] has described the oxidized surface layer as a trap for phosphate. The reactions that release phosphate to the porewater are desorption of phosphate from surface sites on sediment particles, mineralization of organic matter, and reduction of iron oxides in the anoxic zone of the sediments [99].

### 3.5. Inferences from stable isotope signatures in lake sediments and their applications

Organic rich sediments have been reported in sediments from depositional basins of the main Lake Victoria [100, 101]. Previous studies show a slight variability in SOM contents (Figures 11 and 12). Mean sedimentation rates, and organic carbon (total core length mean) of sediment core 103 (core recovered at 56 m water depth in 1990 by Hecky) [9], 96–5 MC (core recovered at 68 m water depth in 1996 by Verschuren et al. [102]), and Itome (core recovered at 25 m water depth in 1995 by Campbell et al. [103]) were 100, 320, and 276  $\text{gm}^{-2} \text{yr}^{-1}$  and 168, 204, and 184  $\text{mgg}^{-1}$  dry weight, respectively. A similar trend in sediment organic matter emerged in surficial sediments in the relatively shallower Nyanza Gulf, with significant spatial differences especially in the zones with significant influence of externally derived riverine inputs. According to Hecky et al. [100], the isotopic analysis of all the three sediment cores recovered by Hecky [9], Verschuren et al. [102], and Campbell et al. [103] recorded an increase in the isotopic signature of the sedimentary organic matter (from a baseline  $-22\%$  to  $-21\%$  in the deepest core and no clear trends for inshore Itome core, which was significantly  $\delta^{13}\text{C}$  enriched). According to Hecky et al. [100], a Mwanza-Port Bell (southern shore-northern shore) surface water transect in October 1995, of main *L. Victoria*, show highly correlated POC and PN ( $r = 0.96$ ) with a mean molar C/N ratio of 7.2 with higher ratios nearshore (up to 8.4). These low, near Redfield ratios, values for C:N are characteristic of Lake Victoria [104] and are indicative that the particulate matter sampled was of algal origin. Isotopically depleted PC occurred offshore, and  $\delta^{13}\text{C}$  was increasingly enriched nearer the coasts as depth shoaled. The  $\delta^{15}\text{N}$  of the PN showed an inverse pattern with highest  $\delta^{15}\text{N}$  values observed offshore.

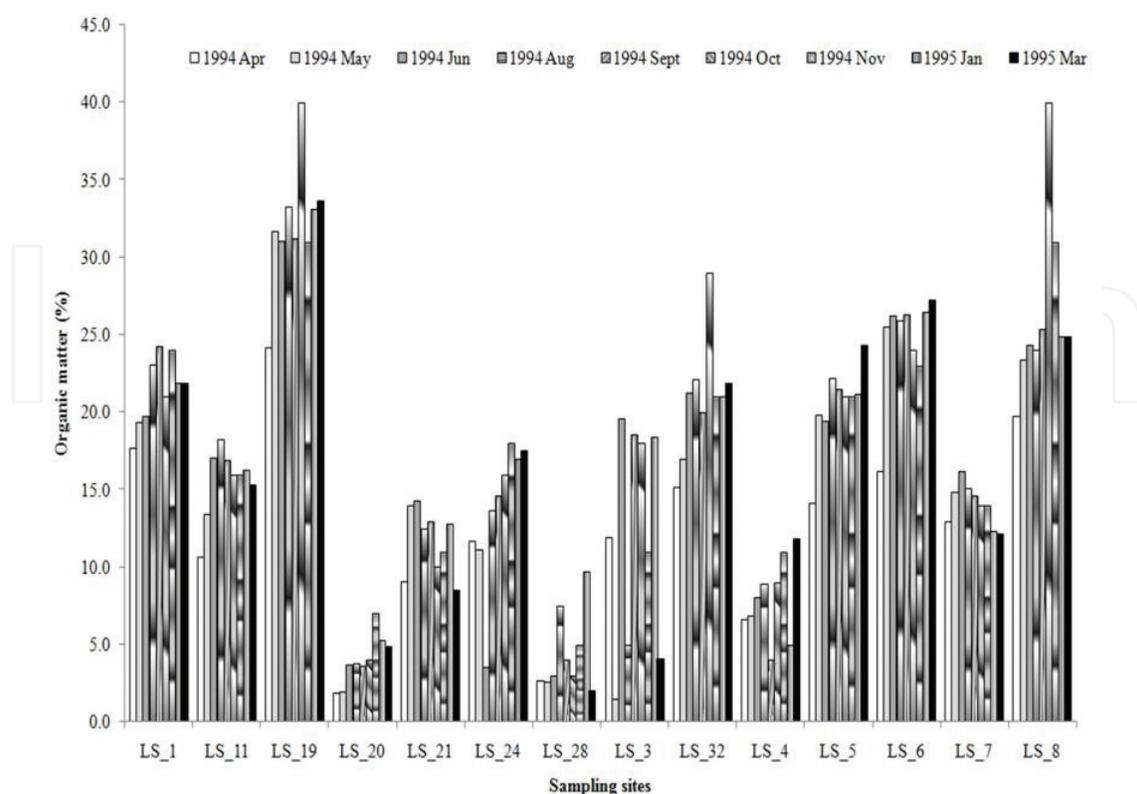


Figure 11. Monthly sediment organic matter contents in surficial sediments.

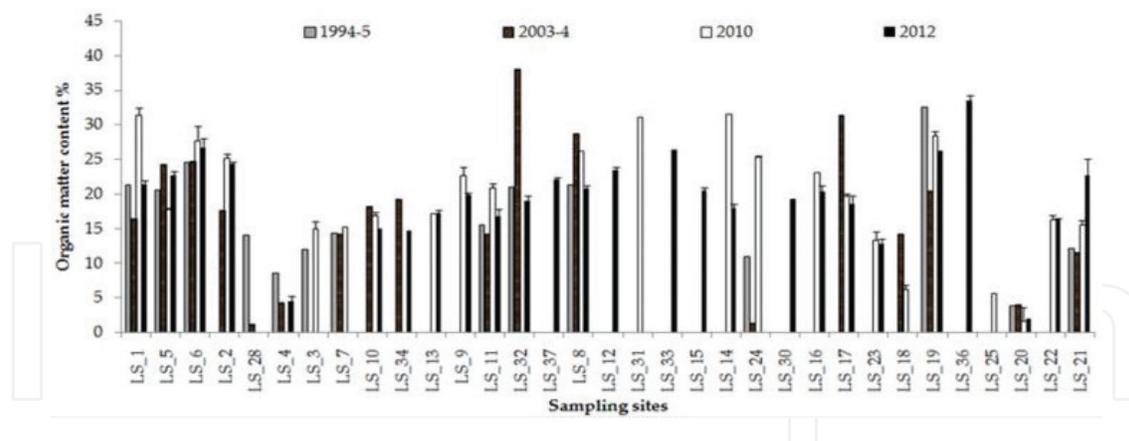


Figure 12. Mean sediment organic matter contents ( $\pm$ SD) in surficial sediments.

Consequently, there was a strong inverse relationship between  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ , with the former decreasing at high algal abundances and the latter increasing as PC increased. The scatter of the isotopic signatures with increasing algal abundances indicates that these relationships are dynamic in nature responding to the availability and demand for  $\text{CO}_2$  and DIN [100]. The Nyanza Gulf is more active in terms of exchanges between the land and the lake, when compared to the offshore depositional basins. Again, exports of organic rich waters from urbanized areas act as important modifiers of sedimentary organic matter derived from in-lake productivity and higher plant production.

### 3.6. Significance of floating water hyacinth mats in Lake Victoria on sediment organic matter accumulation

A major portion of the organic matter in freshwater systems originates from the terrestrial environment. The bulk of allochthonous organic matter consists of structurally complex polysaccharides, lignocelluloses, and other complex organic compounds [105]. Autochthonous production is also an important source of organic matter in lakes and is generally less refractory than allochthonous carbon [106, 107]. Autochthonous organic matter is primarily derived from phytoplankton and macrophytes, but, in shallow clear lakes of Nyanza Gulf from April 1994 to March 1995 from different surveys conducted in Nyanza Gulf between April 1994 to 2012 where light penetrates to the bottom, benthic micro-algae can also be an important source of detritus [106].

Littoral sediments are often heterogeneous because of the presence of rooted macrophytes and the resuspension of particles in shallow water during windy periods, and the net sedimentation of organic matter is small because of alternating sedimentation and resuspension episodes [36]. In addition there can be a significant downward transportation of material along the lake bottom resulting in deposition of organic matter in the profundal sediments [36]. Submerged aquatic macrophytes are generally soft in nature, moderately rich in protein, and are preferred by different herbivorous fish. The production of littoral and pelagic phytoplankton and of the dominant biomass of submerged macrophytes and epiphytes in littoral zone contributes to the total sediment organic matter accumulated over time.

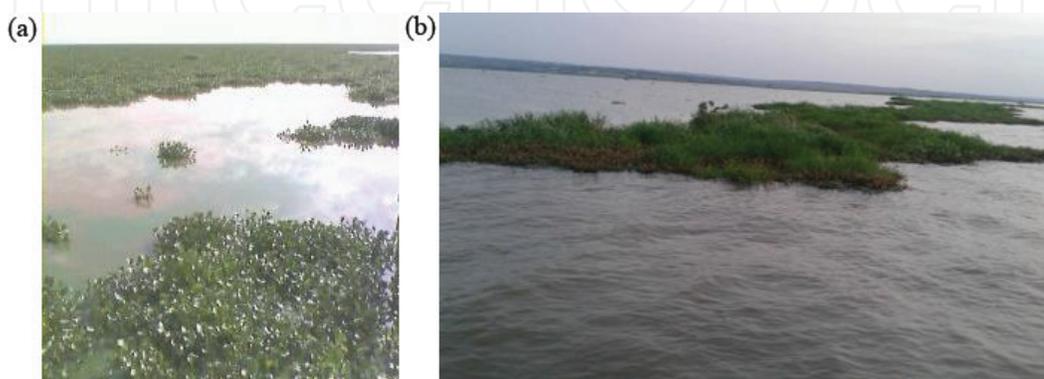
Much of the organic matter produced by these larger aquatic plants remains in the wetlands and littoral zones of lakes and undergo decomposition [20]. During senescence and after

death of organisms, much of the organic matter is released as soluble compounds. The particulate components decompose at various rates depending on their location, composition, and environmental conditions, particularly those of temperature and oxygen availability. When decomposing tissue falls to the sediments in detrital masses, the environment of the aggregates rapidly becomes anaerobic. Under these reducing conditions, rates of decomposition are decreased greatly [20].

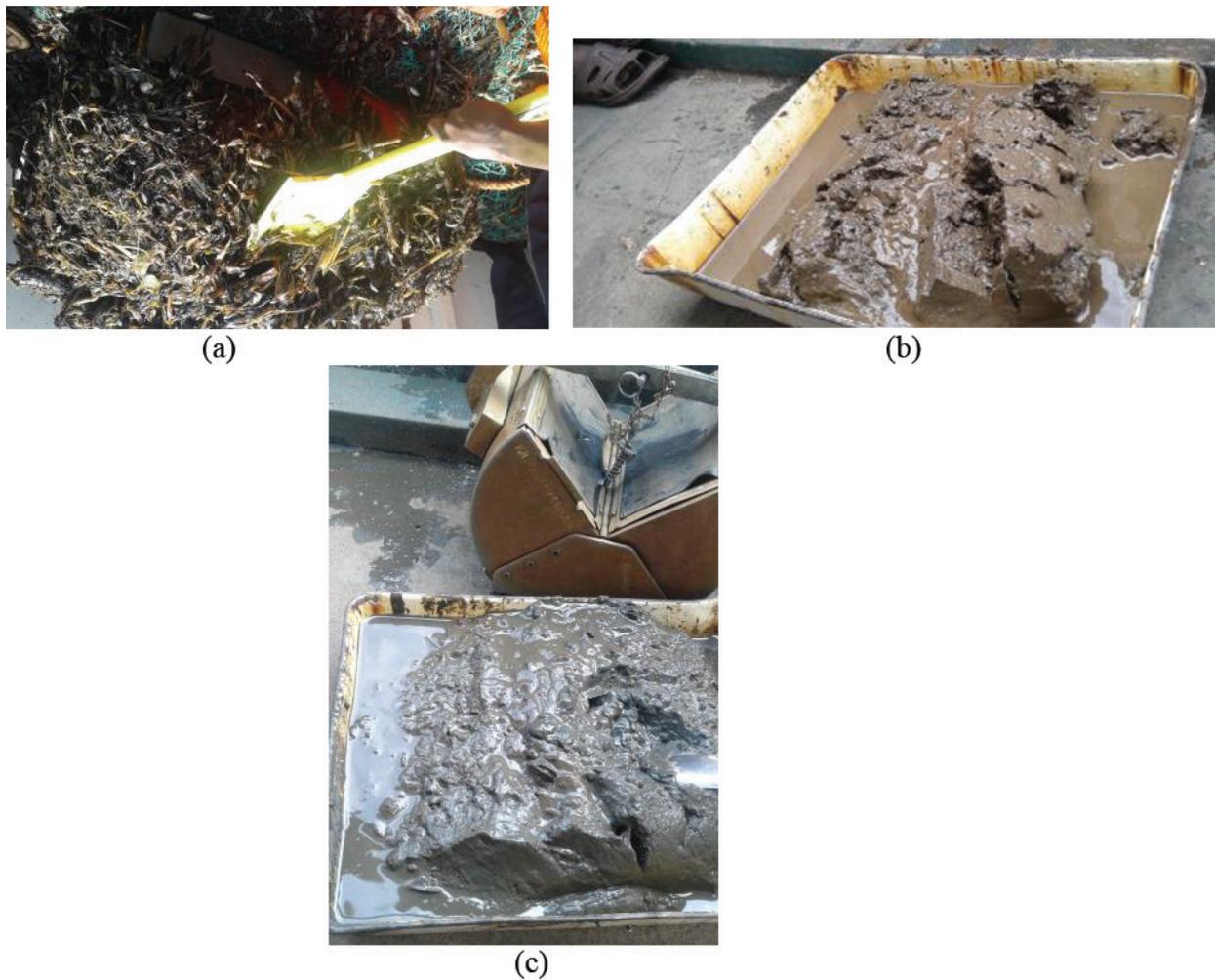
Water hyacinth has contributed to several to various socio-economic impacts in the lake fishery, such as lake transportation, artisanal fishing. Also, Ofulla et al. [108] study on associations between aquatic macrophytes and vector snails for schistosomiasis illustrated that *B. sudanica* and *B. africanus*, the two most common snail hosts of schistosomiasis in the Nyanza Gulf, were found associated with the aquatic macrophytes in the lake waters. Besides this, a form of ecological succession (the progressive displacement of one or more species of plants by other species) has been observed in Lake Victoria, in which stationary mats of water hyacinth along the shores and banks of rivers were replaced by other aquatic plants such as hippo grass (*Vossia cuspidata*) and other aquatic sedges such as *Cyperus papyrus* and climbing plants such as *Ipomoea aquatica* [109–113], creating concern among stakeholders in the region. The dispersal and continuous presence of water hyacinth is therefore still a concern in *L. Victoria* since the 1990s. Kisumu Bay, Homa Bay, Asembo Bay, Luangwa Gembe, off Sondu-Miriu river-mouth, off Kibos river-mouth, and Dunga are in-lake areas commonly found associated with macrophytes, including water hyacinth as observed by Ofulla et al. [109]. Besides this, large *Cyperus papyrus* swamps are found around major river-mouths of Sondu-Miriu, Nyando, Kisumu Bay, Kibos river-mouth, and Dunga areas. Persistence of extensive floating mats of water hyacinth and other macrophytes in major bays of Nyanza Gulf (**Plates 1a, 1b, and 2a**) has the potential to introduce a lot of plant debris and decaying particulate organic materials into the lake sediments (**Plates 2b and 2c**).

### 3.7. Are future potential impacts from cage culture on lake sediments of concerns?

In recent years, aquaculture production has increased worldwide, mainly due to the increasing demand from aquaculture produce and the need for improved food security. These developments are supposed to improve income and livelihoods but can generate negative



**Plate 1.** Water hyacinth and other macrophytes in Nyanza gulf of Lake Victoria in July 2012 (a) and June–July 2017 (b).



**Plate 2.** Undegraded water hyacinth and other macrophytes (a), retrieved from a trawl net and freshly retrieved surficial sediments from shallow riverine zones (b) and from deep open lake areas (c) using a Ponar grab sampler, in Nyanza gulf of Lake Victoria in June–July 2017.

impacts such as pollution, landscape modification, or biodiversity change, if best aquaculture practices are not followed. However, it should be recognized that to date the majority of aquaculture practices have had few adverse effects on ecosystem [114]. First studies on impact of fish cage operations on surrounding water environment in L. Malawi [115, 116] were minimal despite substantial discharges from the cages, due to dispersion by water currents and aggregation of wild fish species feeding on the wastes. Experimental studies on cage culture from Uganda and Tanzanian side of *L. Victoria* found no consistent environmental changes using water quality parameters, phytoplankton and macro-invertebrates [117, 118]. Effect of nutrient discharge on DO was not pronounced. Nevertheless, some cases of environmental degradation in coastal areas have occurred due to, for example, intensive cage culture operations in Europe and shrimp farming practices in Southeast Asia and Latin America [114, 119].

Fecal contamination implies a high risk of contracting waterborne diseases if the water is used for drinking purposes without pretreatment. *Escherichia coli* (*E. coli*) is used as an indicator for human and animal fecal pollution of water. Urban sewage and industrial effluent [120]

around Kisumu and Homa Bay areas are considered more vulnerable to fecal contamination, than open lake sites. Safe water quality implies low risk from bacteriological pollution and acceptable properties in terms of chemical, odor, and taste [121]. Under the World Health Organization (WHO) guidelines, the bacterium *E. coli* should not be detected in a given 100 ml sample of drinking water [122]. Increased nutrients from atmosphere, land and fecal contamination, fuel the growth, and proliferation of algal blooms in surface water. Cyanobacteria are potentially toxic to humans and animals and can also degrade the ecological and esthetic values of water. From previous phytoplankton surveys in Kisumu Bay of the Nyanza Gulf of *L. Victoria* (Kenya), cyanobacteria were the most dominant, contributing 50% to the total phytoplankton biovolume. The highest MC concentrations were recorded between November and March coinciding with the wet season when rainfall and nutrient enrichment from the catchment increased [13]. Algal blooms were thicker and more frequent in Murchison Bay than Napoleon Gulf. Highly toxic blue-green algal scums (*Microcystis* and *Anabaena* spp.) and water hyacinth (*Eichhornia crassipes*) congregated along the shores of the city of Gaba (Uganda) water intake sites. Microcystin levels were between  $<0.5 \mu\text{gL}^{-1}$  and  $3 \mu\text{gL}^{-1}$  [123]. In bays of *L. Victoria* (Tanzania), the level of water exchange from individual bays to the main basin is an important factor influencing eutrophication and microcystin production in nearshore habitats [124]. Microcystins were found in closed bay sites, and concentrations ranged from  $0.4$  to  $13 \mu\text{g l}^{-1}$  microcystin-LR equivalent and coincided with high abundance of *Microcystis* spp.

Particulate matter fluxes into the bottom sediments remove and incorporate particulate-bound metals from the water column, where they can become permanently buried or reintroduced back through sediment resuspension, especially in shallower areas. Similarly types of feed and sources are important factors which can contribute to accumulation of non-essential metals and other organics in aquatic food chains and caged fish. Supplementary fish diets improve fish nutrition. However, understanding how dietary MeHg affects its bioaccumulation in caged fish fed from marine based feeds is unknown but of importance. Variations in sediment metal contents have been reported in the lake from different surveys in 2010, 2012, and 2013. Total mercury concentration in sediments fell within the range of values recorded elsewhere but with low ng/l concentrations in the water. There is paucity of data on Hg contents in biota from the gulf, apart from initial results by Campbell et al. [103]. Recent research indicates that heavy metals do tend to accumulate in the sediments below fish farms. However, most studies have found that concentrations are within acceptable environmental guidelines even at farms that have been in production for many years [125]. Toxic metals that bioaccumulate and magnify along food chains are a concern to human health worldwide. Improvement in feed formulations is expected to decrease Zn loading to the marine environment, as many manufacturers are adding lower amounts of a more available form, zinc methionine [126]. Recently moderate to high levels of sum of seven PCB concentration were provided in sediments and fish, with median values of  $2.2$  to  $96.3 \mu\text{gKg}^{-1}$  dry weight and  $300$  to  $3000 \mu\text{gKg}^{-1}$  lipid weight, respectively. Fish cestode endoparasites biomagnified PCB levels than levels in fish hosts. These levels were found to be comparable with ranges of the PCB values found in other places of the world [127]. In a recent study, Abong'o et al. [128] indicates occurrences of some OCs around island waters of *L. Victoria*, supporting previous reports of use of the same pesticides in the wider catchment by Musa et al. [129]. Antibiotics and therapeutants are administered to recover sick fish, but this has declined in marine aquaculture. Commercially medicated feed

is readily available and is commonly used at farms in response to outbreaks. However, the amount of antibiotics released depends upon the fish species, amount of feeding activity, and absorption in the fish digestive tract [125]. The most obvious detrimental effect of extensive use of antimicrobials in aquaculture is selection of fish and shellfish pathogens resistant to multiple antimicrobials. Antimicrobial resistance determinants in piscine pathogens could also be acquired from environmental antimicrobial-resistant bacteria that have been selected by residual antimicrobials in water and sediments [130, 131]. Considerations suggest that excessive aquacultural use of antimicrobials may potentially have major effects on animal and human health as well as on the environment. There are no detailed assessments to provide information on amounts of antimicrobials in use aquaculture and potential effects.

Biofouling adds weight to nets and equipment, and it changes hydrodynamics of fish cage systems. Chemical antifoulants are used to control or eliminate the growth of marine organisms which attach to aquaculture cages, ropes, and structures [125], and hence their toxic effects on other nontarget organisms around fish farms are of concern. Heavy and persistent biofouling impedes water flow through cages, increases BOD in cages, causes net drag, and can shorten the useful life of nets and ropes [132, 126]. Finally, as documented in a recent study by Biginagwa et al. [133], concerns are emerging on the possible effects of microplastics on fish and as sources of organic contaminants in the lake, although there are increasing public awareness campaigns of uncontrolled disposal of all types of plastics in surface waters.

The cage culture industry is at its infancy in Kenya but with a huge interest in the technology. Currently in *L. Victoria*, cage farms are operational. It is expected that increasing investment in cages (in Kenya, Uganda, and Tanzanian sections of *L. Victoria*) will also create a high demand on feeds and seed, with extensive areas under farms in this transboundary ecosystem. In marine aquaculture, there are many lessons learnt with regards to negative environmental impacts from cage farms. Although there are no incidents of contamination from such activities, it is therefore prudent to ensure full implementation of guidelines on best management practices and awareness creation to ensure cage operations and other farm activities promote a sustainable fishery as a whole. This calls for frequent monitoring of the lake environment.

#### 4. Conclusion

Sediments eroded from watersheds are important determinant factors in water quality and integrated water resource management. Increased concentrations in surface water causes increased turbidity, reduced under water light transmission and siltation, and reduced water storage in dams and shallow lakes.

Maintaining good sediment and water quality today is prioritized due to human health related concerns from faecal contamination from untreated and partially treated domestic wastewaters; discharge of industrial chemical effluents; increased use of pesticides, fertilizers, and herbicides for crop production and livestock rearing; and persistent organic pollutants and pharmaceutical residues which are endocrine disruptors and carcinogens.

Bottom lake sediments are important archives of the lake and anthropogenic indicators of their catchment. In *L. Victoria*, although the deeper (> 40 m) depositional areas are in the open lake, visual observations show that most of the offshore sediments consists of muddy deposits plus significant shell remains, with more sandy type of sediments in some of the areas off river-mouths.

The sediment organic carbon contents varied spatial, but there were no significant variations between the different sampling periods. The surficial sediments are organic rich and are characterized by a relatively high water content, with over 89% of the samples containing water contents of greater than 75%. In 2012 survey, sediment organic matter contents were more variable and ranged from 1.90 to 33.47%.

An evaluation of the SOM at different heating durations at constant temperature 550°C and at very high temperatures of 950°C did not show any significant differences. High primary production and greater settling in deeper area contribute to the nature of sediments deposited and also are reflected in the relatively high OC contents.

The importance of sediments in adsorption of contaminant substances and influencing geochemical processes within the lake are also emphasized. It is recommended that continuous monitoring strategies are adopted in view of the new cage culture developments initiated in most of the African tropical lakes, including Lake Victoria, as uneaten feeds and operations may influence water and sediment quality in cases where designed best management practices are not fully implemented. There is a need to prioritize sediment research including the microbial component, porewater exchanges, and sediment fluxes which are rarely incorporated in major projects.

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## Conflict of interest

The author wishes to declare that there is no conflict of interest and the data used is from original research unless otherwise adapted from cited sources.

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