Environ Sci Pollut Res (2014) 21:5737–5746
DOI 10.1007/s11356-014-2524-5

RESEARCH ARTICLE

Impacts of population growth and economic development on water quality of a lake: case study of Lake Victoria Kenya water

Dauglas Wafula Juma · Hongtao Wang · Fengting Li

Received: 11 October 2013 / Accepted: 6 January 2014 / Published online: 18 January 2014
© Springer-Verlag Berlin Heidelberg 2014

Abstract Anthropogenic-induced water quality pollution is a major environmental problem in freshwater ecosystems today. As a result of this, eutrophication of lakes occurs. Population and economic development are key drivers of water resource pollution. To evaluate how growth in the riparian population and in the gross domestic product (GDP) with unplanned development affects the water quality of the lake, this paper evaluates Lake Victoria Kenyan waters basin. Waters quality data between 1990 and 2012 were analyzed along with reviews of published literature, papers, and reports. The nitrate-nitrogen (NO_3-N), soluble phosphorus (PO_4-P), chlorophyll a, and Secchi transparencies were evaluated as they are key water quality indicators. The NO_3-N increased from 10 μg l^{-1} in 1990 to 98 μg l^{-1} in 2008, while PO_4-P increased from 4 μg l^{-1} in 1990 to 57 μg l^{-1} in 2008. The population and economic growth of Kenya are increasing with both having minimums in 1990 of 24.143 million people and 12.18 billion US dollars, to maximums in 2010 of 39.742 million people and 32.163 billion US dollars, respectively. A Secchi transparency is reducing with time, indicating an increasing pollution. This was confirmed by an increase in aquatic vegetation using an analysis of moderate resolution imaging spectroradiometer (MODIS) images of 2000 and 2012 of Kenyan waters. This study found that increasing population and GDP increases pollution discharge thus polluting lakes. One of major factors causing lake water pollution is the unplanned or poor waste management policy and service.

Responsible editor: Philippe Garrigues

D. W. Juma · H. Wang (✉) · F. Li
Key Laboratory of Yangtze River Water Environment,
Ministry of Education, State Key Laboratory of Pollution Control
and Resource Reuse, College of Environmental Science
and Engineering, Tongji University, Shanghai 200092, China
e-mail: hongtao@tongji.edu.cn

Keywords Water quality · MODIS · Eutrophication · Lake Victoria · Kenya · Water pollution

Introduction

Lake Victoria is the second largest fresh water lake in the world and the largest tropical lake with a surface area of 68,000 km^2 (average depth of 40 m and maximum depth of 79 m). The Lake is shared between Kenya, Uganda, and Tanzania, which controls 6, 45, and 49 %, respectively (Wang et al. 2012b). It is located between 3°S–0°30′N latitude and 31°40′E–34°50′E longitudes at an altitude of 1,134 m above sea level. The Lake has a catchment basin area of 195,000 km^2 which includes Rwanda and Burundi. The catchment has a high human population density whose activities influence the lake intensively (Lung'ayia et al. 2001).

Lake Victoria is of great socioeconomic significance to the riparian states as it is the major source of water for domestic, agricultural, and industrial purposes. The lake also provides a large quantity of fish for East African countries as well as for export markets in USA, Australia, European Union countries, and Israel (Muli 1996). Due to its strategic location of being shared by three nations, it acts as an avenue for transport. It is increasingly becoming a tourist destination for sport fishing, scenic beauty, and wildlife of the area. The lake has also a hydroelectric power plant that supplies electricity to Kenya and Uganda at source of the White Nile.

With the economic relevance attached to the lake by riparian communities, the Lake Victoria basin is one of the densely populated regions and has a rapidly growing population (Cohen et al. 1996). As the population and economy grows, the need of more natural resources leads to more resources being used than the ecosystem can sustain, thus impacting on the ecosystem negatively. A high population and economic developments have led to change in land use in the basin. The land use activities which are mainly agricultural, urbanization, and industrialization have greatly contributed to the degradation of the waters of the lake (Wang et al. 2012a).

Indeed, there have been notable changes in the physical, chemical, and biological regime of the lake when compared with conditions before and during 1960s. Physically, there has been increase in turbidity of the waters as indicated by reduction in Secchi transparencies with time (Mavuti and Litterick 1991; Calamari et al. 1995; Worthington 1930). The lake waters have also indicated nutrients enrichment, according to Hecky (1993). It reported an increase in the concentration of nitrogen in the lake and more prominent in the inshore waters than offshore waters of the lake indicating the occurrence of chemical changes.

Biologically, the phytoplankton community that used to show clear seasonal successions of diatom, blue-green algae (Cyanobacteria), and green algae and several other taxa (Talling and Talling 1965; Talling 1987) is now persistently predominated by cyanobacteria, thus showing changes in the lake (Hecky op. cit. Lung'ayia et al. 2000). Overall, algal biomass has increased and blooms dominated by cyanobacteria are common (Ochumba and Kibaara 1989). Eutrophication in the lake has worsened the water quality by promoting the excessive growth of weeds and increased suspended organic material. These are impacting negatively on the ecological, esthetic, and the economical functions like fishing, transport, and tourism that are usually provided by the lake ecosystem (Hecky and Bugenyi 1992; Cohen et al. 1996).

In response to the degradation, the riparian countries Kenya, Uganda, and Tanzania established the Lake Victoria Environmental Management project (LVEMP) in 1997. It is an integrated program with an aim of rehabilitating the degraded lake ecosystem for it to support the multiple human activities in Lake Catchment in a sustainable manner. The LVEMP has enhanced the capacity of the government in water quality monitoring by establishing monitoring network and operational gauging stations, rehabilitation of water quality laboratories in the lake zones, and training of manpower (Machiwa 2003).

Despite this intervention, there is still continuing degradation thus the need for more interventions. This study aims to show how an increase in the riparian population and increase in the gross domestic product (GDP) with unplanned development of the catchment area of Lake Victoria Kenyan waters affects water quality of the Winam gulf and the generally Lake Victoria waters.

Materials and methods

Study area

The Kenyan waters of Lake Victoria comprise of the open main lake and the Winam Gulf of Lake Victoria which lies just south of the equator between 0°6′S–0°32′S and 34°13′E–34°52′E as shown in Fig. 1. The two together covers an area of 4,200 km^2 (approximately 6 % of whole Lake Victoria). The Winam gulf is connected to the open main lake via the Rusinga channel (Ochumba 1990; Mavuti and Litterick 1991). The catchment is drained by five major rivers as follows: Nzoia, Kuja, Nyando, Yala, and Sondu; through which the catchment contributes approximately 30 % of total riverine inflow into the entire Lake Victoria (Crul 1995). The rivers drain one of the densely populated area, with rich intensive agricultural areas that use agrochemicals extensively, municipalities, and industrial establishments, all of which contribute heavy loads of suspended sediments and nutrients into the gulf and to the open lake thereafter (Gikuma-Njuru et al. 2010; Opande et al. 2004; GIWA 2006).

The Lake Victoria region has an equatorial climate with small seasonal variations in solar radiations (Walter et al. 1960). The area has two rainfall seasons, heavy and light rainfall periods. Yearly rainfall averages 1,000 mm. Heavy rainfall period is between March and May while light rainfall period is between September and November. This is followed by a relatively dry season from January to late February. The hottest month ranging between 29.3 and 31.6 °C (Fusilli et al. 2013; Lung'ayia et al. 2001; Kite 1981).

Kisumu city, which is the main city located on the shores of the lake of Kenyan waters, is the third largest city in Kenya. It is the principal city in Western Kenya and the second most important city in Lake Basin after Kampala city, Uganda. The city has seen tremendous growth in population with a current population of 968,909 according to census 2009 (CRA 2011). The city is located on the shores of the Lake Victoria at the cusp of Winam Gulf as shown in Fig. 1. It has been a major trading Center and water transport hub for East African countries that share the lake. Just like the whole country's economy, Kisumu's economy has been increasing with time and this has seen a lot of industries coming up and other agricultural activities becoming more in recent times (COWI 2002).

Methods

The data from laboratory analysis of Winam gulf and Kenyan open waters of Lake Victoria was acquired from LVEMP offices, Kisumu Kenya. The acquired data was analyzed and computed. Other methods that were used in the study were reviews of published literature, papers, and reports for projects implemented on the study area and Lake Victoria Basin in general. Among the parameters considered were the nitrogen in form of nitrate-nitrogen (NO_3-N), phosphorus as soluble phosphorus (PO_4-P), chlorophyll a, and Secchi transparencies, mainly because of their relevance as water quality indicators, and their contribution to the eutrophication of the lake. The data on population and on GDP of Kenya from 1990 to 2010 was acquired from the International monetary Fund (IMF)

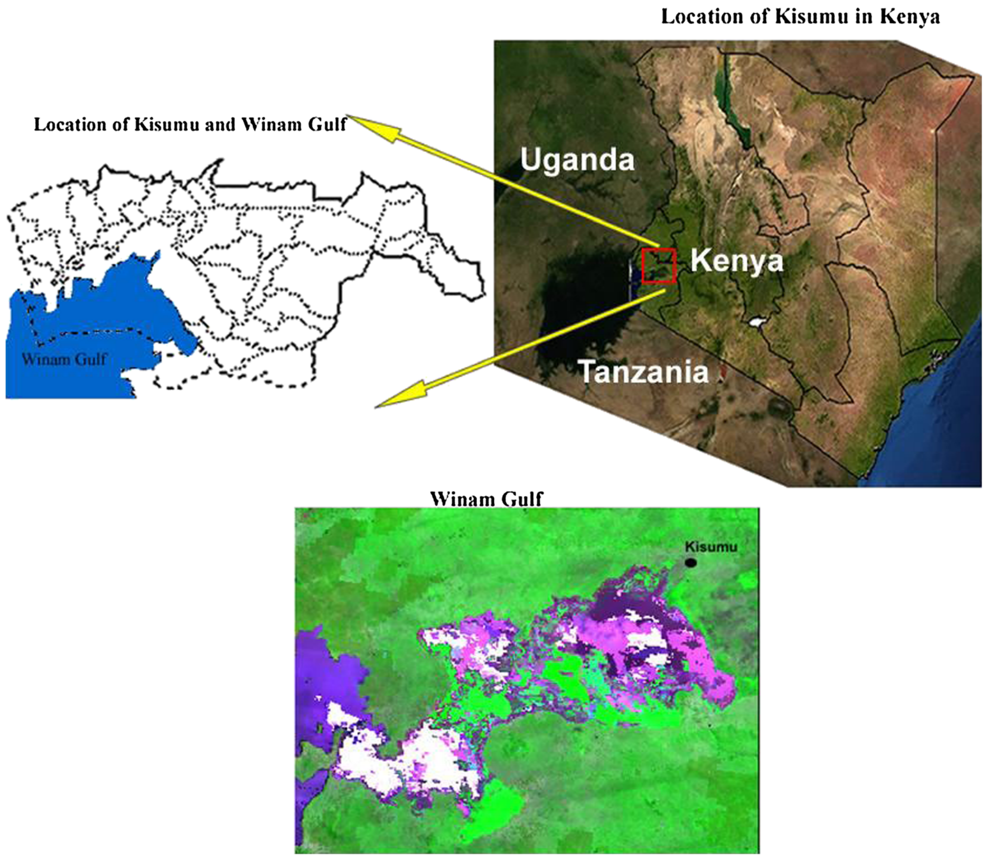

Fig. 1 Location of Kisumu city and Winam gulf (*above*); a color composite of Winam gulf created from the MODIS (*below*)

database (2012). On addition, estimation data from the same IMF database on the population and GDP from 2011 to 2016 were acquired and included in the analysis. The data was analyzed and compared with the water quality change over the same period.

The moderate resolution imaging spectroradiometer (MODIS) data with a spatial resolution of 250 m, which were the images taken in the year 2000 and in 2012, were analyzed to evaluate whether there is an element of eutrophication taking place in the lake. Chlorophyll a pigment has a minimum absorption in the green region (495–570 nm) leading to significant increase of reflectance as a function of pigment concentration (Martinez et al. 2011). Chlorophyll a has also high absorbance spectra in the blue (450–495 nm) and red regions (620–750 nm) that peak at around 430 and 662 nm (Gross 1991).

The Normalized Difference Vegetation Index (NDVI) values were computed from the MODIS data using spectral reflectance values in the red (R) channel (620–670 nm) and the near-infrared (NIR) channel (841–876 nm) using the equation NDVI=(NIR−R)/(NIR+R) in ENVI 4.7 software. To determine the spatial distribution of the chlorophyll a from the MODIS datasets, the NIR, Red and Blue bands were classified under the supervised maximum likelihood function and overlaid with NDVI to assess and attain suitable sample points for bare land, terrestrial vegetation, aquatic vegetation (including algal blooms), and algal bloom-free water. This technique is based on the relationships between reflectance, total absorption, and backscattering coefficients (Gordon et al. 1988). The NDVI value of 0.1 was considered the threshold for vegetation in order to minimize bidirectional reflectance effects arising from turbid waters.

Results and discussion

In the past five decades, researches and studies on the water quality of Lake Victoria have indicated a change in the water quality. It is reported that there has been an increase in nutrient levels in the lake that has led to eutrophication of the lake as evidenced by immense growth of water hyacinth in Winam gulf bay of Lake Victoria. Analysis of various published articles on the Kenyan waters and more so in the Winam gulf was tabulated as shown in Table 1 (Gophen et al. 1995; Lung'ayia et al. 2001; Gikuma-Njuru and Hecky 2005; LVEMP 2002; Sitoki et al. 2010).

Generally, there is increasing nutrients enrichment trend in the lake. The nitrate-nitrogen components in the lake have been increasing in the lake with the minimum being 10 $\mu g\ l^{-1}$ in 1990 to a maximum recorded of 98 $\mu g\ l^{-1}$ in 2008. The phosphorous has also been on increase, from the minimum of 4 $\mu g\ l^{-1}$ in 1990 to a maximum recorded of 57 $\mu g\ l^{-1}$ in 2008.

Table 1 The concentrations of nitrate-nitrogen and soluble reactive phosphorus (PO_4-P) in Lake Victoria Winam gulf, Kenyan waters

Year	NO_3-N(μg l^{-1})	PO_4-P(μg l^{-1})	Source	TN:TP
1990	10–30	4–73	Gophen et al. 1995	2.5:1
1998	66.6±44	59.7±38.5	Lung'ayia et al. 2001	1:1
2000–02	48.2±21.4	29.7±19.1	Gikuma-Njuru and Hecky 2005	1.6:1
2004	81.2±12.3	24.9±8.3	Sitoki et al. 2010	3:1
2005	78 to 140		LVEMP 2002	
2008	98.7±36.44	57±7	Sitoki et al. 2010	1.9:1

The increase in the nutrients into the lake is due to increased runoff from land-based sources like agricultural land, which has led to an increase in biomass in the lake as witnessed by immense growth of water hyacinth in the Winam gulf.

On the other hand, there has been a general decreasing trend of the nitrogen to phosphorus ratio (TN:TP) in the lake with the largest being less than the Redifield ratio of 16:1, which gives an indication that phytoplankton growth in the Lake is nitrogen deficient (Guildford and Hecky 2000). According to Guildford and Hecky (2000), TN:TP <20 (molar) can result in N-deficient algal growth and selects for N fixing cyanobacterial species. Thus, this has promoted the dominance of nitrogen fixing cyanobacteria in line with high nitrogen fixation in the lake (Mugidde et al. 2003).

This has increased the eutrophication in the lake that has resulted in harmful algal blooms that lead to the formation of hypoxic or "dead" zones which could destroy the ecosystem. Low TN:TP ratio is associated with the increased phosphorus loading into the Lake and selective loss of nitrogen through denitrification and enhanced recycling of phosphorus which is associated with increased anoxic conditions in the deep pelagic waters (Hecky 1993; Hecky et al. 1996; LVEMP 2002).

Another parameter of interest is the Secchi transparencies which show clearness of the lake, where the higher the value of Secchi the better the lake because it would have low turbidity. Researches carried out on the Kenyan waters have results as shown in Table 2.

There is a decreasing trend of the Secchi transparencies with time, with a highest value between 1990 and 2012 period being in 1990 of 1.8 m and minimum being 0.4 m in 1994 in the open lake waters of Lake Victoria. There is clear difference of the Secchi values in the open lake of Kenya waters and the Winam gulf, for example Lung'ayia et al. (2001) reported that an open lake has values of 0.9–2.4 m while 0.5–1 m for Winam gulf. This also confirms the difference as seen in Worthington (1930) that noted that in 1930 the Secchi transparencies' in open lake was 7.3–7.9 m and that in Winam gulf was 1.3–1.47 m. This difference is due to the shallow depths in Winam gulf that makes it easy for daily mixing of the water column leading to the recycling and resuspension of nutrients and mineral matter from the bottom which is not the case of the open lake. The difference is also because the gulf being a recipient of pollution emanating from industrial and municipal sources and from agricultural runoff (Calamari et al. 1995). The Secchi transparencies are inversely proportional to the chlorophyll a in the lake waters. In the presence of readily measured PO_4-P and NO_3-N concentrations in the gulf waters, this acts as an accelerator for the eutrophication in the lake and thus increases the chlorophyll a in the water. This in turn reduces the transparencies as it limits light which lowers the Secchi transparencies values (Lung'ayia et al. 2001). The Secchi transparencies vary inversely with turbidity of the waters of the lake. All these pollutions into the lake are linked with human activities in the riparian zones of the lake.

Anthropogenic-induced water pollution is a major environmental problem in freshwater ecosystems today. According to WRI (2009), the study identified population growth and economic development as the major indirect drivers for eutrophication. Kenya like any other developing nations has experienced rapid population growth for the past 20 years, from a population of 24.143 million in 1990 to a population of 39.742 million people in 2010. With a population growth rate of about 2.69 %, the country's population is still increasing each and every day. It is estimated that by the year 2016, the population will be 47.147 million as shown in Fig. 2 (IMF database 2012).

Just as the population of the country is growing, the population of the cities and urban area are also growing rapidly. Kenya has three major cities as follows: Nairobi, Mombasa, and Kisumu city which are all densely populated. The country has 29.9 % of the population living in cities and urban centers amounting to 11.88 million people as of 2010 (CRA 2011).

Table 2 Secchi transparencies in Lake Victoria Winam Gulf, Kenyan waters

Year	Secchi transparencies (m)		Source
	Open lake (Kenya waters)	Winam gulf	
1930	7.3–7.9	1.3–1.47	Worthington 1930
1990	1.8	–	Gophen et al. 1993
1991	–	0.35–1.55	Hughes and Hughes 1992
1994	0.4–1.35	–	Lung'ayia et al. 2000
1998	0.9–2.4	0.5–1	Lung'ayia et al. 2001

Fig. 2 Growth of water hyacinth on Lake Victoria

Kisumu is a lake side city that is located in a densely populated lake basin of Lake Victoria. It has a population of 968,909 people as of 2009, with a high population density of 465 people per square kilometer compared to Kenya's density of 66 people (CRA 2011) per square kilometer. As the population is increasing with time consequently, the population density is also increasing rapidly within the lake basin. This high-density population could be a result of rural–urban migration which is primarily triggered by the perception that there are better job opportunities within urban areas and declining livelihood opportunities within the rural areas.

The increase in population density means management of more people per unit of a natural resource. This puts pressure on the natural resources like water and land resources, as the need continues to grow for domestic use, agriculture, industry, energy, and disposal of effluents. Despite the expansion of urban centers, towns, and cities, there has not been a corresponding investment in the necessary infrastructure to support the increasing population (Wang et al. 2012a). This has led to the development of informal settlements, "slums" in the urban centers as it is the case of Kisumu. The waste management and sewerage disposal facilities have remained inadequate. This has resulted in accumulation of solid and liquid waste to which the lake has become the sink of direct domestic and industrial waste. This situation has been made worse by the usually unplanned expansion of urban areas. The overall impact of these trends on the lake has been increasing levels of eutrophication in the lake (LVBC 2007).

The increase in human population has led to increased land use activities most of which are poorly managed which has had a negative impact on the water quality of the lake. As the population increases, the need for land use intensifies, which has led to wetlands and forests being converted into settlements, industries, and into agricultural farmlands. This in turn impacts negatively on the water quality of the lake as the ecosystem services carried out by a wetland no longer exist, thus exposing the lake to direct pollution from farmland runoff (Sharma 2003; Kishe 2004). For example, the Yala, Nyando, and Sondu swamps have been drained for agriculture purposes (LVBC 2007).

It is reported that the highest rates of deforestation occur in areas with large growing populations such as the lake basin area and the surrounding highlands where farming, grazing, and settlements have expanded at the expense of native vegetation (Allen and Barnes 1985; FAO 2001; Tomberline and Buongiorno 2001; Achard et al. 2002). Increase in population pressure have led to increase in cultivation and grazing intensity. This has resulted in massive deforestation and conversion of natural habitats to farmlands and settlements which have led to loss of biodiversity and land degradation (Olson et al. 2004; Maitima et al. 2004). About 7,084 ha of Mau forest, which is considered as the major water tower of Lake Victoria, were destroyed between 2000 and 2003. In Mt. Elgon (another water tower for Lake Victoria basin) area around Trans Nzoia District, there was a loss of 1,029 ha of indigenous forest, which just shows how the natural resources are being destroyed because of increased population (LVBC 2007). With a bare surface created as a result of deforestation, there has been a lot of runoff that ends up in the lake (Ntiba et al. 2001).

As land scarcity increases in the lake region due to population increase, mechanization of agricultural land has intensified and increased usage of agrochemicals in the farms so as to achieve more yields per acreage. This intensification of agriculture in the lake basin has led to land being converted to medium-scale and larger-scale sugarcane growing from 84 km^2 in 1986 through 102.28 km^2 in 1995 to 262.75 km^2 in 2005, most of which is in reclaimed wetland areas (Twesigye et al. 2011). Small-scale mixed farming increased from 36.29 km^2 in 1986 to 244.036 km^2 in 2005 in the Lake Victoria Kenyan basin (Twesigye et al. 2011). All these factors increase the nutrients loading in the lake, hence polluting the water qualities of the lake. This has drastically changed the biomass in the lake as witnessed by increasing growth of water hyacinth in the Kenyan waters of Lake Victoria.

On the other hand, the rate of nutrients loading into the lake has been to a large extent influenced by the economic growth of surrounding cities and areas of Lake Victoria. Kenyan economy have witnessed growth in GDP from 12.18 billion US dollars in 1990 to 32.163 billion US dollars in 2010, and it was estimated by IMF that the GDP would reach 64.231 billion US dollars by the year 2016 as shown in Fig. 3 (IMF database 2012).

The growth of GDP has brought about an increase in urbanization and industrialization of the nation which in return has its effects on the environment in general because of unsustainable use of natural resources. Kenya is becoming increasingly urbanized. In 1950, less than 6 % of the population lived in urban areas according to United Nations. Since

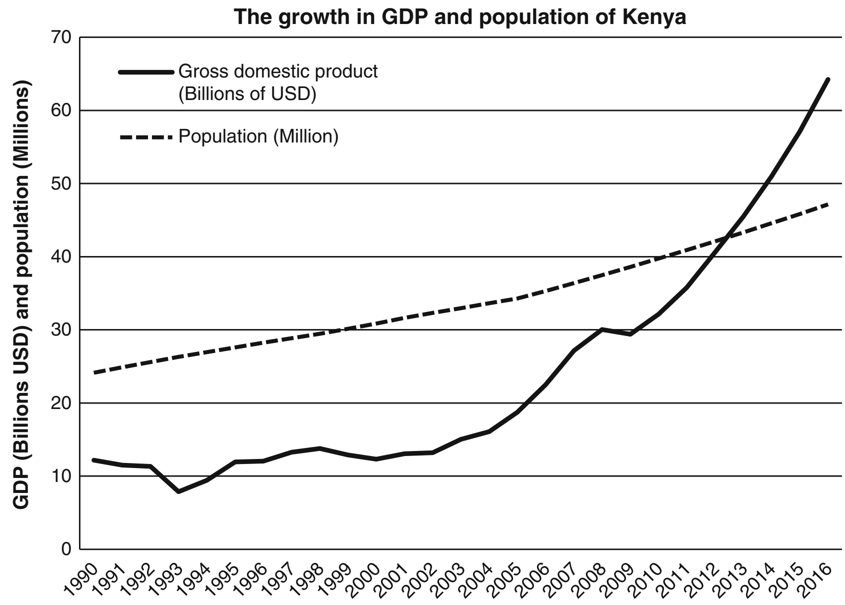

Fig. 3 The GDP and population growth in Kenya. (IMF Database 2012)

then, urbanization has increased fourfold to 24 % in 1990. As of 2010, 29.9 % of Kenyan population was living in urban area representing 11.88 million people, which is larger than its entire 1950 population. It is projected that by 2020 about 27 million people would be living in urban areas (CRA 2011).

Over the last two decades, the lake basin has experienced increasing urbanization with major towns and cities acting as hubs of urbanization, with cities such as Jinja, Entebbe, Kisumu, Homa Bay, Musoma, Bukoba, and Mwanza as examples (LVBC 2007). An increase in the economy has led to improvement in consumption rate, which translates to more energy use, which in turn leads to increase in pollution of the atmosphere with NO_x, CO_x, and SO_x gases. During the rainfall, these gases cause acidic rainfall which pollutes the water sources.

Development and expansion of urban centers and industrial establishments have outstretched existing sewage treatment plants. The pollution of major rivers flowing into Lake Victoria has increased mainly due to the discharge of raw or incompletely treated effluents particularly from urban settlements like Kisumu city. As Kisumu city expands in size and population, there has been no corresponding investment in the necessary infrastructure to support the increasing population (Wang et al. 2013). Thus, waste management and sewerage disposal facilities have remained inadequate in Kisumu city and incidences of direct domestic sewage disposal into the lake are becoming common (Omosa et al. 2012). This has led to Winam Gulf being subjected to heavy pollution by domestic and industrial wastes from Kisumu city more than the ecosystem can handle through self-purification process (Gikuma-Njuru and Hecky 2005). A study conducted by LVBC (2007) revealed that among the cities in the lake basin, Kisumu city is the third most polluter of the lake water with biological oxygen demand (BOD_5) loads per day, as shown in the Fig. 4.

Urbanization affects "patterns of ecologic structure and function" (Walsh 2006) by altering the physical landscape, increasing imperviousness, and changing channel morphology. This leads to pollution of rivers, streams, and other water sources (Paul and Meyer 2001; Sponseller et al. 2001; Walsh et al. 2001; Kearns et al. 2005; Chadwick et al. 2006). The pollution of major rivers flowing into Lake Victoria has increased mainly due to discharge of raw or incompletely treated effluents particularly from urban settlements, sugar industries, pulp and paper mills, and other factories in the basin. A study by Okungu and Opango (2004) on the nutrient loading from rivers into the Lake Victoria Kenyan waters revealed high concentration of both total nitrogen concentration and total phosphorous from the rivers that discharge into the lake.

On other hand, the comparison of the total annual loading of the nutrients into the lake from Kenyan rivers revealed Nzoia River to be leading in pollution loading in both the total phosphorous and total nitrogen transportation in year averaging about 4,900 t per year and 1,375 t per year, respectively (Okungu and Opango 2004). This is because Nzoia River has high volume of water flow and its expansive catchment in which it passes through. The rich agricultural base and effluents from various sugar factories and pan paper mill industry which the river passes have all contributed to the total loading. Despite increased numbers of industries, only a few of them are connected to an urban sewage system thus increasing direct injection into the river or even directly into the lake causing a lot of pollution (Scheren et al. 2000).

Golterman (1993) reported that next to the natural origin of phosphate, human excreta and detergents are the second most

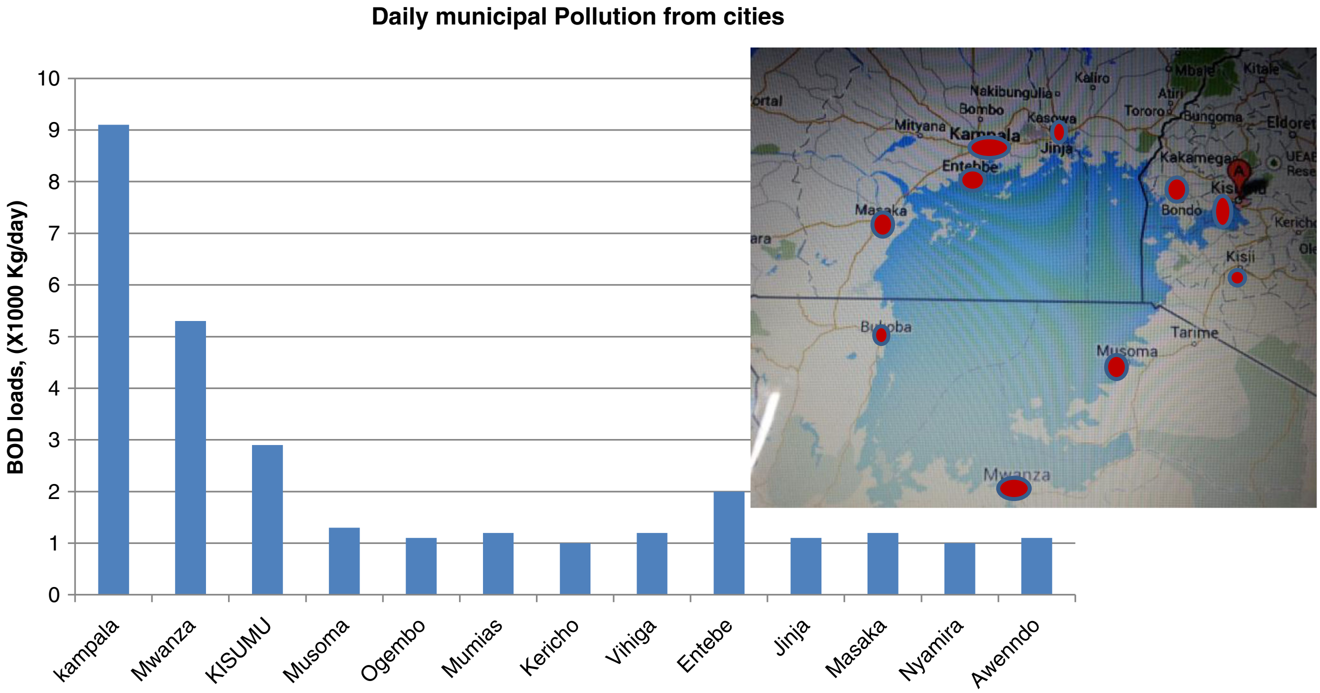

Fig. 4 A modified ranking of major urban point sources of pollution for Lake Victoria. Original source: (LVBC 2007)

important sources of phosphate in rivers, thus an increase in population will lead to more detergent and human excreta, of which if not well managed will lead to increase in the phosphate in water bodies through untreated discharge.

According to a study by COWI (2002), among the cities in the lake basin that pollutes the lake waters with their daily distribution of point source pollution of phosphorous and nitrogen, Kisumu is ranked third after Kampala and Mwanza cities. These loads from the catchment entering at river mouths into the lake are known to have severe local impacts in gulfs, bays, and some near-shore area waters as they have a direct impact on eutrophication of the area.

Economic growth has seen an increase in the number of factories and industries around the lake basin. COWI (2002) established that the Lake Victoria catchment basin has a total of 68 major industries; 18 in Uganda, 34 in Tanzania, and 16 in Kenya. The industries in Kenya range from major sugarcane factories, paper mill, and manufacturing industries among others. Growth in industries has taken place against a backdrop of no infrastructure development for disposal of effluents. The currently existing sewage infrastructure has not been expanded or improved for decades. On the other hand, some of the industries are being allowed to establish their operations in areas that have been designated as “non-industrial,” thus lacking the infrastructure to handle their waste products. The annual pollutant load to the lake from industrial activities in the catchment areas showed that Kenyan lake basin produces a BOD_5 of 860 t/year, a total nitrogen of 57 t/year, and a total phosphorous of 46 t/year (COWI 2002).

The atmospheric sources dominate the nutrient loading for both nitrogen and phosphorus in the loading of the pollutants into the expansive open Lake Victoria. Most of the phosphorus (39,978 t TP per annum) and nitrogen (167,650 t TN per annum enter the lake by atmospheric deposition (LVBC 2007), representing 60–80 % of total deposition as shown in Table 3. The second most important load sources into the Lake are the rivers that contribute an estimated 9,250 t/year of TP and 38,800 t/year of TN (LVBC 2007) as indicated in Table 3. This is because industrialization and urbanization have increased the number of factories and automobiles. Consequently, this causes pollution through increased emissions of gases and smoke into the atmosphere. This later causes acidic rainfall when it rains which finally pollutes the lake.

Kisumu city has greatly contributed to the nutrients loading into Lake Victoria via Winam Gulf, which has consequently led to the eutrophication of the lake. The pollution which comes mainly from residential, industrial, and agricultural

Table 3 Relative magnitude of loading sources to Lake Victoria

Pollution source	TN (tons/year)	%TN	TP (tons/year)	%TP
Atmospheric deposition	167,650	17	39,978	79
Rivers	38,800	4	9,250	18
Biological nitrogen fixation	757,000	78	–	–
Point source	4,300	1	1,690	3
Total	967,750	100	50,915	100

(LVBC 2007)

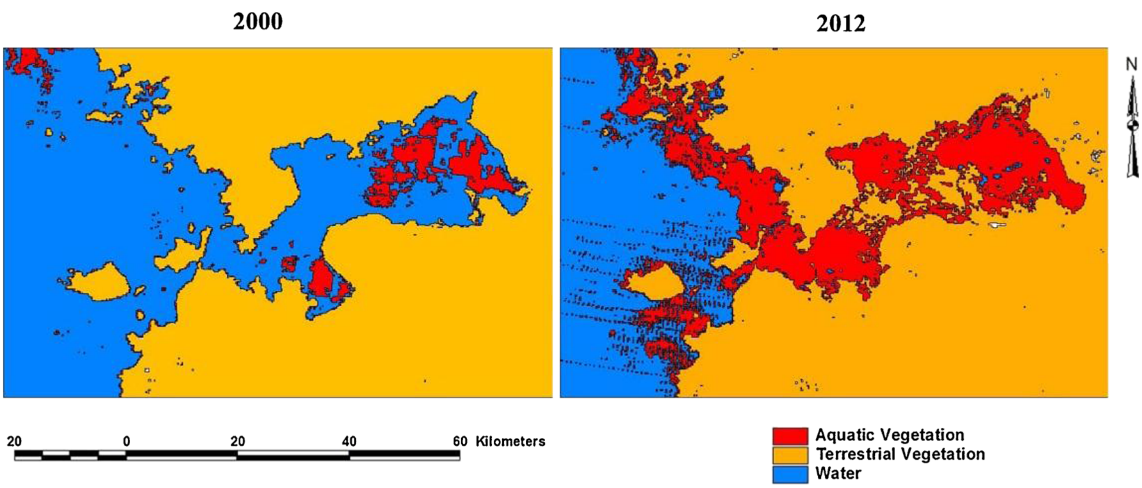

Fig. 5 The changes in aquatic vegetation in the Winam Gulf area

areas is released directly into the lake or through river channel and increasing the nutrient loading into the lake.

Analysis of MODIS images of 2000 and 2012 of the Winam Gulf part of Lake Victoria revealed changes in the aquatic vegetation in the waters as shown in Fig. 5. The images showed an increase of the chlorophyll a levels in the lake which is an indication of increased aquatic vegetation. The aquatic vegetation area increased from 64,564 ha in 2000 to an area of 438,891.1 ha in 2010 as it was deduced from the analysis of the images.

This confirms that there is eutrophication going on in the Winam gulf part of the lake over that period, as witnessed by the increase in the aquatic vegetation cover in the lake, which is attributed to excessive growth of water hyacinth. This is attributed to increase in nutrients loading into the lake that promotes vegetation growth in the lake.

Conclusion

A comprehensive analysis was carried out to investigate the effect of population growth, economic development, and unplanned catchment management on water quality of the Lake Victoria. The study discovered that in general, rapid population growth, growing commercial activities, and industrialization in Kisumu and in Lake Victoria Basin coupled with inadequate provision of waste management services have led to the increase in volume of urban waste being discharged into the lake and environment. This, together with poor urban planning, the use of old dilapidated and inappropriate technologies, poor maintenance of treatment plants, lack of waste treatment, and disposal mechanisms, has resulted in the deterioration of water quality of the Lake.

To reduce the high levels of nutrients loading into the lake, policies need to be put in place, which encourages inclusion of the environmental sustainability component on economic development projects to avert externalities. There is need for proper management of solid waste and waste water from both industrial and municipal sources to improve the quality of natural water resources like rivers and lakes. However, there is still a need to strengthen, monitor, and control anthropogenic activities in the basin that are the root cause ecosystems degradation. There is a need to encourage proper management of land use through public awareness programs geared towards sensitizing the public on the ongoing environmental destruction and how it can be minimized or stopped.

There is also a need to encourage regional interventions and incorporation of harmonized principles, policies, strategies, laws, and other agreements into national legislation to enhance enforcement. Further studies should be conducted in the whole Lake Victoria catchment basin using MODIS technology to assess the effects of population growth and economic development on the water quality of the lake as a whole.

Acknowledgments This study is part of the Africa–China Cooperation Program on Environment which is supported by the Ministry of Science and Technology of China (MOST) and coordinated by the United Nations Environment Program (UNEP) (nos. 2010DFA92820 and 2010DFA92800). It was supported in part by the Fundamental Research Funds for the Central Universities (no. 0400219184).

References

Achard F, Eva H, Stibig H-J, Mayaux P, Gallego J, Richards T, Maling reau J-P (2002) Determination of deforestation rates of the world's humid tropical forests. Report

Allen J, Barnes D (1985) The causes of deforestation in developing countries. Ann Assoc Am Geogr 75(2):163–184

Calamari D, Akech MO, Ochumba PBO (1995) Pollution of Winam Gulf, Lake Victoria, Kenya: a case study for preliminary assessment. Lakes Reserv Res Manag 1:89–106

Chadwick MA, Dobberfuhl DR, Benke AC, Huryn AD, Suberkropp K, Thiele JE (2006) Urbanization affects stream ecosystem function by altering hydrology, chemistry, and biotic richness. Ecol Appl 16(5): 1796–1807

Cohen AS, Kaufman L, Ogutu-Ohwayo R (1996) Anthropogenic threats, impacts, and conservation strategies in the African Great, Lakes: a review. In: Johnson TC, Odada E (eds) The limnology, climatology and paleoclimatology of the East African lakes. Gordon and Breach, Toronto, pp 575–624

COWI Consulting Engineers (2002) Integrated water quality/limnology study for Lake Victoria. Lake Victoria Environmental Management Project, Part II Technical Report

CRA (2011) Commission of Revenue Allocation: Kenya County Fact Sheets, Kenya Bureau of Statistic. https://opendata.go.ke/Counties/Kenya-County-Fact-Sheets-Dec-2011/zn6m-25cf

Crul RCM (1995) Limnology and hydrology of Lake Victoria. UNESCO/IHP Project M-5.1, UNESCO Publishing, Paris

FAO (2001) Global forest resources assessment (2000) FAO forestry paper 140. FAO, Rome

Fusilli LA, Collinsb MO, Lanevea G, Palomboc A, Pignattic S, Santinic F (2013) Assessment of the abnormal growth of floating-macrophytes in Winam Gulf (Kenya) by using MODIS imagery time series. Int J Appl Earth Obs Geoinformation. SciVerse ScienceDirect

Gikuma-Njuru P, Hecky RE (2005) Nutrient concentrations in Nyanza Gulf, Lake Victoria, Kenya: light limits algal demand and abundance. Hydrobiologia 534:31–140

Gikuma-Njuru P, Hecky RE, Guildford SJ (2010) Surficial sediment phosphorus fractions along a biogeochemical gradient in Nyanza (Winam) Gulf, Northeastern Lake Victoria and their possible role in phosphorus recycling and internal loading. Biogeochemistry

GIWA (2006) Challenges to International Waters; regional assessments in a global perspective. United Nations Environment Program (UNEP)

Golterman HL (1993) Aquatic ecosystems, physiological limnology. IHE, Delft

Gophen M, Ochumba PBO, Pollingher U, Kaufman LS (1993) Nile perch (Lates niloticus) invasion in Lake Victoria (East Africa). Verh Internat Verein Limnol 25:856–859

Gophen M, Ochumba PBO, Kaufman LS (1995) Some aspects of perturbation in the structure and biodiversity of the ecosystem of Lake Victoria, East Africa. Aquat Living Resour 8:27–41

Gordon HR, Brown OB, Evans RH, Brown JW, Smith RC, Baker KS, Clark DK (1988) A semi-analytic radiance model of ocean color. J Geophys Res 93:10909–10924

Gross MR (1991) Salmon breeding-behavior and life-history evolution in changing environments. Ecology 72:1180–1186

Guildford SJ, Hecky RE (2000) Total nitrogen, total phosphorus, and nutrient limitation in lakes and oceans. Limnol Oceanogr 6:1213–1223

Hecky RE (1993) The eutrophication of Lake Victoria. Verh Int Ver Limnol Stuttg 25:39–48

Hecky RE, Bugenyi FWB (1992) Hydrology and chemistry of the African great lakes and water-quality issues: problems and solutions. Mitt Int Ver Theor Angew Limnol 23:45–54

Hecky RE, Bootsma HA, Mugidde R, Bugenyi FWB (1996) Phosphorus pumps, nitrogen sinks, and silicon drains: plumbing nutrients in the African Great Lakes. In: Johnson JC, Odada EO (eds) The limnology, climatology and paleoclimatology of the East African Lakes. Gordon and Breach Publishers, Amsterdam, pp 205–223

Hughes RH, Hughes JR (1992) Lake Victoria: lake description. Directory of African Wildlife [18/12/2001] http://www.wcmc.org.uk/dynamic/lcdb/lakesheets/victoria.desc.html

IMF Database (2012) World economic outlook database (2013/03/15). (http://www.imf.org/external/pubs/ft/weo/2012/02/weodata/index.aspx)

Kearns FR, Kelly NM, Carter JL, Resh VH (2005) A method for the use of landscape metrics in freshwater research and management. Landsc Ecol 20:113–125

Kishe M (2004) Physical and chemical characteristics of water in selected locations in Lake Victoria, Tanzania. Tanz J Sci 30(2):1–2

Kite GW (1981) Recent changes in level of Lake Victoria. Hydrol Sci Bull Oxford 26:233–243

Lung'ayia HBO, M'Harzi A, Tackx M, Gichuki J, Symoens J (2000) Phytoplankton community structure and environment in the Kenyan waters of Lake Victoria. Freshw Biol 43. Blackwell Science Ltd: 529–543

Lung'ayia H, Sitoki L, Kenyanya M (2001) The nutrient enrichment of Lake Victoria (Kenyan waters)—Hydrobiologi

LVBC (2007) Regional trans-boundary diagnostic analysis of the Lake Victoria basin. Lake Victoria Basin Commission (LVBC), Kisumu

LVEMP (2002) Lake Victoria environmental management project phase, water quality and ecosystem management component, preliminary findings of studies conducted on Lake Victoria

Machiwa PK (2003) Water quality management and sustainability: the experience of Lake Victoria Environmental Management Project (LVEMP)—Tanzania. Phys Chem Earth 28:111I–1115

Maitima J, Reid S, Gachimbi L, Majule A, Lyaruu H, Pomeroy D, Mugatha S, Mathai S, Mugisha S (2004) The Linkages between land use change, land degradation and biodiversity across East Africa

Martinez JM, Ventura D, Vieira MR, Attayde JL, Bubel AP, Coimbra MR, de Oliveira E (2011) Satellite-based monitoring of reservoir eutrophication in the Brazil Semi-arid region. (Proceedings XV Brazilian Symposium of Remote Sensing—SBSR, Curitiba, PR, Brazil, April 30 to May 05, 2011, INPE p. 5247)

Mavuti KM, Litterick MR (1991) Composition, distribution, and ecological role of zooplankton community in Lake Victoria, Kenyan waters. Verh Int Ver Limnol 24:1117–1122

Mugidde R, Hecky RE, Hendzel LL, Taylor WD (2003) Pelagic nitrogen fixation in Lake Victoria (East Africa). J Great Lakes Res 29(supplement 2):76–83

Muli JR (1996) Environmental problems of Lake Victoria (East Africa): what the international community can do. Lakes Reserv Res Manag 2:47–53

Ntiba MJ, Kudoja WM, Mukasa CT (2001) Management issues in the Lake Victoria watershed. Lakes Reserv Res Manag 6:211–216

Ochumba PBO (1990) Massive fish kills within Nyanza Gulf of Lake Victoria, Kenya. Hydrobiologia 208:93–99

Ochumba PBO, Kibaara DI (1989) Observations on blue green algal blooms in the open waters of Lake Victoria, Kenya. Afr J Ecol 27: 23–34

Okungu J, Opango P (2004) Pollution loading into Lake Victoria from the Kenya catchment. Available from URL:http://www.lvemp.org/L_Publications/kenya/Okunguj.pdf. Accessed 15 August 2004

Olson J, Misana S, Campbell D, Mbonile M, Mugisha S (2004) The spatial patterns and root causes of land use change in East Africa

Omosa IB, Wang HT, Cheng S, Li F (2012) Sustainable tertiary wastewater treatment is required for water resources pollution control in Africa. Environ Sci Technol 46(13):7065–7066

Opande GO, Onyango JC, Wagai SO (2004) Lake Victoria: the water hyacinth (Eichhornia Crassipes [Mart.] Solms), its socioeconomic effects, control measures, and resurgence in the Winam Gulf. Limnologica 34:5

Paul MJ, Meyer JL (2001) Streams in the urban landscape. Annu Rev Ecol Syst 32:333–365

Scheren PA, Zanting HA, Lemmens AMC (2000) Estimation of water pollution sources in Lake Victoria, East Africa: application and elaboration of the rapid assessment methodology. J Environ Manag 58:235–248

Sharma UC (2003) Impact of population growth and Climate Change on the quantity and quality of water resources in the North East of India. Water Resources Systems—Hydrological Risk, management, and development (Proceedings of symposium HS02b held during IUGG2003 al Sapporo. July 2003 J. IAHS Publ. no. 281. 2003)

Sitoki L, Gichuki J, Ezekiel C, Wanda F, Mkumbo OC, Marshall BE (2010) The environment of Lake Victoria (East Africa): current status and historical changes. Int Rev Hydrobiol 95: 209–223

Sponseller RA, Benfield EF, Valett HM (2001) Relationships between land use, spatial scale and stream macroinvertebrate communities. Freshw Biol 46:1409–1424

Talling JF (1987) The phytoplankton of Lake Victoria (East Africa). Arch Hydrobiol Beih Ergebn Limnol 25:229–256

Talling JF, Talling IB (1965) The chemical composition of African lake waters. Int Rev Ges Hydrobiol 50:421–463

Tomberline D, Buongiorno J (2001) Timber plantations, timber supply, and forest conservation. In: Palo M, Usivuori J, Mery G (eds) World forests, markets and policies. Kluwer Academic Publishers, Dordrecht, p 504

Twesigye CK, Onywere SM, Getenga ZM, Mwakalila SS, Nakiranda JK (2011) The Impact Of Land Use Activities On Vegetation Cover And Water Quality In The Lake Victoria Watershed. Open Environ Eng J 4:66–77

Walsh CJ (2006) Biological indicators of stream health using macro invertebrate assemblage composition: a comparison of sensitivity to an urban gradient. Mar Freshw Res 57:37–47

Walsh CJ, Sharpe AK, Breen PF, Sonneman JA (2001) Effects of urbanization on streams of the Melbourne Region, Victoria, Australia: Benthic macroinvertebrate communities. Freshw Biol 46:535–551

Walter H, Lieth H, Rehder H, Karte (1960) Afrika Südlich Des Äquators. In Walter H. & H. Lieth (Eds), Klimadiagramm-Weltatlas. Veg. Fischer Verlag. Jena p. 6

Wang HT, Wang T, Brahima T, Li FT (2012a) Protect Lake Victoria through green economy, public participation and good governance. Environ Sci Technol 46(19):10483–10484

Wang HT, Omosa IB, Keller AA, Li FT (2012b) Ecosystem protection, integrated management, and infrastructure are vital for improving water quality in Africa. Environ Sci Technol 46(9):4699–4700

Wang HT, Wang T, Zhang BR, Li FT, Brahima T, Omosa IB, Chiramba T, Abdel-Monem M, Pradhan M (2013) Water and wastewater treatment in Africa: current practices and challenges. Clean Soil Air Water. doi:10.1002/clen.201300208, accepted

Worthington EB (1930) Observations on the temperature, hydrogen-ion concentration, and other physical conditions f the Victoria and Albert Nyanzas. Int Rev Ges Hydrobiol Hydrogr 328–357

WRI (2009) Eutrophication: sources and drivers of nutrient pollution. World Resources Institute Policy Note: Water Quality: Eutrophication And Hypoxia (Pdf.Wri.Org/Eutrophication_Sources_And_Drivers.Pdf)