

## Research Article

# Chromium Distribution and Spatial Variations in the Finer Sediment Grain Size Fraction and Unfractionated Surficial Sediments on Nyanza Gulf, of Lake Victoria (East Africa)

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Surficial sediments collected from the Nyanza Gulf of Lake Victoria (East Africa) were used to determine spatial concentrations of Cr and determine differences in contents of the unfractionated (whole sediment) and the finer grain size sediments, establishing any changes in Cr enrichment and potential ecological risks using sediment quality guidelines. A single pollution index was also used to evaluate level of Cr contamination. The spatial mean Cr contents in the  $<63 \mu\text{m}$  (silt-clay) fraction were found to be significantly lower than those in the unfractionated sediments, but with a strong linear positive correlation. The study results show decreasing spatial amounts of Cr in surficial sediments of the Nyanza Gulf, when compared to a study done 20 years earlier. However, the 95% confidence limits of the overall mean Cr in unfractionated sediments exceed the threshold effect concentration (TEC), indicating the potential for Cr remobilization from sediments. In general the sediment enrichment is evidence of possible dominance of lithogenous sources of Cr in the surface lake sediments, with potential anthropogenic sources from the drainage system and nearshore urban areas. The sediments are unpolluted with respect to geoaccumulation index, and sediment enrichment factors suggest a minor to moderate enrichment of Cr in surficial sediments of three sites around the Nyanza Gulf zones and around the river mouth in the main lake.

## 1. Introduction

Metals, being recalcitrant to biodegradation process pose a persistent threat to human health and environment. Emissions of metals result from fossil fuels combustion, industrial process, and solid waste incineration. Particulate bound metals in water, dissolved fraction, and aerielly deposited metals all contribute to the total load of metals entering the aquatic environments. Increasing anthropogenic sources of metals often leads to increased enrichments in lake sediments. Lake sediments are regarded as important sinks and secondary sources of metal contaminants, which range from essential or beneficial to detrimental metals. Chromium is a naturally occurring element in rocks, animals, plants, soil, and volcanic dust and gases [1]. Chromium is mined as chromite ( $\text{FeCr}_2\text{O}_4$ ) ore. The most important industrial sources of chromium in the atmosphere are those related to ferrochrome production. Ore refining, chemical and refractory processing, cement-producing plants, automobile brake lining and

catalytic converters for automobiles, leather tanneries, and chrome pigments also contribute to the atmospheric burden of chromium [2, 3]. Hexavalent chromium ( $\text{Cr VI}$ ), along with the less common metallic chromium ( $\text{Cr}^0$ ), is most commonly produced by industrial processes.

Chromium is an essential element as  $\text{Cr}^{3+}$  but is also considered detrimental in its hexavalent state. The metal chromium (Cr) has oxidation states ranging from chromium (II) to chromium ( $6^+$ ). Chromium forms a large number of compounds, in both the chromium (III) and the chromium (VI) forms. Chromium compounds are stable in the trivalent state, with the hexavalent form being the second most stable state [1].  $\text{Cr}^{3+}$  compounds are sparingly soluble in water and may be found in water bodies as soluble  $\text{Cr}^{3+}$  complexes, while the  $\text{Cr}^{6+}$  compounds are readily soluble in water [1]. Chromium (VI) is the toxic form of chromium to flora and fauna. Hexavalent chromium is known to have 100-fold more toxicity than trivalent chromium, for both acute and

chronic exposures because of its high water solubility and mobility, as well as easy reduction [4]. International Agency for Research on Cancer (IARC) has classified chromium (VI) in Group 1 (carcinogenic to humans) and metallic chromium and chromium (III) in Group 3 (not classifiable as to their carcinogenicity to humans) [5, 6].

Discharge of untreated and partially treated wastewaters releases several different metal and nutrient contaminants into the lake and water sediments. Use of untreated and partially treated wastewater may result in negative impacts on irrigated crops, soils, and groundwater through addition of excessive levels of metals and metalloids, nutrients, salts, and specific ionic species and micropollutants [7]. Aquatic organisms have the ability to accumulate metals from the various sources, such as discharge of wastewater, terrestrially derived metal laden soil and other materials, and aerially deposited dust and aerosols. The sediment types and composition are known to influence the metal accumulation in sediments and also amounts taken up by benthic organisms. Surface sediments are complicated mixtures of various inorganic and organic substances, including sulfide (e.g., acid-volatile sulfide), carbonate, quartz, clay minerals, various oxides and hydroxides, and organic matter [8]. Metal (hydr) oxides usually occur as a discrete phase or as coatings on other mineral surfaces in the sediments. Because of their large surface areas, porous structure (amorphous phase), and abundant binding sites, these metal (hydr) oxides (especially Fe, Mn, and Al (hydr)oxides) are very active and can easily adsorb metal cations, such as  $Cd^{2+}$  [9]. Among these factors, the speciation and concentration of metals have the most significant impact on the assimilation of metals by benthic animals [10, 11]. The relative importance of specific sediment components (i.e. iron and manganese oxide, montmorillonite clay, and silica, with or without organic coating) to the uptake of Cd, Co, Ag,  $Hg^{2+}$ , and  $CH_3Hg^{2+}$  by the mussel *Mytilus edulis* has been studied [12]. Therefore, besides the dietary exposure route, sediments are an important pool of trace metals to filter feeders and other aquatic life.

Aquatic ecosystems surrounded by catchments with a known history of mining, near artisanal and small scale mining operations, and expanding agricultural and urban developments are often exposed to varied sources of metal contaminants. Therefore, there is growing need to understand environmental and anthropogenic drivers of pollution in order to improve on the pollution control and reduction of future negative impacts on aquatic habitats, biodiversity, and human health. Sediment quality guidelines have a broad range of potential applications, as do other environmental quality guidelines. They can serve as goals or interim targets for national and regional toxic chemical management programs, as benchmarks or targets in the assessment and remediation of contaminated sites, or as the basis for the development of site-specific objectives. Sediment quality guidelines provide scientific benchmarks, or reference points, for evaluating the potential for observing adverse biological effects in aquatic systems [13]. Metal concentrations exceeding the threshold effect levels but less than the probable effect level are thought to represent only a potential risk to aquatic

organisms, and those concentrations exceeding the probable effect level are associated with adverse biological effects. The main gulf areas of L. Victoria (Napoleon Gulf, Mwanza Gulf, and Nyanza Gulf) are the fastest growing urban areas, and the most exposed to anthropogenic influences around the whole lake. Industrial effluents and waste disposal are unending environmental challenge due to expanding human population and the need for economic developments. There are several studies on concentrations of metals in the lake ecosystems, targeting the potential sources. However, no extensive spatial evaluations have been carried out in the gulf to evaluate any changes in Cr concentrations using previous data sets in the area. Despite the lack of such important historical trends in metal pollutants in the lake sediments, we still need to understand the potential transport and fate of specific toxic contaminants in the main gulf areas of the relatively large and shallow transboundary lake ecosystem.

Sediments of the aquatic environment act as a major reservoir of metals [14] and also as a source of contaminants [15, 16]. In the Nyanza Gulf, long historical trends of individual metal records in sediments are not available. However, sediment cores collected from the deep offshore areas of the main Lake Victoria show peaks of total Hg from the early 1960s [17]. In the Nyanza Gulf, studies on trace metals exist but only very few of them include Cr metal [18–24]. The Nyanza gulf watershed is known for the presence of gold mines [25–27] and also serves as an important agroindustrial zone. These areas together with urban metal sources are a concern as regards metals into surface waters. Adoli et al. [28], Ngure et al. [27], and Omwona et al. [29] have investigated such sources and shown the presence of heavy metals. Chromium is one of the metals associated with industrial processes. However, only a few of these studies have provided extensive information on Cr distribution in the gulf sediments. Evaluation of the spatial concentrations of Cr is important as a first indication of levels of contamination arising from the diverse anthropogenic sources, besides the natural sources, for evaluation of the potential ecological risks to lake ecosystem, since sediments act as an important active secondary pool of Cr. We also do not have large trends data on emissions and pathways to enable more in-depth evaluation of metal contamination, and therefore such localized studies are of relevance in understanding and addressing the great concerns about metal pollution in lake ecosystems. The monitoring of metal contents from anthropogenic activities is particularly important for the assessment of environmental quality and protection of aquatic ecosystem from metal toxicity effects, as human activities increase in the gulf watershed.

The objective was to evaluate the spatial concentrations of Cr in surficial sediments and determine any changes in concentrations by comparing with the existing data from the study area, as part of a monitoring plan on pollution of the lake sedimentary environment. This study provides the spatial distribution of Cr in the unfractionated and finer sediments of the Nyanza Gulf, with an evaluation of the changes in concentrations, sediment quality, and ecological risks. Therefore, the results provide valuable information

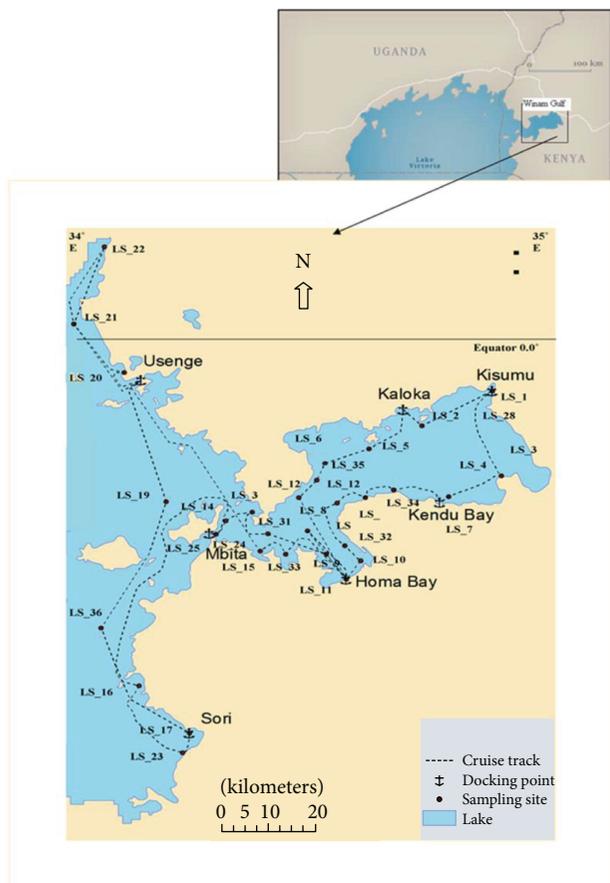


FIGURE 1: Map showing the eastern gulf (Nyanza Gulf) of Lake Victoria (East Africa).

for future improvement of lake management and pollution prevention and control strategies.

## 2. Materials and Methods

**2.1. Study Area.** Lake Victoria, East Africa (Figure 1), is the second largest freshwater lake in the world after Lake Superior in the USA and the largest African inland lake also valued for its commercial fishery and rich biodiversity. It has a surface area of about 68,800 km<sup>2</sup>, a mean and maximum depth of 40 m and 80 m, respectively, and a water volume of about 2,760 km<sup>3</sup>. Rain and river inflow are the main water inputs into the lake, with an estimated flushing time of 140 years and residence time of 23 years [30, 31]. It loses water mainly through evaporation and the Nile river. The main lake catchment area is about 194,000 km<sup>2</sup>.

The oldest supracrustal rocks in Kenya are the Archean Nyanzian metavolcanics and the Kavirondian metasediments [32–34]. These are in most parts separated from the Archean rocks by the Tertiary volcanic associated with the East African rift system [32]. Nyanzian group at the base is composed of tholeiitic basalts, calc-alkaline dacites, and rhyolites [33]. The group is unconformably overlain by the Kavirondian group [34, 35]. The most productive gold deposits in Tanzania and

south western Kenya [36, 37] are in the Nyanzian greenstone belts (2,700 Ma) and the Ubendian system (2000 Ma). Gold mineralisation occurs in proximal facies tuff and iron formation and in oblique and semiconformable quartz veins [38]. Artisanal activities in Au processing have been of interest in the Archean Nyanzaian greenstone belt areas around Lake Victoria basin due to the potential use of Hg.

Lake Victoria bottom is mainly covered by a thick layer of organic mud, but with patches of hard substrate, sand, and shingle or rock [39]. Water hyacinth [40] and eutrophic conditions [41–45] are also a common phenomenon in the lake, linked to ecological changes in the lake. Fish inhabiting shallow waters are also at risk from periodic upwelling of hypoxic waters [40].

Nyanza Gulf, the eastern section of the main lake forming the Kenyan portion, consists of a small open lake section and the Winam Gulf. The Winam Gulf is relatively shallow but deepens westwards, and its catchment area is dissected by several rivers and tributaries. Rivers Nyando, Sondu-Miriu, Awach, Nzoia, Yala, Sio, and Kuja are major inflowing rivers. The several inflowing river mouth areas, shallow inner bays, and island shore are important habitats for fish and aquatic organisms. The shallow (less than 5 m deep) inshore zone has been known to be the main area of artisanal fisheries [46]. Critical habitats in Lake Victoria basin include shallow inshore areas, rocky areas of the lake, sheltered bays, and vegetated shorelines. The lakeshore wetlands inflowing rivers and streams and the different types of bottom (rocky, sandy, and muddy) and depth are among features that account for the patchy distribution and variable abundance of fish species in the lake [46].

**2.2. Sampling.** The monitoring survey was conducted in June 2012 by maintaining as close as possible the same (Global Positioning System, GPS Coordinates) marked sampling stations (Figure 1) used during the 2010 survey to ensure they coincide with sites where many of the historical data sets were derived from. Some of the physicochemical conditions of bottom water (water overlying the bottom sediments) were determined in situ using a CTD-90 M sensor (Sea & Sun Technology) and data downloaded into a computer using windows based standard data acquisition software.

Urbanisation and rapid population growth in the catchment and along river drainage basins are thought to lead to water quality degradation and pollution of downstream areas and underground waters. The study was designed to capture urban, terrestrial, and riverine influences from the extensive river drainage basins dotting the Kenyan side of L. Victoria. In terms of the influence of inflowing rivers, the Kenyan portion can be distinguished as follows: inner shallow bays, Zone I: the inner shallow bay with influence from major rivers Kibos-Nyamasaria, Nyando, Awach, and Sondu-Miriu, with average water depths of about 5 m. The rivers are located in the south eastern zone and drain agricultural and urban areas (sites: LS\_1 (Kisumu Pier); LS\_2 (Maboko Is.); LS\_3 (Off Nyando river mouth); LS\_4 (Off Sondu-Miriu); LS\_6 (Asembo Bay); LS\_7 (Off Awach river mouth); LS\_8 (Gingra rock); LS\_34 (Mitimbili); LS\_35 (Achieng Oneko); LS\_13 (Balarawi); LS\_28 (Off Kibos RM); LS\_5 (Off Ndere Isl.)). The gradual and

general westward deepening of the lake basin is evident from this shallow section of the gulf, although the slope is variable from the different shoreline areas.

*Middle Deeper Zone II.* The middle deep gulf zone with deep waters and connected to open waters, urban developments, and agricultural zones are on both sides, with R. Oluch drainage entering the lake near Homa Bay (sites: LS\_9 (Soklo); LS\_10 (Oluch RM); LS\_11 (Homa Bay); LS\_12 (Kopiata); LS\_14 (Utajo); LS\_15 (Luanda Gembe); LS\_24 (Mbita East); LS\_37 (Mid gulf); LS\_33 (Mirunda Bay); LS\_30 (Luanda Kotieno); LS\_26 (Rusinga Channel); LS\_31 (Madundu); LS\_32 (Kowuor)). This zone is considered less impacted by the large riverine influences as it is not connected to the very extensive river drainage basins, except smaller streams and R. Oluch.

*Offshore and Open Lake Zone III (South and North).* The offshore open lake waters with shallow nearshore margins are exposed to heavy wind and wave action. This section forms connection with the catchment through river Kuja in the southern zone and rivers Sio, Nzoia, and Yala in the northern zone. These are extensive rivers draining expanse and rich agricultural areas. Both the middle and inshore zones of the gulf are often covered by water hyacinth (sites: southern section: LS\_16 (Matara Bay); LS\_17 (Sori-Karungu); LS\_18 (Muhuru Bay); LS\_25 (Mbita west); LS\_36 (Remba); northern section: LS\_19 (Bridge Is.); LS\_20 (Off Yala RM); LS\_21 (Off Nzoia RM); LS\_22 (Off Sio RM); LS\_23 (Off Kuja RM)); Sites LS\_36 and LS\_19 represent areas with very minimal riverine and land derived anthropogenic influences.

*2.3. Physicochemical Parameters.* Surface water temperature, conductivity, dissolved oxygen, and pH were measured in situ using a multiparameter (Hydrolab) instrument. Water transparency and turbidity were measured using a Secchi disk and Hach Turbidimeter (2100P), respectively. All the meters were calibrated in the laboratory and in the field according to the specified conditions from the manufacturer's manuals. The total alkalinity and total hardness were determined in the field by titration as outlined in APHA [47], immediately after sample collection.

*2.4. Collection of Bottom Sediments.* Surficial sediments were collected using a precleaned Ponar grab sampler. The innermost portions of the surface sediments were scooped (to avoid portions in contact with the grab sampler) and transferred into sterile precleaned density polythene bags and used for gravimetric determinations and trace metal chemical analysis. The field samples were kept frozen in precleaned high density polythene bags in the field, prior to initial sample preparation in the laboratory. The sediments were characterized by determination of the percentage water, carbonate, and organic matter contents. The water content was determined by oven-drying about 5.0 g of the wet sediment at 105°C for 6 hours and to constant weight. About 1.0 g of the dry sediment was used to determine the carbonate and organic matter contents. The percentage Loss on Ignition (% L.O.I) was also determined by heating about 1.0 g of the dry sediment at 550°C [48] in a furnace and determining the weight loss. Sediment bulk density ( $\text{g}/\text{cm}^3$ ) was also determined.

*2.5. Digestion and Chemical Analysis of Bottom Sediments.* 1.0 g of the sediment was digested with 10 ml (3:1 v/v ratio) of conc. HCl-HNO<sub>3</sub> mixture at 90°C for 60 minutes. Acid blanks together with the digested sample solutions were diluted to mark in 50 ml volumetric flasks. All glassware used in the extractions were soaked in 10% HNO<sub>3</sub> v/v, rinsed with deionised water. All reagents used were of analytical grade to check for possible contamination, and blanks were carried through the same procedures. Elemental concentrations in both samples were determined using Atomic Absorption Spectrophotometer (Varian Techtron Spectra AA-10, Varian Techtron PTY Ltd. Varian Associates Inc.), according to the manufacturers conditions with appropriate standard solutions.

The sediment enrichment factor [49–52] and geoaccumulation index [53] are usually applied to evaluate the sources and degree of pollution. For this study, the sediment enrichment factor [49] is defined as follows:  $\text{SEF} = [(X/\text{Al})_{\text{sediment}}]/[(X/\text{Al})_{\text{crust}}]$ , where  $(X/\text{Al})$  is the ratio of Cr to aluminum. Iron (Fe) was also used to replace Al in the equation and applied in the calculation of  $\text{SEF}_{\text{Fe}}$  for both sediment portions. The baseline or background aluminum and iron content in the earth crust was excerpted from the data published by Taylor [54] and Turekian and Wedepohl [55]. When the EF of a metal is greater than 1, the metal in the sediment originates from man-made activities, and vice versa. The EF value can be classified into 7 categories [56]: no enrichment for  $\text{EF} < 1$ , minor for  $\text{EF} < 3$ , moderate for  $\text{EF} = 3\text{--}5$ , moderately severe for  $\text{EF} = 5\text{--}10$ , severe for  $\text{EF} = 10\text{--}25$ , very severe for  $\text{EF} = 25\text{--}50$ , and extremely severe for  $\text{EF} > 50$ . The Cr  $\text{SEF}_{\text{Al}}$  was calculated for similar sites (11 sites only) sampled in 2012, based on the 1994/5 study where mean Al values for each site for the silt and clay fraction ( $<63 \mu\text{m}$  grain size fraction) were used and ranged  $\text{SEF}_{\text{Al}}$  from 0.07 to 0.71 (using  $\text{Al} = 82,300 \mu\text{g}/\text{g}$  as baseline or background value [54, 55]) and 0.05 to 0.51 (using a calculated overall mean  $\text{Al} = 58,732 \mu\text{g}/\text{g}$  as baseline, during 1994/5 study where  $n = 140$ ).

*2.6. Statistical Analysis.* Statistical analysis was performed using the SPSS (ver. 10.0) and Statistica (ver. 4.3) packages. Significant Pearson's ( $r$ ) correlation coefficients were determined and mean metal concentration was compared using one-way analysis of variance, ANOVA, at 5% significance level, after testing for normality of the data. Instrumental analysis of Cr was done after digestion of samples in the mines and geological laboratories Nairobi.

### 3. Results

In the gulf zones, the surface and bottom water pH, temperature, dissolved oxygen, and conductivity were in the ranges of 7.60–8.51, 23.87–25.86°C, 5.07–11.12 mg/L, and 0.12–0.18 mS/cm and 7.37–8.50, 23.40–25.22°C, 4.75–8.59 mg/L, and 0.13–0.23 mS/cm, respectively. The range values of pH, temperature, dissolved oxygen, and conductivity in surface and bottom water of the main lake zones were 7.59–8.26, 25.15–25.93°C, 6.85–10.13 mg/L, and 0.11–0.12 mS/cm and 7.37–8.05, 23.02–24.95°C, 3.45–9.71 mg/L, and 0.10–0.18 mS/cm, respectively. Surface water total alkalinity

ranged from 40 to 194 mgCaCO<sub>3</sub>/l (gulf zones) and 18 to 60 mgCaCO<sub>3</sub> (main lake zones), whereas the water hardness varied from 32 to 80 mg/L (gulf zones) and 26 to 28 mg/L 9 (main lake zones). The water Secchi depth ranged from 0.22 m to 0.9 m (gulf zones) and 0.2 m to 3.2 m (main lake zones), and the sampling sites water depth ranged from 2 m to 20 m (gulf zones) and from 1.4 m to 54 m (main lake zones). Surface water in offshore and deeper areas is more clear than in nearshore areas. Water transparency increases towards the offshore and open waters, whereas the conductivity decreases towards the main lake.

Sediments of Nyanza Gulf range from the more sandy type around areas off river mouths to the flocculent muddy sediments in deep zones of the lake (water contents mean range of 27.34 ± 0.80% to 91.55 ± 0.91%), with moderate to high organic matter contents (mean range of 1.90 ± 0.10% to 33.47 ± 0.93%) and low sediment carbonates (mean range of 0.21 ± 0.01% to 8.09 ± 0.36%). Sediment organic carbon contents ranged from 0.95% to 16.75% and bulk or wet density ranged from 0.0205 g/cm<sup>3</sup> to 0.0875 g/cm<sup>3</sup>. Relatively higher organic matter contents were found in deeper sediments as compared to nearshore sites, but in the gulf some areas also showed sediments OM contents greater than 10%. However, the range values of OM appear are similar to those found in 1994/5 surveys. Lower concentrations were associated with the sandy sediments (LS\_4 and LS\_20) encountered around the river mouth areas.

The concentration of Cr in Nyanza gulf surficial sediments ranged from as low as 7.0 µg/g to 65.50 µg/g in the silt and clay fraction and from 10.75 µg/g to 102.80 µg/g in dry weight basis, in the unfractionated sediments. The mean (± standard deviation) Cr concentration was 33.85 ± 21.70 µg/g (unfractionated sediments) and 22.11 ± 11.68 µg/g (silt and clay fraction). The analysis of variance of the mean Cr contents showed a significant difference between the two contents ( $p = 0.008$ ,  $F_{1,59}$ ,  $n = 30$ ). The 25th, 50th, 75th, and 95th percentile values of Cr were 19.80 µg/g, 30.25 µg/g, 36.30 µg/g, and 98.00 µg/g and 15.81 µg/g, 19.88 µg/g, 28.25 µg/g, and 53.54 µg/g, in unfractionated and the finer sediment fraction, respectively. The sites which recorded high concentrations were LS\_21, LS\_22, LS\_35, LS\_20, and LS\_34 (Figure 2). The Cr concentration revealed a moderately strong and significant (Pearson's correlation coefficient,  $r = 0.546$ ;  $p < 0.01$ , 2 tail test) positive linear correlation between the two sediment portions analysed (Figure 3).

Table 1 shows the mean sediment Cr contents in the four zones and according to the water depths at each sampling site. The Cr contents show a decreasing trend in the gulf, but with higher means in the open lake northern zone, for both the silt-clay fraction and the unfractionated sediment. Main lake sites showed higher sediment Cr content than sites in the gulf zones. However, the mean differences between the gulf and main lake sites were not significant ( $p = 0.141$ ,  $F_{1,27}$ ;  $\alpha = 0.05$ ). Significant differences in mean sediment Cr contents between the zones were observed for the unfractionated sediments only ( $p = 0.005$ ,  $F_{3,25}$ ;  $\alpha = 0.05$ ). When the mean Cr contents between the three depth ranges were compared, only Cr concentrations in unfractionated sediments, in <5 m water depth sites, were significantly different, using the combined

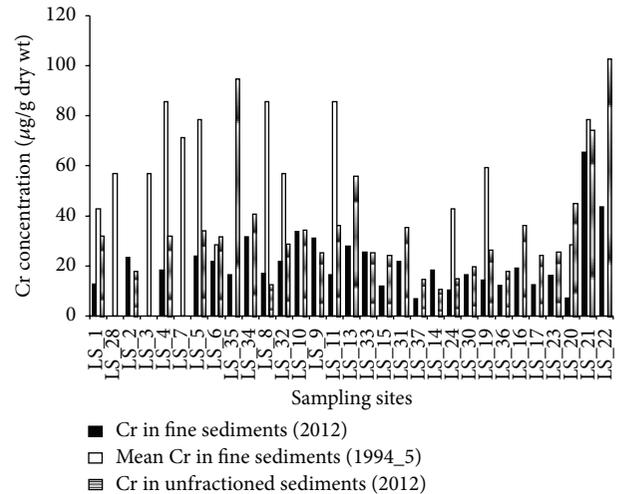


FIGURE 2: The spatial distribution of Cr in unfractionated surficial sediments and <63 µm grain size fraction of surficial sediments of Nyanza Gulf.

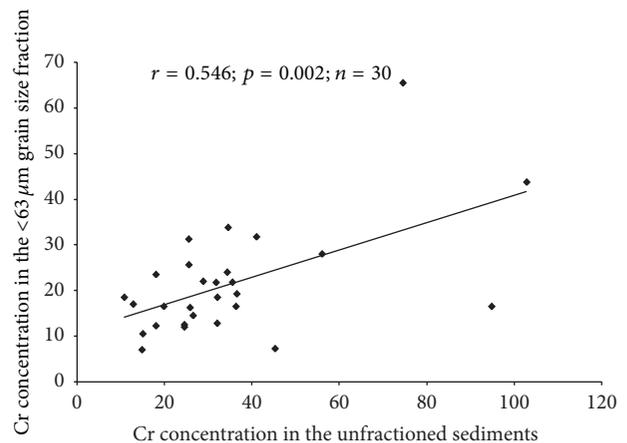


FIGURE 3: The relationship between the Cr contents in unfractionated surficial sediments and <63 µm grain size fraction of surficial sediments of Nyanza Gulf.

sediment Cr contents data from the main lake and gulf zones.

The mean (±sd) of sediment Cr from near urban areas (25.89 ± 11.21 µg/g) and off river mouth (33.28 ± 1.73 µg/g gulf and 62.09 ± 33.72 µg/g main lake) and offshore sediments (19.77 ± 6.05 µg/g) in unfractionated sediments were higher than those in the silt and clay fraction (urban areas = 15.08 + 2.92 µg/g, off river mouth = 26.15 + 10.82 µg/g gulf rivers and 33.19 + 26.55 µg/g main lake rivers, and offshore sediments = 11.25 + 3.85 µg/g).

The Cr concentrations recorded in the silt and clay sediment fraction during this study appear to be lower (overall mean of 22.11 µg/g), when compared ( $p = 0.020$ ,  $F_{1,18} = 22.787$ ,  $\alpha = 0.05$ ) to concentrations found in 1994/5 study by Mwamburi and Oloo [62]. The mean chromium concentration in the same sediment fraction ranged from 28.6 µg/g to 85.7 µg/g, with much lower dissolved and total

TABLE 1: Mean ( $\pm$ standard deviation) Cr concentration ( $\mu\text{g/g}$  dry weight) in surficial lake sediments in the gulf and main lake zones and at different site water depths (n: northern; s: southern part of the main lake).

	Lake zones and sites			
	Zone I	Zone II	Zone III <sub>s</sub>	Zone III <sub>n</sub>
Unfractioned	42.49 ( $\pm$ 23.67)	23.04 ( $\pm$ 8.95)	26.20 ( $\pm$ 7.67)	62.26 ( $\pm$ 33.47)
	30.45 $\pm$ 18.38 gulf zones (I + III)		44.23 $\pm$ 29.61 (main lake zones (III <sub>s</sub> + III <sub>n</sub> ))	
<63 $\mu\text{m}$ fraction	22.1 ( $\pm$ 6.15)	19.37 ( $\pm$ 8.04)	15.06 ( $\pm$ 3.34)	32.75 ( $\pm$ 26.94)
	20.46 $\pm$ 7.29 gulf zones (I + III)		23.91 $\pm$ 20.13 (main lake zones (III <sub>s</sub> + III <sub>n</sub> ))	
Number of sampled sites	8	12	4	4
	Water depths at sampling sites (gulf and main lake zones)			
	<5 m	5 m–10 m	>10 m	
Unfractioned	47.52 ( $\pm$ 26.85)	23.11 ( $\pm$ 8.67)	23.68 ( $\pm$ 10.87)	
<63 $\mu\text{m}$ fraction	26.39 ( $\pm$ 15.16)	17.31 ( $\pm$ 6.87)	15.55 ( $\pm$ 5.41)	
Number of sampled sites	13	9	6	

concentrations in lake water. Cr concentrations showed low linear correlations with sediment OM, water content, and carbonate (Section 5), although Cr was highly correlated in both sediment portions (Figure 3). Cr contents in the finer sediments showed moderately strong positive linear correlations with Ni ( $r = 0.616$ ,  $p < 0.01$ ) and Co ( $r = 0.460$ ,  $p < 0.05$ ) and a negative correlation with Fe ( $r = -0.396$ ,  $p < 0.05$ ).

Figures 4(a), 4(b), 4(c), and 5 show the plotted values of the calculated geoaccumulation index and sediment enrichment factors. The  $\text{SEF}_{\text{Al}}$  suggested that at those sites Cr in sediments (Figure 4(c)) originated mainly from lithogenous materials for 2012 survey, but some  $\text{SEF}_{\text{Al}}$  for 1994/5 were above 1 (1.2 to 3.4), indicating some anthropogenic influences in the fine sediments. A further exploration of the Cr sources using three different values of Fe (Fe = 46,700  $\mu\text{g/g}$  average shale, 56,000  $\mu\text{g/g}$  crustal abundance, and a mean of 49,900  $\mu\text{g/g}$  in unfractioned sediments and 60,800  $\mu\text{g/g}$  in fine sediments, from 2012 data) as the normalizing element in both unfractioned and fine sediments (Figures 4(a) and 4(b)) shows that  $\text{SEF}_{\text{Fe}}$  ranged from 0.05 to 0.5 (for 60,800  $\mu\text{g/g}$  as baseline), 0.04 to 0.4 (46,700  $\mu\text{g/g}$  as baseline), and 0.04 to 0.48 (56,000  $\mu\text{g/g}$  as baseline) in the finer sediments. Only sediments of five sites showed  $\text{SEF}_{\text{Fe}}$  above 1. The  $\text{SEF}_{\text{Fe}}$  in unfractioned sediments ranged from 0.22 to 3.4 (for 49,900  $\mu\text{g/g}$  as baseline), 0.17 to 2.6 (46,700  $\mu\text{g/g}$  as baseline), and 0.2 to 3.2 (56,000  $\mu\text{g/g}$  as baseline). Therefore, in general  $\text{SEF}_{\text{Fe}}$  also indicate lithogenous Cr sources, although Cr in sediment from the five areas (LS\_37, LS\_31, LS\_22, LS\_35, and LS\_12) suggests minor to moderate enrichment, as found using Al as the normalizing element.

The geoaccumulation index ( $I_{\text{geo}}$ ) is defined as  $I_{\text{geo}} = \log_2(C_n/1.5B_n)$  [53], where  $C_n$  is the measured content of Cr in the fine sediment fraction (<63  $\mu\text{m}$  grain size fraction) and  $B_n$  is the background content of Cr in the average shale. The classes are as follows: Class 0:  $I_{\text{geo}} < 0$  (none), Class 1:  $I_{\text{geo}} = 0-1$  (none to medium), Class 2:  $I_{\text{geo}} = 1-2$  (moderate), Class 3:  $I_{\text{geo}} = 2-3$  (moderate to strong), Class 4:  $I_{\text{geo}} = 3-4$  (strongly polluted), Class 5:  $I_{\text{geo}} = 4-5$  (strong to very strong), and Class

6:  $I_{\text{geo}} > 5$  (very strong). The geoaccumulation index values (Figure 5) were all negative for the 2012 (range of  $-4.3$  to  $-1.0$ ) and 1994/5 (range of  $-2.2$  to  $-0.66$ ) surveys, suggesting no Cr pollution in the finer sediments, according to the  $I_{\text{geo}}$  classes of Müller [53].

#### 4. Discussions

The bulk density, water content, and organic contents are physically related to each other in lake sediments, and hence significant relationships are found between the gulf sediments bulk density and water ( $r = -0.915$ ,  $n = 27$ ,  $p < 0.01$ , 2-tail test) and organic matter ( $r = -0.730$ ,  $n = 27$ ,  $p < 0.01$  2-tail test) contents. The sediment water content and organic matter contents in sediments show positive relationships, although the Pearson correlation coefficients ( $r$ ) between % OM versus % carbonate ( $r = 0.225$ ,  $n = 26$ ) and % carbonate versus % water content ( $r = 0.244$ ,  $n = 25$ ) were low. A significant positive relationship was found between the % organic matter contents and % water contents ( $r = 0.662$ ,  $p < 0.01$ , two-tailed test) in sediments. In most sediments, the organic content can positively influence the water contents highly, but other factors are also important (water depth, sediment compaction, and mineralogical composition). The unfractioned sediments consist of the whole sediment components (sand, silt, and clay). The grain size of the material influences the sedimentation processes, the capacity for entrainment, and the capacity of the material to bind pollutants. The potential active binding area increases significantly with decreasing particle size. According to Hakanson and Johansson [48], the relationship between mean grain size and water depth shows that finer particles dominate in deep waters sediments, where continuous accumulation prevails. There was no detailed sedimentological analysis conducted in this study. Verschuren et al. [63] also described the deep offshore Lake Victoria sediments as flocculent surface muds, with dark brown organic muds below, in six short sediment cores (core length of 24 cm to 48 cm) collected at water depth of 48 m to 68 m. Such organic rich and Si-rich

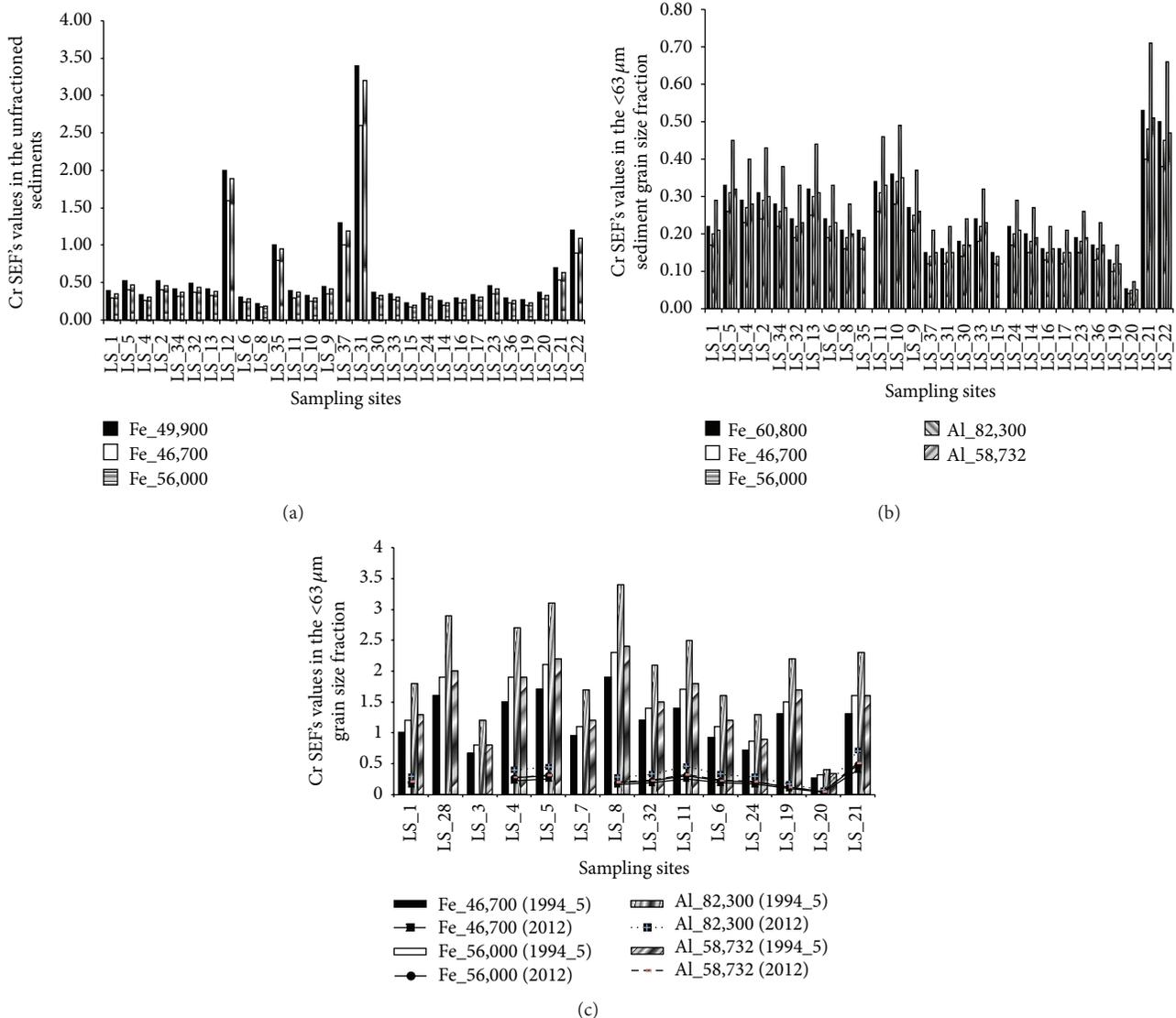


FIGURE 4: (a) The calculated SEF's values (using Fe baseline values) of Cr in unfractured surficial sediments of Nyanza Gulf. (b) The calculated SEF's values (using Fe and Al baseline values) of Cr in  $<63 \mu\text{m}$  grain size fraction of surficial sediments of Nyanza Gulf. (c) A comparison of the calculated SEF's values (using Fe and Al baseline values) of Cr in  $<63 \mu\text{m}$  grain size fraction of surficial sediments of Nyanza Gulf from selected sites, using 1994/5 and 2012 data.

sediments are characteristic of many other cores from the depositional basin in Victoria [64] reflecting the relatively low rates of detrital inputs from the catchment in proportion to the enormous surface area of this great lake. Linear regression of total organic matter determined by Coulometry versus present organic matter determined by weight loss at  $550^\circ\text{C}$  yielded the relationship of  $\% \text{TOC} = [0.555 * \% (\text{OM})] - 0.028$ , ( $r^2 = 0.98$ ,  $n = 117$ ). With the total inorganic carbon below detection level, all total carbon contents measured by a Leco Carbon analyser represented total organic carbon. In this study, the values of sediment organic carbon found in the Nyanza gulf ranged from 0.95% to 16.75% in the deepest main lake area and appear to reflect the transition from sandy to muddy sediments. Shallow cores from main Lake Victoria [65–67] at 56 m water depth (off Nyanza Gulf,

core 103, collected in 1990) and 25 m water depth (Itome core, in northeastern L. Victoria, Uganda, collected in 1995) revealed lower sediment accumulation rates of  $100 \text{ g/m}^2/\text{yr}$  and  $276 \text{ g/m}^2/\text{yr}$ , compared to a core from the deepest lake zone (sediment accumulation rate of  $320 \text{ g/m}^2/\text{yr}$ , at 68 m water depth), with organic carbon contents of  $168 \text{ mg/g}$  and  $184 \text{ mg/g}$  dry weight, respectively. In surficial sediments of Winam Gulf, data from five sites along a biogeochemical gradient [68] also showed a general increasing trend in organic carbon from  $66.6 \text{ g/kg}$ ,  $52.8 \text{ g/kg}$ ,  $72.4 \text{ g/kg}$ , and  $92.5 \text{ g/kg}$  to  $82.1 \text{ g/kg}$  (gulf) and  $143.7 \text{ g/kg}$  (main lake, 1 site). Lower values of sediment TOC [69] have been found in arid Lake Turkana (mean of 0.93% and a range of 0.41% to 4.31%), but with high carbonate contents (mean of 10.04% and range of 1.27% to 28.08%). Carbonate contents in gulf sediments

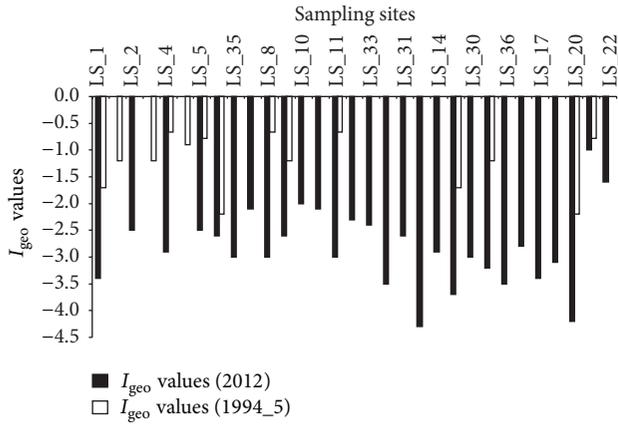


FIGURE 5: The calculated  $I_{geo}$  values for Cr in  $<63 \mu\text{m}$  grain size fraction of surficial sediments of Nyanza Gulf from selected sites, using 1994/5 and 2012 data.

were comparatively lower, and variations in most cases reflect the type of catchment lithology and biogenic sources, such as shell remains of organisms.

The spatial Cr contents show high concentrations in off river mouth sediments around the gulf and main lake zones (northern) and some of the nearshore areas, with significantly ( $p < 0.05$ ) much higher mean Cr contents in unfractured sediments than the silt-clay fraction, accompanied by a strong positive linear correlation. The silt-clay fraction Cr concentrations are also decreasing when the same sites are compared to values of 1994/5. Anthropogenic influences seem to have more effects on the Cr contents as the highest Cr concentrations in the finer sediment fraction were observed in only 14% of the sediments. The sources of heavy metals can be from rock weathering, soil erosion, industrial processing of mineral ores, utilization of metals and metal components, and leaching of metals from garbage and solid waste dumps. The natural variability in lake surficial sediments is expected, especially in the shallow more littoral areas, where particulate materials from diverse catchment sources are transported and deposited at the bottom, with periodic possibilities of lateral distributions. These could explain the much higher levels of Cr than the finer fractions in the gulf surficial sediments, a different scenario from the known concentration of metals in the finer fraction. Unprocessed wastewaters are usually emptied into most inflowing rivers, and, together with land surface runoffs and aerial deposits, these materials are capable of providing significant diffuse amounts of chemical contaminants. For the 12 samples whose metal concentrations were quantified in particular grain size fractions, the highest values were observed in the finest fraction ( $<0.063 \text{ mm}$ ) for more than 75% of the total sampling sites for Al, Co, Cr, Cu, Fe, Mg, Mn, and Zn. The highest concentrations of Ca, Cd, K, Na, Ni, and Pb were observed in the finest fraction for 42–58% of the sites analysed [70]. However, such comparisons need caution as the regions lithological characteristics are different, and these sediments contained lower total organic matter which ranged from 0.4 to 7.8%, compared to the high OM contents in gulf surficial sediments. Organic matter is an important

concentrator of metals in sediments and can limit their mobility. Values of OM observed in sandy sediments, near river mouths areas, were similar to the range of data values for Szalinska et al. [70]. Also, sediments in those areas were previously exposed to significant historical anthropogenic impacts, and hence anthropogenic factors were shown as primary regulators of metal mobility.

An understanding of the pathways and fate of contaminants in aquatic ecosystems is critical for assessing their potential danger to the environment. Inorganic and organic contaminants have a high affinity for particulate matter. Heavy metals are strongly associated with suspended particulates [71], especially with fine grained sediments [72]. Adsorption-desorption is a function of surface area. It follows that smaller sediment particles would be more effective in recycling contaminants. Contaminant partitioning in sediments is strongly influenced by sediment type [73]. The bottom sediments from the lake exhibit similar characteristics when moving from littoral to deeper areas of the lake. In general, most of the fine grained sediments occur in the deep central parts of the lake basin while coarser grained sediments occur along the basin rims. The differences in spatial metal contents can be expected where influences from the shallower littoral areas are greater, as compared to the deeper sediments, with minimal resuspension events in relatively shallow basins.

Sediments in the lake accumulate from deposition of settling particulate organic matter and inorganic matter sourced internally and from diverse external materials (rocks, soils, vegetation, and agricultural, industrial, and domestic sources). This may indicate the heterogeneous nature of most bottom sediments and hence the noticeable variations in Cr (Section 5) and other elements reported by different investigators. However, determined factors such as sediment grain size and the organic matter and others not evaluated, such as Fe-Mn oxy hydroxides, redox conditions, and sediment pore water pH are important in regulating metal mobility. The relationships between Cr concentrations and sediment characteristics determined were low and poor, but significant positive correlations were found with other metals (Ni and Co, unpubl.), indicating nondominance of lithogenous processes in influencing the spatial distributions of Cr. Chromium concentrates in the heavy fraction of soils and sediments. This is supported by the few areas which showed minor to moderate Cr enrichment in surficial sediments, a sign of anthropogenic Cr sources. Fe in the finer fraction also showed a negative, but significant relationship, and this could possibly be due to the more mobile nature of Fe in the secondary environment as compared to the more stable Cr and presence of high organic matter in sediments, besides the common lithogenous sources. Other investigations by Mwamburi [74] have found detectable but low amounts of Cr bound in bioavailable forms in surficial sediments. The mean (% coefficient of variation) Cr in all five geochemically defined phases (phase summation, including residual phase) was  $14.7 \mu\text{g/g}$  (65%) for the Nyanza gulf surficial sediment (finer fraction) and an overall mean value ( $\pm\text{sd}$ ) for  $43.4 \pm 7.1 \mu\text{g/g}$ , as a single determination (not sequential fractionation determination). Also Ongeru et

al. [75] found the following trends in readily mobilizable fraction (fractions 1–4) in decreasing order  $Pb > Mn > Sn > Cu > Co > Zn > Mg > Cd > Mo > Ni > Cr > Fe > Al$  in sediments at Carwash and  $Mn > Mo > Sn > Pb > Cd > Mg > Cu > Zn > Co > Ni > Fe > Cr > Al$  in sediments at Usoma beach. In other areas of L. Victoria, such as Mwanza Gulf, Kishe and Machiwa [76] found out that all heavy metals did not show any significant variation in their concentrations in surficial sediments with increasing distance from the shore (at 25 m, 500 m, and 2000 m), except for Cr. Chromium mean concentrations increasing from  $10.6 \pm 1.7$  ppm (at 25 m),  $11.4 \pm 2.1$  (at 500 m), and  $12.8 \pm 0.8$  ppm (at 2000 m).

For aquatic ecosystems considered to be of high conservation/ecological value (condition 1) a precautionary approach is recommended and naturally occurring toxicant (e.g., metals) should not exceed background sediment concentrations [57], if determined background values are available. The overall average Cr concentrations were lower than the concentration recommended [57, 77] as sediment quality guideline (low, trigger value, 80 mg/kg,) value established for sediments elsewhere. However, when compared to other national SQG values [57–61, 78] there were exceedances at some areas of the gulf (Table 2), for both the threshold effect (TEL 37.3 mg/kg, ERL, 80 mg/kg, MET 55 mg/kg, LEL 26 mg/kg, and consensus based TEC 43.4 mg/kg) and mid-range effect concentration values (PEL 90 mg/kg). This is supported by SEF's values found during 1994/5 and 2012 surveys. In a different lake ecosystem, Szalinska et al. [70] reported on Cr surficial sediment  $EF_{Al}$ , of 1 to 2.5 using different Al and Cr background values for St. Clair lake. The sediment Cr concentrations in Nyanza Gulf are above threshold effect concentration values (Table 2), of which further ecosystem specific investigations are recommended, but toxicity effects, especially for Cr, demand specific Cr species determination as only Cr (VI) is toxic and factors such as amounts of bioavailable Cr in sediments are important in influencing toxicity to organisms.

Chromium occurs ubiquitously in nature ( $<0.1 \mu\text{g}/\text{m}^3$  in air). The concentration of Cr in rocks varies from an average of 5 mg/kg (range of 2–60 mg/kg) in granitic rocks, to an average 1800 mg/kg (range, 1100–3400 mg/kg) in ultrabasic and serpentine rocks [79, 80]. Natural levels in uncontaminated waters range from fractions of  $1 \mu\text{g}$  to a few  $\mu\text{g}/\text{L}$  [80]. Except for regions with substantial Cr deposits, the natural content of Cr in surface waters and drinking-water is very low, most of the samples containing between 1 and  $10 \mu\text{g}/\text{L}$  [81]. Substantially higher concentrations are almost always the result of human activities, reflecting pollution from industrial activities and sewage discharges [82].

As shown in Section 5, most studies in the Nyanza Gulf report low to undetectable levels of Cr ( $<60.82 \mu\text{g}/\text{L}$ ) in water. However, Oyoo-Okoth et al. [20] and Ogoyi et al. [22] studies show relatively high Cr in lake water, a reflection of the urban influence of the sites surveyed. The distribution of compounds containing Cr (III) and Cr (VI) depends on the redox potential, the pH, the presence of oxidizing or reducing compounds, the kinetics of the redox reactions, the formation of Cr (III) complexes or insoluble Cr (III) salts,

TABLE 2: Evaluation of sediment quality using the available threshold, mid-range, and extreme effect values (values given as % of samples exceeding the value for Cr).

(a) Threshold effect sediment quality guideline values (mg/kg)		
	Unfractionated sediments ( <i>n</i> = 31)	<63 $\mu\text{m}$ grain size fraction ( <i>n</i> = 30)
TEL <sup>a</sup> (37.3)	20.7%	7.1%
ERL <sup>a</sup> (80)	6.9%	0%
MET <sup>a</sup> (55)	14%	3.6%
LEL <sup>a</sup> (26)	51.7%	21.4%
CB-TEC <sup>a</sup> (43.4)	17.2%	7.1%
(b) Mid-range effect sediment quality guideline values (mg/kg)		
	Unfractionated sediments	<63 $\mu\text{m}$ grain size fraction
PEL <sup>a</sup> (90)	6.9%	0%
ERM <sup>a</sup> (145)	0%	0%
EC (PEL) <sup>b</sup> (160)	0%	0%
(c) Extreme effect sediment quality guideline values (mg/kg)		
	Unfractionated sediments	<63 $\mu\text{m}$ grain size fraction
TET <sup>a</sup> (100)	0%	0%
SEL <sup>a</sup> (110)	0%	0%
CB (PEC) <sup>a</sup> (111)	0%	0%

TEL<sup>a</sup>: threshold effect level; ERL/M<sup>a</sup>: effects range low/medium; LEL<sup>a</sup>: lowest effect level; CB<sup>a</sup>: consensus based; MET<sup>a</sup>: minimal effect level; SQAV: sediment quality advisory value (36 mg/kg threshold value); ISQG<sup>d</sup>: interim sediment quality guideline (80 mg/kg threshold value); PEC: probable effect concentration; PEL: probable effect level; SEL: severe effect level; TET: toxic effect threshold; [57]<sup>e</sup>: Australian and New Zealand Environment and Conservation Council (81 mg/kg threshold value); EC-TEL<sup>b</sup> (52.3 mg/kg threshold value); NOAA-ERL<sup>c</sup> (81 mg/kg threshold value); (a): [58]; b: [59]; c: [60]; d: [61]).

and the total Cr concentration [83]. In the environment, Cr (VI) occurs mostly as  $\text{CrO}_4^{2-}$  or  $\text{HCrO}_4^-$  and Cr (III) as  $\text{Cr}(\text{OH})_n^{(3-n)+}$  [83]. In water, Cr (III) is a positive ion that forms hydroxides and complexes and is adsorbed at relatively high pH values [83]. At  $\text{pH} > 6.5$ ,  $\text{CrO}_4^{2-}$  species dominate while at  $\text{pH} < 6.5$ ,  $\text{HCrO}_4^-$  counterparts dominate at low concentrations ( $<0.03 \text{ mol}/\text{L}$ ), but at concentrations greater than  $0.001 \text{ mol}/\text{L}$ , and  $\text{HCrO}_4^-$  ions begin to change to  $\text{Cr}_2\text{O}_7^{2-}$  which becomes the dominant entity at concentrations greater than  $0.03 \text{ mol}/\text{L}$  [84]. Trivalent Cr is an acid that forms strong complexes with various O-, N-, and S-containing ligands and many organic compounds. The solubility of Cr (III) is limited by the formation of highly insoluble oxides, hydroxides, and phosphates and its strong tendency to adsorb to surfaces [85]. In surface waters, the ratio of Cr (III) to Cr (VI) varies widely, and relatively high concentrations of the latter can be found locally. In general, Cr (VI) salts are more soluble than those of Cr (III), making Cr (VI) readily mobile [83].

Chromium is unique among regulated toxic elements in the environment in that different species of Cr, specifically

Cr (III) and Cr (VI), are regulated in different ways, in contrast to other toxic elements where the oxidation state is not distinguished. In both industrial and environmental situations, Cr (III) and Cr (VI) can interconvert, with reduction of Cr (VI) to Cr (III) generally being favored in most environmental situations [86].  $\text{Cr}^{3+}$  has very low solubility and low reactivity resulting in low mobility in the environment and low toxicity in living organisms [87]. In water, Cr speciation is very important and selective determination of Cr (VI) is of particular importance because of its toxicity. Due to the importance of Cr (III) and Cr (VI), the accurate and sensitive determinations of these ions are the important part of the analytical chemistry [80, 88]. Therefore, total chromium measurements alone cannot determine the actual environmental impact. Speciation of trace levels of Cr in water sample requires high-capacity separation and high sensitivity detection [88, 89].

Chromium is not known to accumulate in the bodies of fish, but high concentrations of Cr, due to the disposal of metal products in surface waters, can damage the gills of fish that swim near the point of disposal. In animals Cr can cause respiratory problems, a lower ability to fight disease, birth defects, infertility, and tumor formation.  $\text{Cr}^{3+}$  is an essential element in humans, with a daily intake of 50 to 200  $\mu\text{g}/\text{day}$  recommended for adults [1, 80], although debates on the nutritional biochemistry of Cr are also documented. Food is a major source of exposure to chromium, and estimated oral intakes for infants (1 yr), children (11 yr), and adults are 33–45, 123–171, and 246–343  $\mu\text{g}/\text{person}/\text{day}$ , respectively [90] in UK. Soil ingestion, particularly common in young children, can contribute to oral intake [90, 91]. Cr (III) is essential to normal glucose, protein, and fat metabolism and is thus an essential dietary element. The body has several systems for reducing Cr (VI) to Cr (III). Cr (VI) detoxification leads to increased levels of Cr (III) [1].

An extensive review on the human and animal toxicity data and the nutritional biochemistry for chromium is available [92–95]. Cr enters the air, water, and soil as the Cr (III) and Cr (VI) form through natural processes and human activities. Anthropogenic activities accelerate the incorporation of Cr compounds in surface and underground water, especially in areas with significant industrial and mining activities. Cr salts (in particular chromium sulphate) are the most widely used in tanning substances today [96], especially because they have a high rate of penetration into the interfibrillar spaces of the skins [97]. High and elevated concentrations of Cr have been reported in other areas as a result of tannery discharges into rivers [98]. In lakes the water-bottom sediments interface is an active zone for possible chemical and physical remobilization of accumulated chemical contaminants, especially metals. Metal contamination of sediments resulting from urban runoff exerts a deleterious impact on freshwater macroinvertebrates, particularly the loss of metal sensitive orders such as Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) [99, 100].

Benthic organisms have been used in determination of sediment toxicity [101]. In general, invertebrate species, such as polychaete worms, insects, and crustaceans, are more

sensitive to the toxic effects of chromium than vertebrates, such as some fish [102]. The lethal chromium level for several aquatic and nonaquatic invertebrates has been reported to be 0.05 mg/L [103]. Among the more than 30 fish species studied, Salmonids seem to be the most sensitive group [104]. Invertebrates are the most sensitive organisms to hexavalent chromium. Among the more than 40 invertebrate species studied, the chronic toxicity effects range from 0.01 mg/L for *Ceriodaphnia dubia* (14 d LOEC) to 1000 mg/L for *Chironomus tentans* (decrease in rest time), while acute toxicity effects range from 0.015 for daphnids, *Simocephalus vetulus*, and *Daphnia magna* (24 h EC50) to 500 mg/L for the crayfish *Procambarus clarkii* (96 h LC40). Aquatic plants such as *Selenastrum capricornutum* can be inhibited in growth by levels of chromium as low as 0.6 mg/L [85, 105].

Treatment of wastewater can prevent increased total concentrations of Cr in surface waters. Cr can be removed from drinking water sources by coagulation/filtration, ion exchange, reverse osmosis, and lime softening. Cr used in the electroplating and tanning industries causes environmental pollution through the generation of effluent. Various methods such as precipitation-flocculation coupled with pre/postoxidation, reduction, and concentration are often employed to control environmental pollution. Though these techniques, referred to as “removal-disposal,” serve the purpose of satisfying water pollution norms, they produce solid residues containing  $\text{Cr}(\text{OH})_3$  as the sludges, which are usually dumped as landfill [106]. As contamination of soil and water has threatened the wellbeing of humans and natural environment, microorganisms play crucial role in combating the widespread pollution of global environment. Cr (VI) removal through common physicochemical techniques is highly expensive and inappropriate at low concentration. Microbial (Cr reducing bacteria) reduction of Cr (VI) to trivalent form is considered a favorable technique for Cr (VI) removal from wastewater, as it reduces the highly toxic form of Cr to less toxic form [107].

Trivalent chromium can be oxidised to hexavalent Cr with disinfectants, particularly chlorine, chlorine dioxide, and ozone [108]. The guideline value of 0.05 mg/L has been used in many countries for a number of years with no known cases of Cr toxicity [83, 92, 108]. Analysis for the separate valence states of Cr is time-consuming and hence the guideline value applies to total Cr. If concentrations of total Cr exceed the guideline value, it is recommended that separate analyses for Cr (VI) and Cr (III) be undertaken [108]. In the study area, some of the recorded and compiled concentrations of Cr in lake surface water border on the guideline value compared to very low levels reported in some highland streams in more pristine areas, and, therefore, with use of more sensitive techniques, follow-up investigations can attempt to provide data on Cr species.

## 5. Comparative Levels of Chromium in Lakes and Rivers

Variable Cr concentrations data documented in lake and river compartments, soils, livestock products, anthropogenic

products, and crustal materials, from different authors, are listed as follows.

**5.1. Lake and River Surface Water.** For lake and river surface water, the following values were obtained: Nyanza Gulf (lake water:  $0.23 \pm 0.04$  to  $0.79 \pm 0.02$  mg/L,  $0.08 \pm 0.016$  to  $0.19 \pm 0.02$   $\mu$ g/L, and  $24.3 \pm 6.4$  to  $87.9 \pm 9.2$   $\mu$ g/L [19–21];  $0.06$  mg/L highest concentration recorded [18];  $0.049$  to  $0.159$  ppm [22]); L. Kanyaboli ( $5.26$  to  $60.82$   $\mu$ g/L) [23]; inflowing rivers of Nyanza Gulf (nd to  $50$   $\mu$ g/L) [24]; Nyanza Gulf (dissolved Cr in inflowing rivers and lake water = nd to  $50$   $\mu$ g/L; total Cr in unfiltered inflowing rivers water = nd to  $50$   $\mu$ g/L and unfiltered lake water = nd to  $4$   $\mu$ g/L) [49, 108, 109]; satellite lakes around Nyanza Gulf (below detection level) [110]; Nakivubo channel, Uganda (channel, wetland, and inner Murchison bay =  $0.003$  to  $0.21$  mg/L) [111]; L. Victoria, Uganda ( $<0.01$  to  $0.02$  mg/L) [112]; tributaries of R. Mara in Kenya ( $0.35$  to  $3.14$   $\mu$ g/L) [113]; reported European streams (stream water  $<0.01$  to  $43.0$   $\mu$ g/L) [114].

**5.2. Algae.** For algae, the following value was obtained: Winam Gulf ( $0.095$  to  $0.114$   $\mu$ g/g) [22].

**5.3. Fish and Other Food Crops.** For fish and other food crops, the following values were obtained: Winam Gulf (fish = nd to  $0.70$  mg/kg [18]; food crops =  $0.07 \pm 0.05$   $\mu$ g/g to  $0.65 \pm 0.22$   $\mu$ g/g; fish species =  $0.22 \pm 0.02$  to  $1.28 \pm 0.12$   $\mu$ g/g [21]); Nakivubo wetland food crops ( $0.0$  to  $14.30$  mg/kg) [111].

**5.4. Livestock Products.** For livestock products, the following value was obtained: Winam Gulf (beef and milk =  $0.18 \pm 0.03$   $\mu$ g/g to  $5.51 \pm 0.92$   $\mu$ g/g) [21].

**5.5. Soils.** For soils, the following values were obtained: Nyanza Gulf (soils:  $6.7 \pm 1.1$  to  $11.8 \pm 2.0$   $\mu$ g/g) [21]; Nakivubo channel wetland soils ( $24.50$  to  $105.30$  mg/kg) [111]; reported African soils (top soils range:  $1.0$  to  $6230$  mg/kg; subsoils range:  $<1.0$  to  $2140$  mg/kg) [114]; reported European soils (top soils range:  $1.0$  to  $6230$  mg/kg; subsoils range:  $<1.0$  to  $2140$  mg/kg) [114]; reported sub-Saharan Africa soils (some Kenyan soil types included, median value =  $45$  mg/kg; range =  $0.7$  to  $598$  mg/kg; mean contents by soil class: Acrisols, Alisols, and Plinthosols =  $71$  mg/kg; Arenosols =  $39$  mg/kg; Calcisols, Cambisols, and Luvisols =  $56$  mg/kg; Ferralsols, Acrisols, and Nitisols =  $45$  mg/kg; Fluvisols, Gleysols, and Cambisols =  $44$  mg/kg; Leptosols =  $244$  mg/kg; Vertisols =  $13$  mg/kg; Plinthosols =  $86$  mg/kg; Nitisols and Andosols =  $68$  mg/kg; Lixisols =  $64$  mg/kg; Ferralsols =  $53$  mg/kg) [115].

**5.6. Lake and River Bottom Sediments.** For lake and river bottom sediments, the following values were obtained: Nyanza Gulf (sediments:  $0.42 \pm 0.05$  to  $1.12 \pm 0.11$  mg/kg) [19, 20]; Winam Gulf ( $21.0 \pm 0.70$  mg/kg [18]; nd to  $0.275$  ppm) [22]; L. Kanyaboli (lake,  $3.7$  to  $7.73$   $\mu$ g/g) [23]; inflowing rivers of Nyanza Gulf ( $2.92$  to  $5.36$   $\mu$ g/g) [24]; Nyanza Gulf and inflowing rivers (rivers = nd to  $125$  mg/kg; lake = nd to  $85.7$  mg/kg) [62, 108, 109]; satellite lakes around Nyanza Gulf ( $15.9$  to  $44.6$  mg/kg) [110]; Nakivubo channel (channel and inner Murchison bay =  $29.0$  to  $103.0$  mg/kg) [111]; L. Victoria,

Uganda ( $2.3$  to  $156.9$  mg/kg) [112]; Mwanza Gulf, Tanzania (sediments,  $11.6 \pm 0.8$  ppm and a mean range of  $10.6 \pm 1.7$  to  $12.9 \pm 1.0$  ppm) [76]; L. Nakuru (sediments =  $23.8$  ppm) and L. Bogoria (sediments =  $21.3$  ppm) [116]; L. Naivasha (core sediments =  $3$  to  $36$   $\mu$ g/g) [117]; L. Turkana (sediments  $54 \pm 24$  ppm) [118]; L. St. Clair (sediments =  $6.83$  to  $20.08$  mg/kg) and St. Clair delta (sediments =  $2.22$  to  $44.37$  mg/kg) [70]; core sediment from 3 main Kenyan river estuaries' core (R. Ramisi =  $35.0$  to  $37.3$   $\mu$ g/g; R. Sabaki =  $35.0$  to  $59.8$   $\mu$ g/g; R. Tana =  $37.8$  to  $56.4$   $\mu$ g/g) [119]; reported European streams (stream sediments  $<3.0$  to  $3320$  mg/kg, flood plain sediment  $3.0$  to  $2730$  mg/kg) [114].

**5.7. Anthropogenic by-Products.** For anthropogenic byproducts, the following values were obtained: average in anthropogenic byproducts (fertilizers:  $151$   $\mu$ g/g and  $60$   $\mu$ g/g, sewage sludge:  $1,221$   $\mu$ g/g) [120, 121].

**5.8. Crustal Materials.** For crustal materials, the following values were obtained: Shale ( $120$   $\mu$ g/g,  $90$   $\mu$ g/g) and Granite ( $20$   $\mu$ g/g,  $10$   $\mu$ g/g) [120, 122]; upper continental crust ( $35$  ppm) (Taylor and MacLennan, 1995); upper crust ( $69$  ppm, average in soils  $61$  ppm) [123].

## 6. Conclusions

Levels of Cr in surficial sediments are within ranges reported for major soils in sub-Saharan Africa. The spatial mean Cr contents in finer silt-clay fraction were found to be significantly lower than those in the unfractionated sediments, but with a strong linear positive correlation. The highest Cr concentrations were observed in only 14% of the finer sediment fraction. The relatively high organic matter contents, coupled with precipitated coatings of oxyhydroxides of Fe-Mn on sediment particles, means increased potential for complex Cr remobilization and bioavailability of sorbed Cr from sedimentary sources, depending on particular equilibrium conditions dominating, as chromium (III) species can be transformed to the more toxic Cr (VI) and vice versa.

The study results show decreasing spatial amounts of Cr in surficial sediments of the Nyanza Gulf, when compared to a study done 20 years earlier. However, the 95% confidence limits of the overall mean Cr in unfractionated sediments exceed the threshold effect concentration (TEC), indicating the potential for Cr remobilization from sediments, as the element has been previously found bound in remobilizable forms, in operationally defined geochemical phases of surficial sediments. In general the sediment enrichment is evidence of possible dominance of lithogenous sources of Cr in the surface lake sediments, with potential anthropogenic sources from the drainage system and nearshore urban areas. The geoaccumulation index indicates unpolluted sediments, with a minor to moderate enrichment of Cr in surficial sediments of three sites around the Nyanza Gulf zones and around the river mouth in the main lake. Increasing urban activities, where wastewaters are not effectively treated (especially tannery wastes and chrome pigments), are, in most cases, the main sources of Cr contamination in nearby lake ecosystems. Therefore effective treatment of industrial

waste sources and more stringent pollution management regulations will reduce potential impacts of Cr pollution to aquatic ecosystems, where the trivalent Cr can be oxidized to the more toxic hexavalent Cr species.

## Competing Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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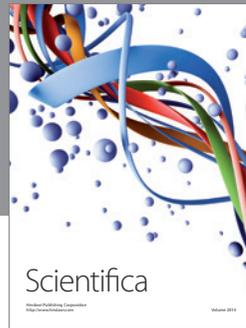
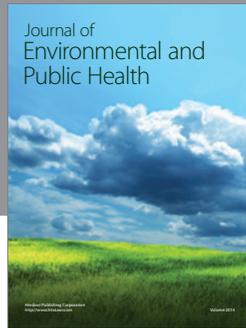
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