Bioavailability of particle-associated nutrients as affected by internal regeneration processes in the Nyanza Gulf region of Lake Victoria

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Abstract

Land-use changes have been implicated a lot in the eutrophication of many lakes while forgetting the role of internal loading as influenced by the hydrological regimes of a given lake. The phosphorus loading of Nyanza Gulf is influenced both by internal and external loading with the internal loading playing a greater role in its eutrophication. The shear on the Apatite Phosphorus (AP) rich residual rock in the western end of the gulf through strong currents across the Rusinga Channel erodes the rock into non-apatite inorganic phosphorus (NAIP) which is readily available for primary productivity. The current suspends the phosphorus rich apatite sediment together with the reserved phosphorus within sediments to the water column. The NAIP concentration on the western end of the gulf is exceptionally high, >1500 mg kg^{-1}, and together with the hydrological forcing; is believed to be the driving force of Nyanza Gulf eutrophication. External loading through rivers and municipal discharges exacerbates the problem. The external loading mainly influences the inner gulf on the eastern shore while the internal loading affects mainly the western end of the gulf. Nyanza Gulf eutrophication can be managed by adopting the following measures: (i) the Mbita Causeway needs to be opened and a bridge erected in its place in order to reduce the strong current through the Rusinga Channel and the residence time within the gulf, by increasing the flushing rates; (ii) the farming communities within the basin need to be sensitized on the controlled use of fertilizers; (iii) the municipal wastes should be treated to tertiary level before discharge into the lake; and (iv) reduce erosion within the basin through re/afforestation.

Key words

apatite phosphorus, currents, eutrophication, Lake Victoria, non-apatite inorganic phosphorus, Nyanza Gulf.

INTRODUCTION

Lake Victoria is the second largest freshwater lake in the world, with a surface area of 68 800 km^2 and a catchment area of 195 000 km^2 (Odada & Olago 2006; Sitoki *et al.* 2010). Increased population density has resulted in rapid land-use changes within the basin in terms of agriculture, industrialization, urbanization and deforestation (Swallow & Mungai 2002). Some of these activities have led to increased soil erosion and subsequent nutrient influx from the catchment into the lake (Scheren *et al.* 2000; Walsh *et al.* 2002). The major soil types within the Lake Victoria basin are oxisols (red or yellow), acrisols and vertisols (black clay) (Okalebo *et al.* 2005). Oxisols are infertile and have low phosphorus content (Buol *et al.* 2011). They are common in the upland regions of the basin, and have a characteristic of low cation exchange capacity (Buol *et al.* 2011) and are common in the upland regions of the basin. They are, however, enriched in iron (Fe) and aluminium (Al) that form ligands for phosphorus adsorption (Buol *et al.* 2011). Thus, excessive fertilizer use is common in these regions (USDA-NRCS 2013). Vertisols are thick black clay soils and, while not acutely deficient in phosphorus, they are enriched in Al (Blyth & de Freitas 1974; Buol *et al.* 2011). The Vertisols are derived from the basalts (Blyth & de Freitas 1974), a common rock within the basin. Because of deleterious deforestation and other land-use changes, erosion within the basin has increased tremendously, resulting in increased sediment loads being transported into Nyanza Gulf (Swallow & Mungai 2002). Raw effluents from the urban centres and industries also are discharged into the lake. Nutrients from these sources

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are in sundry times transported, adsorbed onto sediment particles and onto organic matter, via rivers or sewerage disposal systems into the lake (Syers *et al.* 1973). In addition to the external nutrient loading, lake sediments act as nutrient sinks, and, limnological and hydrological changes in the water may remobilize them back into the water column (Tsujimura 2004).

Major ecological changes have occurred in Lake Victoria over the past 2–3 decades (Hecky 1993). There has been a shift in fish faunal diversity and abundance attributed to the introduction of alien fish species, and changes in the trophic status of the water mass (Hecky 1993, 2003). The trophic status has changed from mesotrophic (intermediate nutrient content) to hypereutrophic (heavily nutrient-laden) conditions. The thickness of the mixed water layer has changed from about 40–50 m to 30–40 m (Hecky 1993). The trophic change has resulted in massive fish kills (Ochumba 1990; Hecky 1993 and Lowe-McConnell 1994). There has also been a dramatic reorganization of the algal species composition, from abundant diatoms to nitrogen-fixing blue-green cyanobacteria (Kling *et al.* 2001). The chlorophyll-a concentration has increased 2- to 10- fold (Hecky 1993; Adams & Ochola 2002). The N:P ratio has decreased, and the algal biomass has become limited by nitrogen. High δ^{15}N values occur in the uppermost sediments in the lake, declining down core, probably because of the limnological changes (Talbot 2001). The rising trend in δ^{15}N is attributed to the impact of denitrification, a consequence of a larger, more persistent anoxic hypolimnion (Hecky *et al.* 1996). An increased supply of isotopically heavy soil N also is implicated for the change (Talbot 2001).

Lake sediments play a significant role in phosphorus availability for primary productivity in lakes, with their impacts dependent on their ability to retain or release phosphorus under changing limnological conditions (Syers *et al.* 1973). Phosphorus is a macronutrient, playing a major factor in excessive and deleterious fertilization of lakes (Syers *et al.* 1973; Sonzogni *et al.* 1982). The level of internal phosphorus loading, and the time lag for recovery after reduction of the external loading, will influence the degree of lake eutrophy. During the dry season, the external nutrient loading is generally low, although it is not unusual for the phosphorus concentration in the water column of eutrophic lakes to be several times higher than in the inflowing waters (Pettersson 1998). This observation highlights the role of sediments in nutrient sequestration and remobilization, and the consequent impacts on lake eutrophication. The present study, therefore, seeks to understand the role of particle-associated phosphorus of non-apatite inorganic phosphorus (NAIP) and apatite phosphorus (AP) in the eutrophication of Nyanza Gulf. NAIP is a group of labile and bioavailable particulate phosphorus adsorbed onto the oxides and hydroxides of cation ligands of iron (Fe), aluminium (Al) and manganese (Mn) within sediments (Bostan *et al.* 2000). AP is a calcium-associated phosphate mineral consisting of orthophosphate present in the crystal lattice of apatite. It refers to hydroxylapatite ($Ca_{10}(PO_4)_6(OH)_2$), fluoroapatite ($Ca_{10}(PO_4)_6(F)_2$) and chloroapatite ($Ca_{10}(PO_4)_6(Cl)_2$) (Blyth & de Freitas 1974; Bostan *et al.* 2000). It has a higher chemical stability than NAIP, being practically insoluble in surface water. The primary use of apatite is in the manufacture of phosphate fertilizer (Blyth & de Freitas 1974).

This study is restricted to the Nyanza Gulf, also known as Winam Gulf (Fig. 1), Kenya, to determine the present limnological status of the lake water and the spatial distribution of bioavailable particle-associated phosphorus fractions as affected by internal regeneration mechanisms. The study area was chosen because of the following factors: (i) its wide catchment area; (ii) numerous rivers draining into the gulf; (iii) high number of urban settings within the catchment; (iv) agricultural activities within the catchment; and (v) observed limnological changes within the gulf's ecosystem. The lake is monomictic, with the water column mixing throughout its entire depth during the June to August period (Hecky 1993). A blanket of algal biomass always covers the Nyanza Gulf during this period. Considering the proliferation of algal biomass, and the elevated nutrient concentrations in the neighbourhood of Homa Bay (Gikuma-Njuru *et al.* 2005), one might be tempted to believe this ecozone is more polluted because of effluent discharges than is Kisumu Railways Pier. The present study is meant to elucidate the cause of Homa Bay's pollution, and the spatial distribution and probable source of bioavailable phosphorus.

MATERIALS AND METHODS

Field sampling was designed to address both point and non-point sources of pollution in the Nyanza Gulf. Four transects consisting of 13 geo-referenced stations were sampled for water and sediment within the Nyanza Gulf between 20th and 23rd July 2007 (Fig. 1). The stations were geo-referenced using a Magellan Global Positioning System (GPS). Water samples for nutrient analyses were collected using a Van Dorn water sampler near the sediment/water interface and at the surface for acetone chlorophyll-a measurements. The water samples were filtered and preserved with concentrated sulphuric acid (H_2SO_4) and stored in polyethylene bottles under refrigeration at about 4°C for further analyses. Chlorophyll-a samples were filtered with GF/C Whatman filters, with the filtrate wrapped in an aluminium foil and stored in a dessicator for subsequent laboratory analyses. The depth profiles for chlorophyll-a were measured using a Sea-bird multiparameter water monitoring equipment (Sea Cat SBE 19; Sea-bird Electronics®, Bellevue, Washington, USA), in comparison with the acetone method for surface samples. Chlorophyll-a concentrations were extracted using reagent-grade acetone under subdued light, with the absorbance of the supernatant, after centrifuging, being measured photometrically. This was assumed to represent the living phytoplankton biomass. Sediment samples were collected using a Ponar grab sampler, being subsampled from the mid portion of the grab to avoid contamination. The sediment samples were collected for particulate phosphorus and elemental analyses, stored in polyethylene bags and kept as cool as possible at temperatures of about 4°C. The sediments were dried at 45°C in the laboratory until attaining constant weights before chemical extraction of phosphorus.

Chemical analyses of dissolved nutrients were carried out in the laboratory using photometric methods. The analysed dissolved nutrient compounds were reactive phosphorus (soluble reactive phosphorus (SRP); PO_4^{-}-P), total phosphorus (TP), nitrate-N, nitrite-N, ammonium-N and total nitrogen (TN). The nitrogen load was included because of its important subservient role in primary productivity, other than phosphorus and silica (Talbot 2001). SRP samples were filtered using 0.45-μm membrane filters, with the filtrate subsequently analysed using the ascorbic acid method. TP concentrations were analysed by hydrolysing the unfiltered samples with potassium persulphate, under heat and pressure, to orthophosphate, which was subsequently analysed using the ascorbic acid method. Nitrite was analysed by diazotising the samples with sulphanilamide and using N-(1-naphthyl)-ethylenediamine as a coupling reagent. The coloured azo compound was then measured photometrically. Nitrate was reduced to nitrite using cadmium filings treated with copper sulphate. The resultant nitrite solution was analysed photometrically, using the method outlined above for nitrite. TN was measured by first hydrolysing all forms of nitrogen to nitrate, using potassium persulphate, before adopting the cadmium reduction method. Ammonium and silica were analysed using phenate and heteropoly blue methods, respectively. All these methods were adopted from APHA (2005).

Sediment samples for elemental analyses of iron (Fe), aluminium (Al), manganese (Mn) and calcium (Ca) were dried overnight at 105°C. A subsample of 2.5 g was then taken and digested with 40 mL of concentrated hydrochloric acid (HCl) for 16 hrs. The digested samples were subsequently filtered with GFF filters, and the supernatant analysed using AAS (Williams *et al.* 1976). The non-apatite inorganic phosphorus (NAIP) and apatite phosphorus (AP) fractions of dry sediments were measured through sequential extractions, using the harmonized Standards, Measurements and Testing programme (SMT) protocol method, as modified by Burrus (1984) (Fig. 2). The data were subsequently used to try to identify the source(s) of bioavailable fraction of phosphorus and their speciation.

RESULTS

Water chemistry and productivity

Silica

The silica concentrations ranged from 5.39 to 14.02 mg L^{-1} (Fig. 3). They exhibited a general decline from transect A to D. The highest concentration was observed at site A3. The northern shore sampling sites (A1, B1 and C1), which had fewer inflowing rivers, exhibited higher silica concentrations than their southern shore counterpart sampling sites (Figs 1,3).

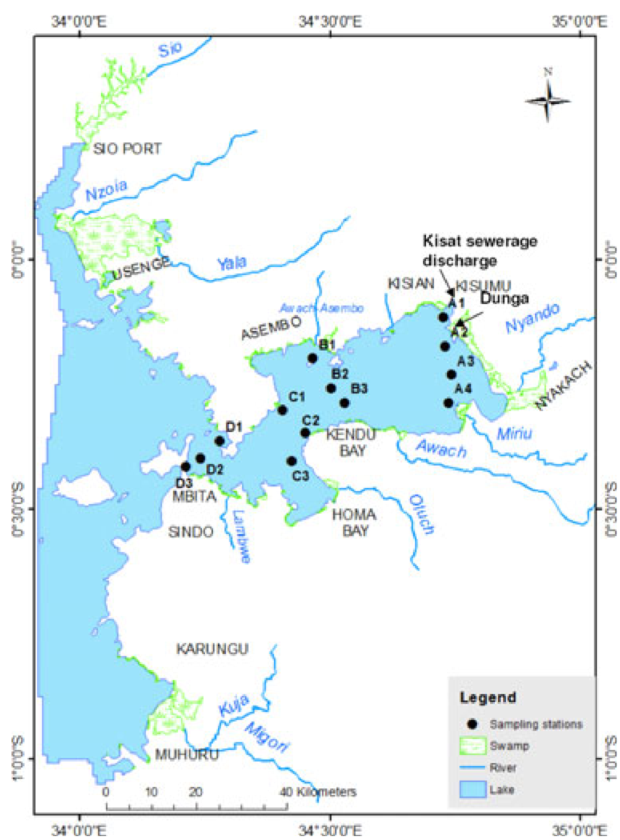

Fig. 1. Location of study area and sampling sites (sampling transects: A1–A4; B1–B3; C1–C3; D1–D3).

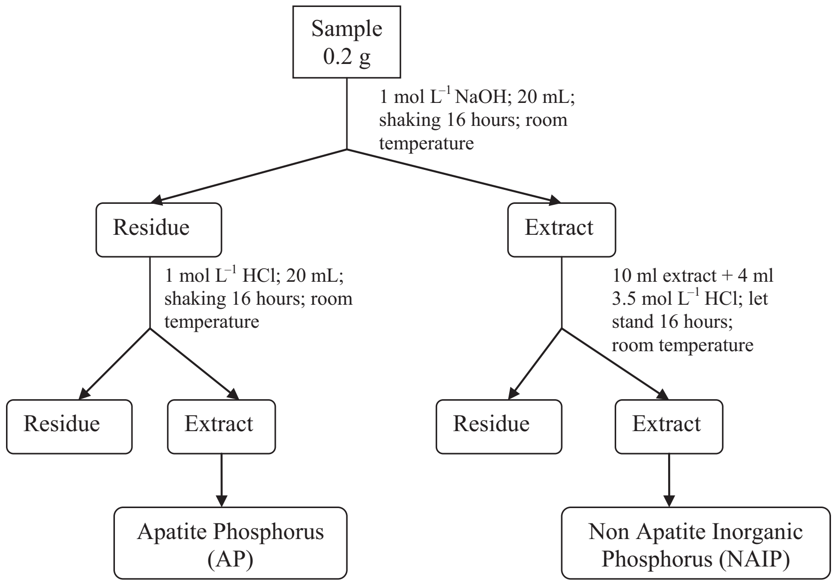

Fig. 2. Sequential extraction method for particulate inorganic phosphorus (Williams *et al.* (1978) modified SMT harmonized protocol method).

Total phosphorus

The total phosphorus (TP) concentrations ranged from 199.83 to 533.17 μg L^{-1}, exhibiting a decreasing trend from transect A to D (East – West) (Fig. 4). There were generally declining TP concentrations in transect A, from site A4 to A1 (Fig. 4). The TP to SRP ratios generally decreased from transect A to D. The sediment exhibited a good adsorptive capacity for phosphorus, as evidenced by the significant correlation (R^2 = 0.6316) between TP and silica concentrations (Fig. 5).

Reactive phosphorus

The soluble reactive phosphorus (SRP) concentrations ranged from 108.43 to 214.14 μg L^{-1}. The concentrations increased from transect A to B and C and then decreased to transect D (Fig. 4). The SRP concentrations on the eastern shore were lower than those observed on the western end transects of the gulf. The difference in concentrations between total phosphorus (TP) and soluble reactive phosphorus (SRP) were also greater for transect A sampling sites than for those of the other transects.

Nitrogen species

Concentrations of the reduced forms of nitrogen, ammonia and nitrite increased from transect D to B. They were lowest in transect A, except for sampling site A4 (Fig. 6). Site A4 exhibited high concentrations of ammonium and nitrite. All nitrogen nutrient fractions in transect A were low, including the most oxidized form (nitrate), except for site A4. Nitrite (which is an intermediate oxidation state of nitrogen, both in the oxidation of ammonia to nitrate and in the reduction of nitrate, and which is usually common at wastewater treatment plants) were high at sampling sites A1, B1, C1 and C3.

Chlorophyll-a

The Seabird chlorophyll-a depth profile concentrations decreased from transect A to B, then increased to transect D, while the acetone surface chlorophyll-a concentra-

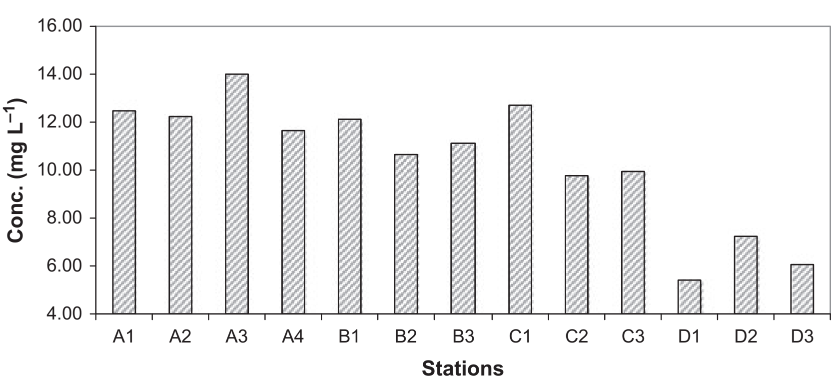

Fig. 3. Spatial dissolved silica concentrations at sampling sites across Nyanza Gulf.

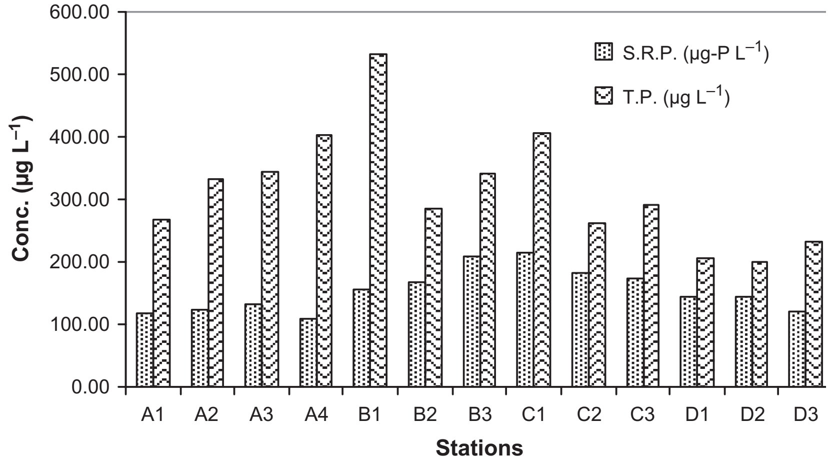

Fig. 4. Spatial distribution of phosphorus concentrations within Nyanza Gulf between sampling sites.

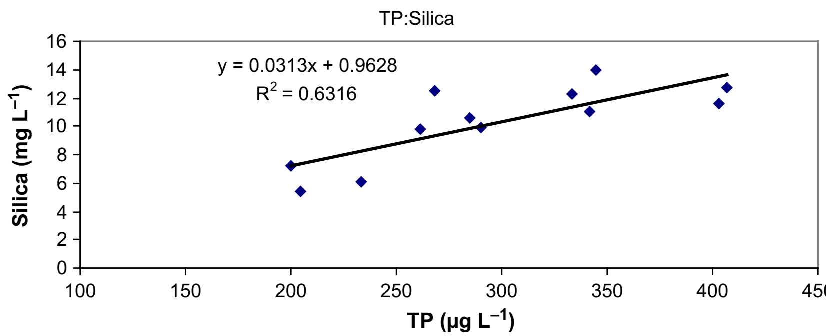

Fig. 5. Correlation between dissolved silica and total phosphorus concentrations.

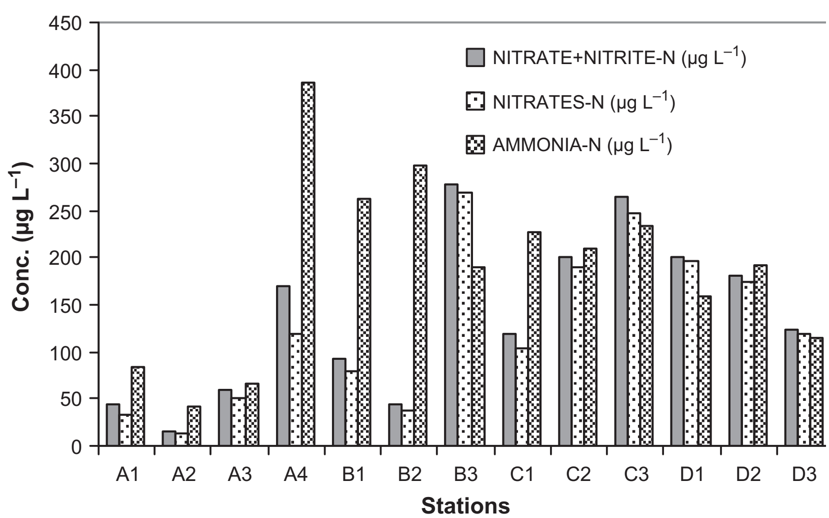

Fig. 6. Dissolved spatial nitrogen concentrations across Nyanza Gulf.

tions were highest in transect A (Fig. 7). In terms of nutrient levels, the western end of the gulf exhibited higher concentrations of bioavailable nitrogen and phosphorus than did transect A, therefore exhibiting higher depth profile chlorophyll-a concentrations. No depth profile measurement of chlorophyll-a was taken at sampling site A1.

Particulate phosphorus speciation

Non-apatite inorganic phosphorus (NAIP) exhibited a concentration range between 834.23 and 1838.08 mg.kg^{-1}. The lowest concentration was observed for sampling site A1, while the highest concentration was noted for site D2 (Fig. 8). Concentrations exceeding 1500 mg kg^{-1} were observed for site A3 (Nyakach Bay

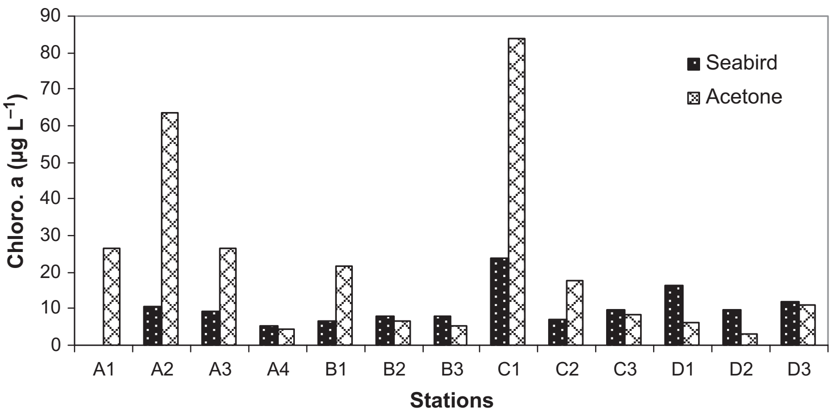

Fig. 7. Chlorophyll-a concentrations within the water column (Seabird method) and surface waters (acetone method).

area) and sites D1, D2 and D3 (Rusinga channel areas; Fig 8 and 9).

Apatite phosphorus (AP) concentrations ranged between 416.88 and 974.00 mg kg^{-1} (Fig. 8 and 10). The eastern shore exhibited low concentrations, whereas the western regions of the gulf were enriched. Sampling site A3 exhibited the lowest concentration, while D2 had the highest concentration. Transect D generally exhibited higher concentrations than the other transects. Thus, the Rusinga Channel zone exhibited higher AP concentrations.

Trace elements

The trace elements iron (Fe), aluminium (Al) and manganese (Mn) exhibited higher concentrations in transect A, compared to the near constant concentrations in transects B, C and D. The highest concentrations in transect A were observed at site A3, which received the River Nyando inflow. Calcium (Ca) exhibited an increasing concentration from transect A to D (Fig. 11). The highest Ca concentration was observed at site D3, concomitant with the AP concentration (Fig 8 and 11). Based on the present study, manganese (Mn) exhibited the lowest concentrations, compared to the rest of the ligands.

The correlation between non-apatite inorganic phosphorus (NAIP) and the ligand elements and calcium was tested using regression analyses (Fig. 12). The results indicated a high correlation between NAIP and Fe, Al and Mn, and a very low correlation with Ca within transect A (Fig. 12).

The regression results indicated a very high correlation between Fe and Mn (Fig. 13). Transects B, C and D exhibited a low correlation between NAIP and the ligand elements of Fe, Al and Mn, although it had a higher correlation with Ca, excluding a few outlier points (Fig. 14 and Table 1).

Table 1 illustrates that, even in areas exhibiting low correlations between NAIP and the cation ligands of Fe, Al and Mn in transects B, C and D, Al still exhibited a higher correlation (R^2 = 0.4881) than the other elements.

A satellite image (downloaded from Google Earth Map, USA) highlighted an anticlockwise NW transport current from the Nyando and Sondu-Miriu River mouths along the eastern shore of the gulf. This is evident from the direction of sediment transport from the plume source at the Nyando River mouth in Nyakach Bay in the south-east corner (Plate 1).

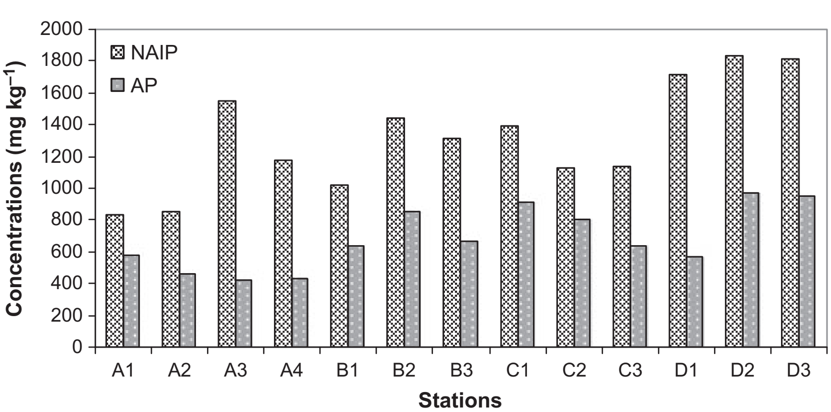

Fig. 8. Spatial distribution of particulate non-apatite inorganic phosphorus (NAIP) and apatite phosphorus (AP) phosphorus concentrations.

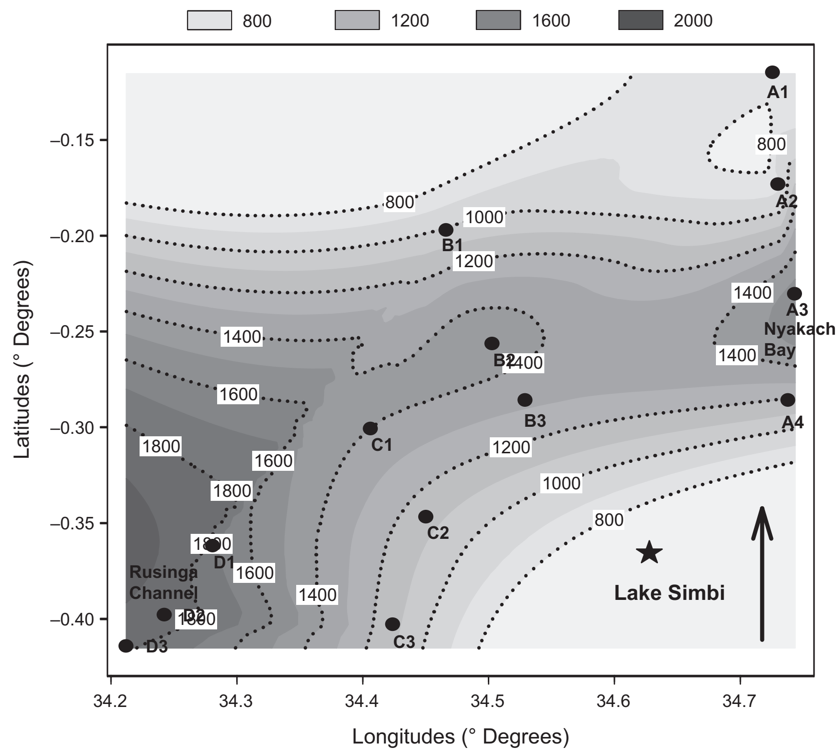

Fig. 9. Contour diagram of sampling sites and corresponding non-apatite inorganic phosphorus (NAIP) concentrations (mg kg^{-1}).

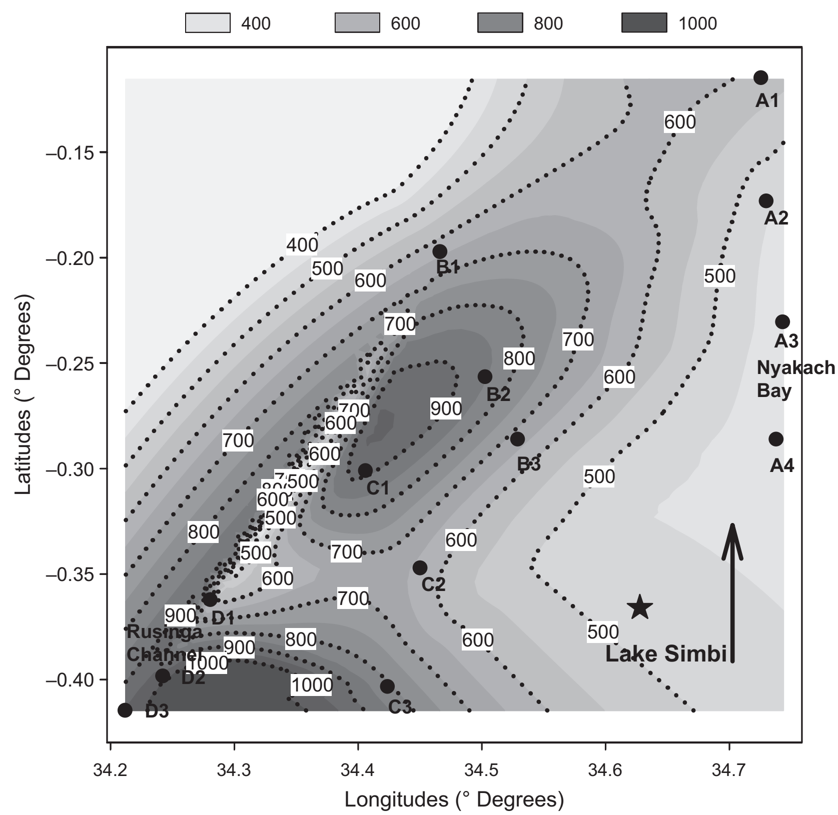

Fig. 10. Contour diagram of sampling sites and corresponding apatite phosphorus (AP) concentrations (mg kg^{-1}).

DISCUSSION

The study area can be divided into two regions: Zone 1 and Zone 2. Zone 1 covers transect A and its environs, while Zone 2 covers the environs of transects B, C and D. Based on the results of the present study, Zone 1 is likely influenced both by river discharges, especially

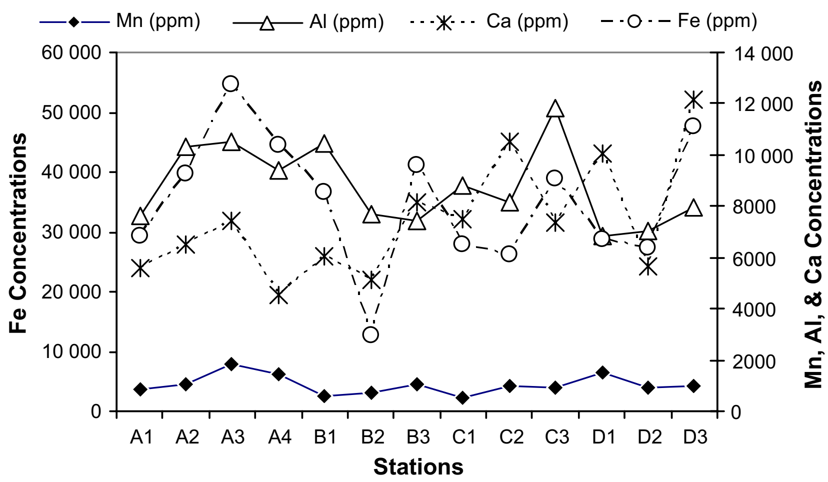

Fig. 11. Elemental concentrations of sediment ligands between sampling sites.

Sondu-Miriu and Nyando Rivers, and the effluent from the Kisumu municipality. This zone is affected by an anti-clockwise advection current along the eastern shores of the gulf, transporting sediment and water masses north-west from Nyakach Bay, where the Sondu-Miriu and Nyando Rivers drain (Plate 1). The transported sediment and the hydrological regimes along the advection current zone determines the limnology of transect A and its environs. The major point source of pollution is River Nyando, attributable to high industrialization and agricultural activities within the basin (Fig. 9; Swallow & Mungai 2002; Walsh *et al.* 2002). Zone 2 covers areas that are thought to be influenced by water mass currents from the open lake moving through Rusinga Channel into Nyanza Gulf, through to transect B. The open lake water mass is believed to be pressurized through the Rusinga Channel, resulting in an increased current velocity and a near laminar flow at the channel entrance. As the water mass passes through the channel, the pressure decreases and subsequently also the current velocity, with the water mass getting turbulent within the environs of Zone 2 between transects B and C. This hydrological condition is believed to influence the limnology of Zone 2, which exhibits a high algal biomass, especially around Homa Bay. Thus, it was previously believed that Homa Bay is highly eutrophic as a result of anthropogenic influxes from Homa Bay town (Gikuma-Njuru *et al.* 2005). The question arises as to how Homa Bay, which is a small town compared to Kisumu, can have effluent discharges surpassing those of Kisumu. This can be answered by considering the results of coliform counts conducted by Werimo (2005), which showed that coliform counts at Homa Bay exhibited lower concentrations than at Kisumu Pier. Thus, effluent discharges do not appear to be the primary reason for algal proliferation at Homa Bay.

Figure 3 indicates that silica concentrations were higher on the eastern shores of the gulf, with declining concentrations as one moves towards transect D. The northern shore sampling sites, although influenced by fewer rivers, exhibited higher concentrations of silica, compared to the southern shore, a scenario attributable to the river influxes from Nyando and Sondu-Miriu Rivers, and the subsequent north-west direction advection current transport (Plate 1). This silica source is reaffirmed by the present study results (Fig. 3), indicating that sampling site A3 near the Nyando River mouth exhibited the highest silica concentration. SRP, the most bioavailable form of phosphorus, exhibited the lowest concentrations along transect A. The concentrations increased towards transect C, with a subsequent decrease towards transect D (Fig. 4). The high SRP concentration in Zone 2 between transects C and D is presumably related to phosphorus remobilization as a result of intense mixing within this zone. The total phosphorus (TP) concentration decreased from transects A towards D (Fig. 4). A greater portion of phosphorus within Zone 1 exists in a particulate form, being transported as adsorbed phosphorus on sediment cation ligands, as inferred from the difference between the SRP and TP concentrations. There was a significant correlation between TP and silica (Fig. 5), indicating a greater sediment adsorption capacity for phosphorus, compared to the organic matter within the gulf. The TP/SRP ratio decreased from transect A towards D, due to a high mixing rate and nutrient remobilization on the western end of the gulf (Fig. 4). Thus, phosphorus exists more in a particulate form on the eastern shore of Nyanza Gulf, being more soluble as one moves to the western end of the gulf. The silica and TP concentrations decreased in the direction of the advection cur-

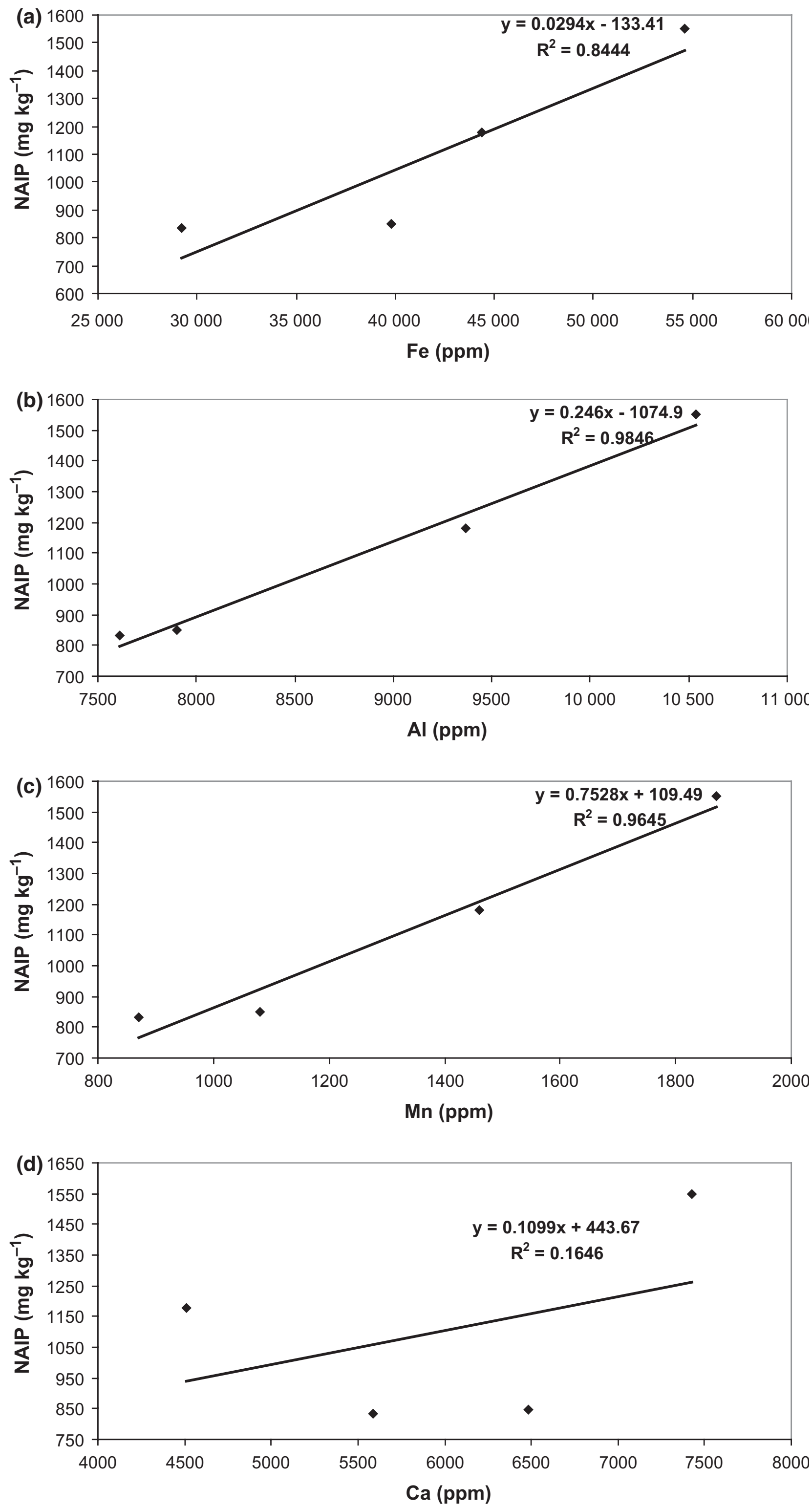

Fig. 12. (a–d) Regression analyses of non-apatite inorganic phosphorus (NAIP) in relation to sediment element ligands within transect A.

rent from sampling sites A3 to A1, which could be attributed to settling, rather than dissolution, as the SRP concentration is not increasing. Thus, phosphorus enrichment in Zone 1 is determined based on external phosphorus loading from the rivers and Kisumu town effluent discharge points. In contrast, it is likely due to resuspension in Zone 2.

Although the values of the nitrogen nutrient fractions are low in transect A (Zone 1), they are high in transects B, C and D (Fig. 6). Transect C exhibited slightly higher

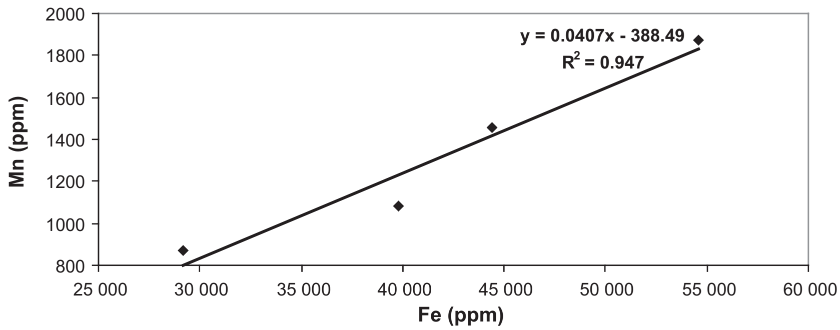

Fig. 13. Regression analyses between sediment Mn and Fe within transect A.

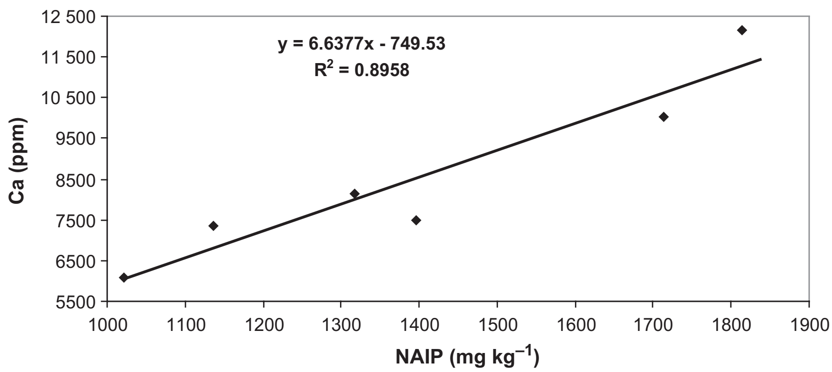

Fig. 14. Regression analyses between sediment non-apatite inorganic phosphorus (NAIP) and Ca within transects B, C and D.

Table 1. Regression coefficient (R^2) between sediment NAIP and ligand elements within Nyanza Gulf

R^2	Iron (Fe)	Aluminium (Al)	Manganese (Mn)	Calcium (Ca)
NAIP (A1 – A4)	0.8444	0.9846	0.9645	0.1646
NAIP (B – D)	No correlation	0.4881	0.1938	0.8958

NAIP, non-apatite inorganic phosphorus.

mean concentrations than the remaining transects. Sampling site A4 had the highest concentrations of the reduced nitrogen fractions (NH_4^+ -N; NO_2^--N). A fringing wetland exists there, which probably contributes to the elevated concentrations at sampling site A4. The elevated nitrogen nutrient fraction concentrations in transects B and C are likely due to remobilisation from decaying water hyacinth and other aquatic plants at the lake bottom. The high nitrite concentrations at sites A1, B1 and probably C1 could be attributable to Kisat sewerage treatment plant discharges and their subsequent dispersal by the north-west trending current on the eastern shore. High nitrite concentrations at site C3 is attributed to Homa Bay sewerage disposal.

The Seabird chlorophyll-a depth profile concentrations were high between transects C and D, while lowest in transect B. The high concentrations observed in transects C and D are highly due to intense mixing and subsequent remobilization of nutrients. Diatoms are known to proliferate in regions with high mixing (Chisholm 1992; Bopp *et al.* 2005). Diatom populations have also been noted to be abundant in Lake Victoria during periods of isothermal mixing of the whole water column during the months of June to August (Talling 1966, 1987). Within Nyanza Gulf, large surface accumulations of blue-green algal biomass of *Microcystis* have been observed on the eastern shores (Zone 1), while diatoms predominate in the Rusinga Channel regions, the latter being areas exhibiting high bioavailable phosphorus concentrations (Gikuma-Njuru & Hecky 2005; Sitoki *et al.* 2012). The predomination of diatoms in the western end is believed to be due to high physical mixing and nutrient regeneration. Increased chlorophyll-a concentrations at transect A, relative to those at transect B, is likely due to high Fe concentrations, as dissolved nutrient concentrations are low within this zone. Based on the USA eutrophication survey guidelines for lakes and reservoirs as outlined by Moore and Thornton (1988), the Nyanza Gulf is highly eutrophic. The total phosphorus concentration is more than 20 μg L^{-1}, the total nitrogen more than 500 μg L^{-1}, and the chlorophyll-a concentrations in most of the sampling sites exceeded 10 μg L^{-1} at the water surface.

Based on the results highlighted in Figure 9, NAIP concentrations exceeding 1500 mg kg^{-1} were observed at sampling site A3 (Nyakach Bay) and sites D1, D2 and D3 (Rusinga Channel). Nyakach Bay is the location in which the River Nyando drains into the gulf, whereas Rusinga Channel is the location through which the open lake water mass is pressurized. The pressure creates a shear at the lake bottom, eroding the *in situ* rocks, herein believed to be apatite rich, and transporting the subsequent sediments into the gulf. The nutrients are remobilized back to the water column at the turbulence zone, between transects B and C, resulting in the algal blanket. This zone also forms the major fishing ground, as micro- and macro-organisms, including plant detritus, are resuspended at the turbulence point, thereby making this area a foraging zone for several fish species (Guya F. J., Personal Observation). This also explains the high SRP concentrations within zone 2. AP-rich rocks are believed to be the source of bioavailable phosphorus (NAIP), as observed from the high correlation between NAIP and Ca within this zone. There is no clear correlation between NAIP and Fe, Al and Mn within this zone, however, as these elements within the gulf sediments are mainly riverine in source. The probable directions of the open lake current forcing into the gulf influencing the sediment transport, nutrient speciation, algal transport and the sorption and desorption of nutrients within Zone 2 are illustrated in Fig. 15 (adopted from Okely *et al.* 2010). Okely *et al.* (2010) also identified a similar two zones within Nyanza Gulf, herein identified as Zones 1 (transect A) and 2 (transects B-D). The gulf was believed to be influenced by diurnal- to semi-diurnal baratrophic stresses, with west–north-west winds from the open lake occurring in the afternoons, with speeds >5 m s^{-1}. Reversed east–south-east winds are observed after midnight, with wind speeds of about 4 m s^{-1}. They observed a peak shear at the lake bottom in the afternoons, coincident with strong winds and channel flow. Between transects B and D, Okely *et al.* (2010)recorded a vigorous vertical mixing, using the Richardson number (Ri) index. The median Ri in the water column was often <0.25, which is the critical value for shear instability (Fig. 15). Romero *et al.* (2005) identified the same vigorous mixing within this region. Using the salinity gradient, Nyanza Gulf exhibited a higher salinity (>0.07 g kg^{-1}) than the open lake (approximately 0.05 g kg^{-1}). Within Nyanza Gulf, the western end exhibited almost saline waters, while a less saline water mass was observed in the eastern end, attributable to the north-west transport current from the Sondu-Miriu and Nyando Rivers (Okely *et al.* 2010; Fig. 15).

These results support the findings of the present study that an apatite-rich residual substrate exists at the western end of the gulf, whose shear erosion and dissolution results in high dissolved nutrient and Ca concentrations that support high salinity and an enhanced algal biomass within the vigorous mixing zone around transects B and C (Fig. 4, 6 and 15). This also explains the high salinity within the gulf, compared to the open lake. Lake Simbi, a brackish water mass located approximately 1 km from the southern shores of Nyanza Gulf, is a small enclosed, but highly productive, lake covering approxi-

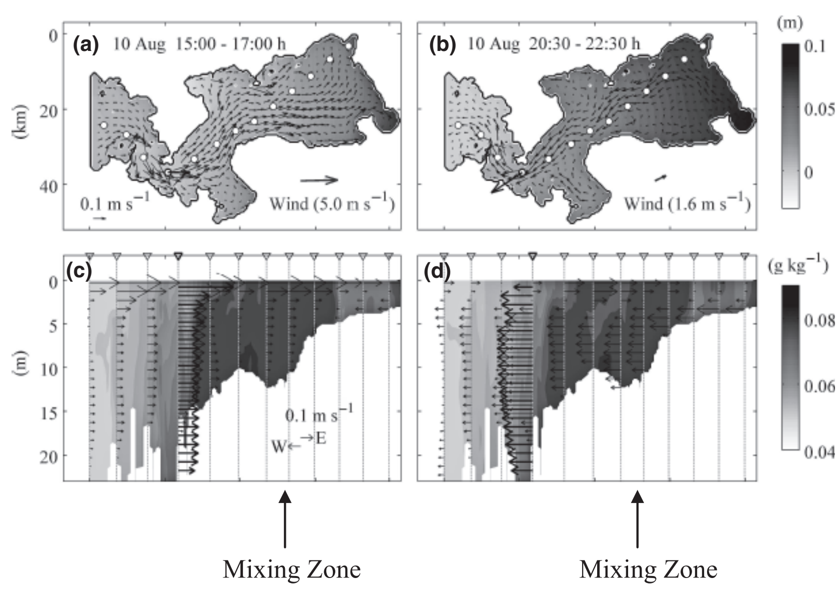

Fig. 15. Nyanza Gulf current directions, velocity (a, b), salinity distribution and probable mixing zones (c, d) (after Okely *et al.* 2010).

PLATE 1. Satellite image illustrating NW transport of sediment plume originating at the south-east corner of Nyanza Gulf from Nyando and Sondu-Miriu River mouths.

mately 0.04 km^2, with a maximum depth of 12 m, and an algal blanket (Guya F. J., personal observation). Thus, it is believed that this small satellite lake also is impacted by the same apatite mineral dissolution.

The eastern region exhibits the most notable positive correlations between NAIP and the trace element ligands, the latter being riverine in origin (Fig. 15). Fe, Al and Mn concentrations were high in transect A, but nearly constant in transects B, C and D, whereas the Ca concentrations increased from transect A to D (Fig. 11). Fe, Al and Mn have mainly allochthonous (those transported from outside the aquatic basin) sources through the Nyando and Sondu-Miriu Rivers, while Ca has a mainly autochthonous (those generated within the aquatic basin) source via erosion of the apatite mineral on the western end of the gulf. Mn is usually found in sediments in minor quantities, with its role in the phosphorus cycle being less relevant than that of Al and Fe (Pardo *et al.* 2003). Thus, Mn exhibited the lowest concentrations among the ligands between sampling sites. Sediments are the transporting medium for the bioavailable phosphorus fraction (NAIP). NAIP fractions are transported via chelation onto Fe, Mn and Al ligands, as suggested by the good correlation factors for Fig. 12. The Fe concentrations also were found to be high in the littoral zones than at the offshore stations and at the river mouths (e.g. Site A3). Fe is an element that all organisms, including algae, require for survival. The importance of Fe to primary productivity was first noticed by Redfield, subsequently becoming known as the Redfield Ratios (Redfield 1934). Iron (Fe) is vital for phytoplankton growth, although only required in very small quantities. Although phytoplankton are stimulated to a certain degree by nutrients (nitrate, phosphate, silicate), they do not receive sufficient iron to make full use of the nutrients. In August 2008, ash from the explosive eruption of Kasatochi volcano in the Aleutian Islands not only snarled air travel in the region, but also fuelled the largest plankton bloom ever observed in the North Pacific, covering an area almost one-fifth the size of Canada (Roberta Hamme; University of Victoria, personal communication). The volcanic eruption provided iron that ocean plankton needed to grow. Some scientists have suggested that climate change could be reversed through purposefully fertilizing the ocean with iron, thereby increasing photosynthesis and carbon export. The primary productivity within transect A, although exhibiting lower dissolved nutrient concentrations than the remaining transects, is more enriched in chlorophyll-a than transect B (Fig. 4, 6 and 7). This is believed to result from the high Fe concentrations discharged by the rivers. Thus, primary productivity on the eastern shore is envisaged to increase as a result of an envisaged increase in iron (Fe) discharged by the rivers, which was triggered by increased deforestation within the catchment and global warming. Lake shore erosion also increased Fe concentrations within the littoral sampling sites, which would increase primary productivity within these regions, compared to the offshore sites. Thus, it would be interesting to monitor the limnological transformation of the Nyanza Gulf. The regression results between Fe and Mn indicated a very high correlation indicative of a probable common source (Fig. 13). The common occurrence of Mn and Fe is not well understood, but is thought herein to emanate to some degree from a limestone quarry within the River Nyando basin.

The source of Al is herein believed to be erosion of the Vertisols (black clay), which have a higher content of expansive clay known as montmorillonite ($Al_4Si_8O_{20}(OH)_4$). This is the form of clay that swells and forms deep cracks in drier seasons (Buol *et al.* 2011; USDA-NRCS 2013). Because of the fine texture of clay, and the high affinity of Al for phosphorus, the correlation coefficient of NAIP to Al in Zone 1 is higher than for Fe and Mn (Fig. 12; Table 1). Because of this high affinity of Al for phosphorus, it has been used as alum to sequester SRP from water bodies, especially ponds and dams.

Following a public outcry over water quality deterioration of the Laurentian Great Lakes, Canada and the United States undertook a joint programme under the US-Canada International Joint Commission. The programme, known as PLUARG (Pollution from Land-Use Activities Reference Groups) studied pollution sources from throughout the entire Great Lakes drainage basin (Ongley 1996). Phosphorus was observed to be the most significant contributor to eutrophication (Williams

Table 2. Comparisons of NAIP concentrations observed in present study and studies adopted from Thomas *et al.* (1991)

Field station	Year	Mean NAIP concentrations, mg kg^{-1} (SD)	References
Lake Victoria (Nyanza Gulf)			
Transect A (Zone 1)	2007	1103.17 (337.67)	Present study (2007)
Transect B – D (Zone 2)		1423.03 (307.26)	
Total lake		1324.61 (339.20)	
Lake Geneva			
Petit Lac	1988	103.3 (82.2)	Arbouille *et al.* (1989)
Dranse Delta		266.3 (159.9)	
Rhone Delta		111.9 (66.5)	
Grand Lac.		167.7 (69.8)	
Total lake		174.7 (111.0)	
Lake Erie			
Western	1971	542.6 (654.0)	Williams *et al.* (1976)
Northern		241.9 (290.4)	
Central		292.4 (227.3)	
Eastern		288.4 (238.5)	
Total lake		336.2 (374.1)	

NAIP, non-apatite inorganic phosphorus.

et al. 1976 & Ongley 1996), with different phosphorus fractions, including NAIP, OP (Organic Phosphorus) and AP, being analysed. Similar studies were carried out in a number of different environments (e.g. Danube delta; Rhone River; Lake Geneva Basin) (Bostan *et al.* 2000; Arbouille *et al.* 1989**;** Burrus *et al.* 1990; Thomas *et al.* 1991; Table 2). Observations with the alga *Scenedesmus quadricauda* indicated that 75% of the NAIP from sediments was used by algae in a 12–18 h experimental period in an environment poor in dissolved phosphate (Williams *et al.*, 1980). The NAIP concentrations within these latter basins (Table 2) are far below those found in Lake Victoria, meaning the Lake Victoria basin is in dire need of appropriate management measures to be implemented than in these basins.

CONCLUSIONS

Lake Victoria is a dynamic lake, with the pollution of Nyanza Gulf being influenced by both allochthonous and autochthonous sources. The allochthonous sources, in turn, are influenced by changes in land-use patterns (deforestation, farming, urbanization), whereas the autochthonous source is driven mainly by in-lake currents. With a shallow mean depth, strong winds and a bottleneck opening to the open lake, the nutrient dynamics of Nyanza Gulf are driven mainly by strong currents, eroding the apatite-rich residual rock and remobilizing the buried/stored nutrients back into the water column. As a result, the lake is eutrophic throughout the annual cycle, with a probable algal peak observed between June and August during complete mixing of the lake. The allochthonous source originates from industries, farms, eroded soils and municipal wastes. To mitigate Nyanza Gulf eutrophication requires enforcement of the following action plans: (i) The Mbita Causeway must be opened and a bridge erected in its place, to reduce the strong currents through the Rusinga Channel, and the residence time of the gulf water mass, by increasing the flushing rates; (ii) The farming communities within the basin must be sensitized about the controlled use of fertilizers; (iii) The municipal wastes must be treated to a tertiary level before being discharged into the lake; and (iv) Erosion must be reduced within the basin through re/afforestation. Similar studies should be carried out in the lake's contributing river basins, especially River Nyando, to better determine the point and non-point pollution sources, and to provide informed management solutions.

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