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Research Article

Effect of Landscape Changes on the Water Quality of Murchison Bay

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Abstract The water quality in Murchison Bay of Lake Victoria, the Africa's largest fresh water lake, is on decline due to rapid urban sprawl, decrease in vegetative surface and increase in impervious surface of the drainage area resulting in eutrophication of the lake. The objectives of our study are 1) to analyze the nutrient and metal concentrations in the Murchison Bay; 2) to identify and map the long-term landscape changes in Murchison Bay Watershed (MBW); 3) to analyze the impact of the landscape changes on the water quality of Murchison Bay. Water samples were collected from Miami Beach (MB), Ggaba Beach (GB) and Mulungo Beach (MuB), along the Murchison Bay and analyzed for various metal and nutrient concentrations. Landsat satellite imagery, sampled over three decades (1995-2019) of the MBW were analyzed for the land cover changes. The chemical analysis of the water samples showed that the P concentrations were above the critical limits while the As and Pb concentrations were higher but remained below the critical limits in water. The remote sensing analysis reveal that the impervious surface in the MBW increased by about 21.9% while the vegetative surface decreased by 4.2% during the period of 1995 to 2019. The Chlorophyll a concentration in the Murchison Bay increased over the period of time resulting in deterioration of water quality. Integration of environmental chemical analysis along with geospatial data aids in understanding the impact of land scape changes on the Murchison Bay water quality and to identify the areas vulnerable to change.

Keywords *Urban Watershed; Lake Victoria; Wetlands; Remote Sensing; Landsat and Geographic Information Systems (GIS)*

1. Introduction

Lake Victoria is the largest freshwater body in Africa, with an area of about 68,800 km^2 and a mean depth of around 40 m and lies in a catchment area of 184,000 km^2 (Oyoo-Okoth et al., 2013). The lake is surrounded and bordered by three countries Kenya, Tanzania and Uganda and is the source for the Nile River. Lake Victoria is a fresh water ecosystem of high socio-economic importance in Africa, as it is the predominant source of irrigation and drinking water, large quantity of fish and provides water for various agricultural, industrial and transportation purposes (Juma et al., 2014; Orata et al., 2009) in East Africa.

Kampala, the capital city of Uganda is located in the Northern catchment area of Lake Victoria. The Kampala urban and suburban regions and the surrounding wetlands, including Nakivubu wetland system (area 31 km^2) to the East of Kampala constitute a natural drainage network which flows into Murchison Bay and then further into the Lake Victoria (Richard, 2009). The wetlands around Kampala, receive industrial and domestic wastewater from the surroundings (Fuhrimann et al., 2015) and surface water runoff from the city of Kampala. These wetlands are under considerable pressure due to rapid urbanization, industrial expansion, increased highway and road networks, agricultural and human encroachment (Mbabazi et al., 2010; Kayima et al., 2008; Dalahmeh et al., 2018).

Kampala is one of the fastest growing city with an annual population growth rate of 4.03% over the period of 2006 to 2020 (City Mayors Foundation 2020; UBOS 2018), this rapid increase in population is mainly attributed to high fertility rate, increase in migration of rural communities to urban areas in search of employment, livelihood and better standard of living. This large expansion of urban areas is resulting in loss of natural habitat such as wetland and forests to human encroachment. As only 10% of the urban residents are connected to the sewage network (O'Brien et al., 2017), most of the Kampala residents and several small businesses and industries dispose wastewater into open streams and drainage channels. This is mainly attributed to lack of planning and poor financial resources for construction of sewage network especially within the suburban and poorer areas of the city (O'Brien et al., 2017; UN-Habitat, 2007; Kulabako et al., 2010).

Lake Victoria is composed of several shallow gulfs and bays, especially in the northern parts of the lake, which receive point source pollutants from municipal and industrial centers along with the non-point source pollutants from agriculture and other informal settlements. Murchison Bay, located in the northern part of the lake (Figure 1), has been affected by several anthropogenic influences such as encroachment, conversion and degradation of wetlands, overfishing, increased industrial pollution, and decline in water level (Hecky et al., 2010; Scheren et al., 2000; Akurut et al., 2017). Several studies reported continuous occurrences of blue green algal blooms such as cyanobacteria and water hyacinth infestation in Murchison Bay due to increase in nutrient contamination to the lake (Cózar et al., 2007; Haande et al., 2011).

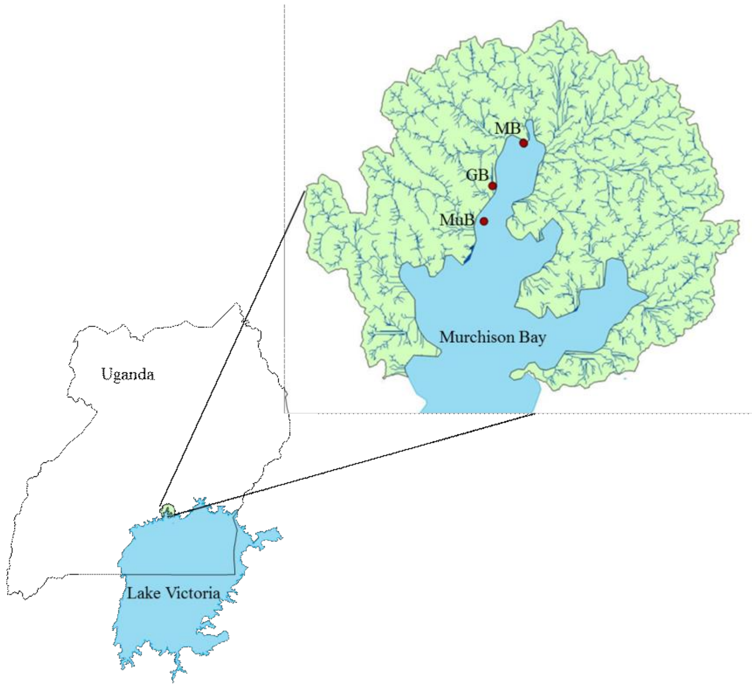

Figure 1: *Murchison Bay along with its surrounding watersheds and the water flow lines that drain into the bay. Also shown are the water sampling locations at Miami Beach (MB), Ggaba Beach (GB) and Mulungo Beach (MuB) in the Murchison Bay of Lake Victoria. The subset image shows the location of Murchsion Bay in the NorthWestern part of Lake Victoria in Uganda.*

The water quality in Murchison Bay is on steady decline, due to increased nutrient runoff from agricultural and industrial areas, intense urban runoff from vast impervious surfaces of the watershed drainage area, poor domestic sewage disposal, resulting in eutrophication of the bay (Selman et al., 2008; Thamaga et al., 2018). Urban growth, population dynamics, industrial expansion has significant impact on the decline in the Murchison Bay water quality. Hence, it is important to monitor and study the long-term land cover and water quality changes of the Murchison Bay.

Water sample collection and monitoring the continuous land cover changes using traditional techniques is very expensive and time-consuming. The traditional methodology includes systematic field collection of the water samples, followed by acid digestion of the samples and then analyzing the chemical concentrations using various analytical instruments. Remote sensing is a cost effective, technologically sound monitoring technique that can be used for continuous monitoring of the landscape and water quality changes at a large scale and to quantify its effect on the extent of environmental contamination and the subsequent impact of the natural resources. The goal of this study is to analyze the long-term water quality changes in the Murchison Bay, in Uganda. The landscape changes in the surrounding watersheds draining into the Murchison Bay of Lake Victoria and its impact on the water quality changes was investigated in this research. Specific objectives of the study are: 1) to analyze the nutrient and metal concentrations in the Murchison Bay; 2) to identify and map the long-term landscape changes in Murchison Bay Watershed (MBW) and; 3) to analyze the impact of the landscape changes on the water quality of Murchison Bay.

2. Materials and Methods

2.1. Sampling Locations along Murchison Bay

The locations of the surface water samples and their distribution across the Murchison Bay is shown in Figure 1. Twelve water samples were collected from three different sampling locations namely, Miami beach (MB), Ggaba beach (GB) and Mulungo beach (MuB) along the Bay, which are popular publicly accessible locations for recreation, tourism, fishing, business and other day to day activities. Water samples from every location were collected in triplicate and the GPS coordinates of the sampling sites were recorded by using a potable Global Positioning System (GPS) receiver (Trimble Inc., Sunnyvale, CA). Samples were immediately transported to the laboratory in US, and kept refrigerated until further chemical analysis was performed.

2.2. Chemical Analysis

Water samples collected were microwave (Mars 6, CEM, Matthews, NC) acid digested using a microwave digestion unit using EPA 3015a method. About 45 ml of water sample was mixed with 5 ml of nitric acid for acid digestion in the sealed microwave vessels. The vessel contents were further cooled and filtered using Whatman 1 Filter paper. The samples were analyzed for of Al, As, B, Ba, Ca, Cd, Co, Cr, Fe, K, Mg, Mn, Mo, Na, P, Pb, S, Sr and Zn concentrations by using Inductive Coupled Plasma Mass Spectrometry (ICP-MS, Agilent 7500 Series, Santa Clara, CA). Results of water samples were statistically analyzed using the MINITAB statistical software (MINITAB Inc., State College, PA, USA).

2.3. GIS Analysis

The watershed and the hydrological stream network of the study area were delineated based on the Digital Elevation Models (DEM) using the hydrology tools of the spatial analyst extension of the ArcMap (ESRI, 2014). The Shuttle Radar Topographic Mission (SRTM) DEM data at 30 m resolution for Uganda was downloaded from the RCMRD website *(http://opendata.rcmrd.org/datasets/uganda-srtm-dem-30-meters).* All these data were used to create stream network and delineate watersheds for the Murchison Bay study area.

The spatial data for the study area was collected from various public and freely available datasets. These include, Energy sector GIS working group of Uganda *(http://www.energy-gis.ug/gis-data),* World Resources Institute *(https://www.wri.org/resources/data-sets/uganda-gis-data),* Uganda Bureau of Statistics *(https://www.ubos.org/data-portals-2/)*, Humanitarian Data Exchange *(https://data.humdata.org/)* and from RCMRD Geoportal *(http://geoportal.rcmrd.org/).* Study areas of Murchison Bay, Lake Victoria and other geographical data were extracted and separated to derive the watershed study areas. Water sampling points of the study area were imported into GIS as separate vector layer. A 100m spatial buffer was created along the streams (with 50m on each side) within the study area and the land cover changes within the buffer was also evaluated from the downloaded satellite imagery.

2.4. Satellite Data Analysis

Four Landsat imagery from the time periods of 1) Jan 19, 1995, 2) Jan 28, 2010, 3) Feb 27, 2015, and 4) Jan 5, 2019, all having zero percent cloud cover, were chosen for this study. No cloud free Landsat imagery of study area prior to 1995 were found. Landsat imagery were downloaded from USGS Earth Explorer *(https://earthexplorer.usgs.gov/)* website, and processed using the ER Mapper V16.6 software (Hexagon Geospatial, 2020). Several single band and spectral ratio combinations were derived from the Dark Object Subtracted (DOS) values from each of the 7 bands in case of Landsat 5 imagery and from each of the 11 bands in case of Landsat 8 imagery. A DOS value of a spectral band is defined as one value less than the minimum digital number found in all pixels of that particular image for that spectral band (Vincent et al., 2004; Sridhar et al., 2009; 2011).

The vector data layers of Murchison Bay Watershed (MBW) study area was overlaid, clipped and the extracted study area from each of the Landsat imagery was then used for subsequent analysis. The land cover changes were evaluated by mapping the vegetative and impervious surface characteristics as environmental indicators to map and monitor the landscape changes in MBW. Normalized Difference Vegetation Index (NDVI) was calculated by using Equation 1 (Rouse et al., 1974) for Landsat 5 imagery and using equation 2 for Landsat 8 imagery, to map the green vegetation in the study area. An NDVI value of greater than 0.2 was applied as a mask to map only the vegetation. A Water Index (WI), equation 3 in case of Landsat 5 Imagery and equation 4 in case of Landsat 8 was used to map the water content of the study area. An Impervious Surface Area Index (ISAI), equation 5 was used to map the impervious surface areas in the Landsat 5 imagery while equation 6 is used for the Landsat 8 imagery. The spatial and temporal changes in impervious surface, water and vegetative surface areas from 1995 to 2019 were mapped and quantified individually for each of the selected images of MBW.

The changes in the Chlorophyll a concentration in the Murchison Bay water was visualized by applying the Landsat model developed to map the changes in the Chlorophyll a concentration in the water. The Chlorophyll a model that was applied to Landsat 5 imagery is given in equation 7 and for Landsat 8 imagery is given in equation 8 (Sridhar, 2019). Finally, the chemical analysis data, spatial and temporal data were integrated to analyze the overall landscape change pattern, in Murchison Bay and MBW.

$$NDVI = \frac{Band\ 4 - Band 3}{Band\ 4 + Band\ 3} \quad \text{Equation 1}$$

$$NDVI = \frac{Band\ 5 - Band 4}{Band\ 5 + Band\ 4} \quad \text{Equation 2}$$

$$WI = \frac{Band\ 2}{Band\ 5} \quad \text{Equation 3}$$

$$WI = \frac{Band\ 1}{Band\ 6} \quad \text{Equation 4}$$

$$ISAI = \sqrt{Band\ 6\ x\ Band\ 3} \quad \text{Equation 5}$$

ISAI = $\sqrt{Band\ 10\ x\ Band\ 3}$ Equation 6

Chl a (mg/l) = 14.39 - 78.5 R21 + 34.49 R52 - 17.87 R73 Equation 7

Chl a (mg/l) = -42.2 + 39.7 R32 - 83.1 R52 + 105.9 R53 + 56.8 R72 - 75.3 R73 Equation 8

Where Rxy = Band x/ Band y

3. Results and Discussion

The water samples collected from the Miami Beach (MB), Ggaba Beach (GB) and Mulungo Beach (MuB) of Murchison Bay showed profound spatial heterogeneity in terms of the concentrations of different elements. The concentrations of As and Si were significantly higher in MB compared to other locations. The concentration of Al was significantly higher in GB and MuB while the concentration of Pb was significantly higher in MB and MuB compared to other location. The concentration of P was significantly higher in MB and GB compared to MuB (Table 1). The concentrations of all the other elements were below the proposed critical limits of WHO and EPA for drinking water (WHO, 2017; USEPA, 2018). The concentration of As in MB and the concentration of Pb in MB and MuB were high and almost close to the proposed maximum critical limit of 10 ppb (Table 1). The P concentrations in the MB and GB were well above the recommended maximum level of 100 ppb which is the proposed critical limit of EPA for algal bloom occurrence in surface water (Table 1).

Table 1: *Heavy metal and nutrient elemental concentration in water samples collected from Murchison Bay of Lake Victoria. Miami Beach (MB), Ggaba Beach (GB) and Mulungo Beach (MuB) represents sampling locations along the bay. Given are mean values (n = 3) of three replicates. Also given are the proposed critical limits of WHO and EPA for drinking water (WHO, 2017; USEPA, 2018).*

Elemental Concentrations (ppb)	Miami Beach (MB)	Ggaba Beach (GB)	Mulungo Beach (MuB)	WHO	EPA
Al	2.8	20.8*	25.6*	200	200
As	8.8*	0.1	0.6	10	10
B	11.2	11.8	10.6	2400	1000
Ba	23.6	22.5	22.3	1300	2000
Ca	8320	7596	6573	-	-
Cd	0.6	0.2	0.2	3	5
Co	1.0	0.2	0.3	-	-
Cr	0.5	0.6	0.4	50	100
Fe	25.6	25.6	25.8	-	300
K	4657	4207	3369	-	-
Mg	2838	2673	2461	-	-
Mn	3.3	0.8	0.1	400	50
Mo	2.6	2.1	2.1	70	-
Na	10553	9565	8261	-	20000
P	120.9*	152.7*	35.8	-	-
Pb	7.0*	3.2	8.0*	10	10
Si	1600*	1152	887	-	-
Sr	80.9	76.7	71.4	-	-
Zn	10.7	8.0	11.3	-	5000

† Means followed by asterisk (*) for the same element are significantly different at the 0.05 probability level.

The pseudo color Landsat imagery of the watershed areas that drain into the Murchison Bay shows that the urban impervious surface increased significantly from 1995 to 2019 at the expense of the vegetative cover (Figure 2). The gradual progression of the urban sprawl all along the western part of the Murchison Bay can be seen distinctly. An unsupervised classification of the Landsat imagery with the ratio inputs of WI, NDVI and ISAI showed that the western part of the bay was significantly covered with impervious surface compared to the eastern part of the bay (Figure 3). The impervious surface area in the watershed increased by 21.9 % from 1995 to 2019 while the vegetative cover decreased by 4.2 % over the same period (Figure 4).

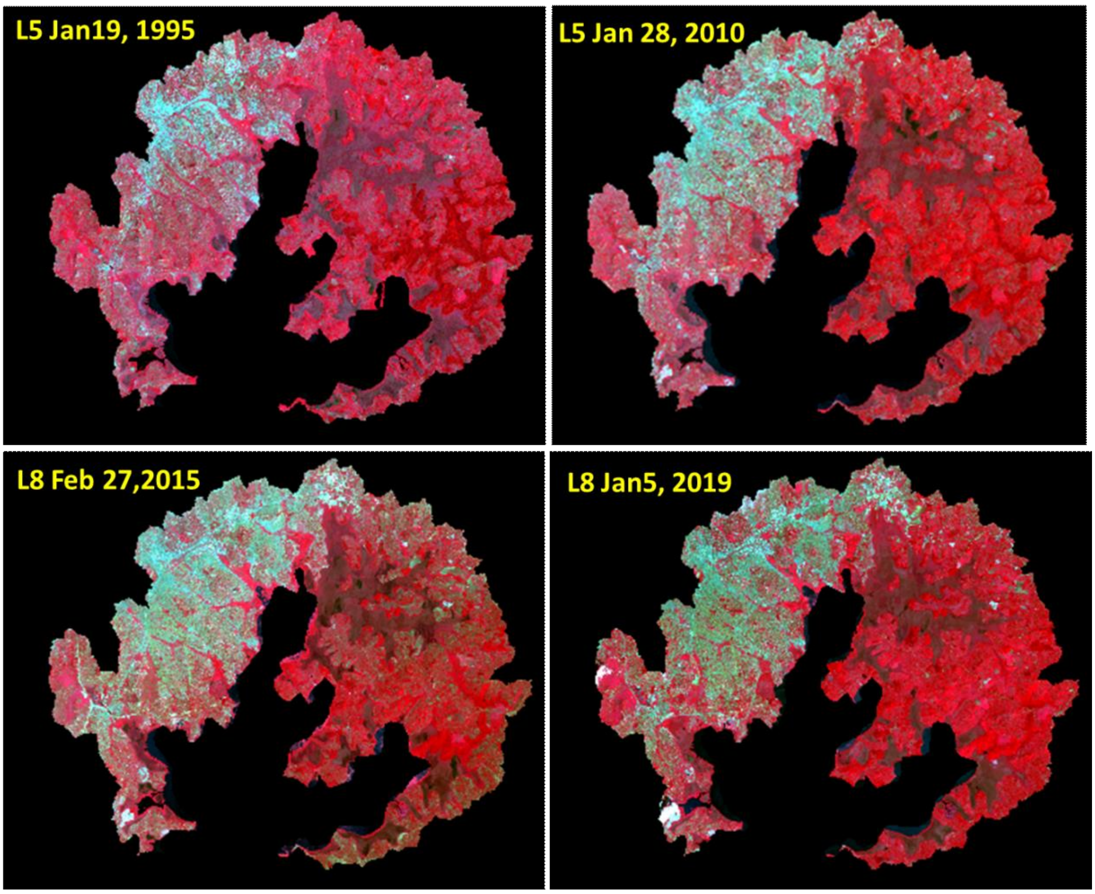

Figure 2: *The pseudo color image of the Murchison Bay watershed where Landsat 5 bands 2, 3, 4 were shown in blue, green and red, respectively, while the Landsat 8 bands 3, 4, 5 were shown in blue, green and red, respectively. The vegetation appears in shades of red while the urban areas appear in pale white to lighter shades, the wetland areas and water appear dark. The western part of the study area is dominated by urban impervious surface while the eastern part by vegetation.*

To identify the extent of land cover changes along the stream buffers within the watershed that drain into the Murchison Bay, a 100 m buffer zone along the streams were created and analyzed. All along the stream buffer zones, impervious surface area has increased and the vegetative surface area has decreased (Figure 5; Figure 6). The loss of vegetation along the stream buffer zone is distinct along the western and northwestern areas of the Murchison Bay compared to the eastern areas. The impervious surface area increased by 119 % from 1995 to 2019 while the vegetative cover decreased by 12 % over the same period along the stream buffer zones (Figure 5). The Chlorophyll a concentration in the Murchison Bay increased significantly from 1995 to 2019 (Figure 6), the algal blooms seem to arise from the Inner Murchison Bay, which is located in the northern part of the bay and spread towards the Outer Murchison Bay in the south.

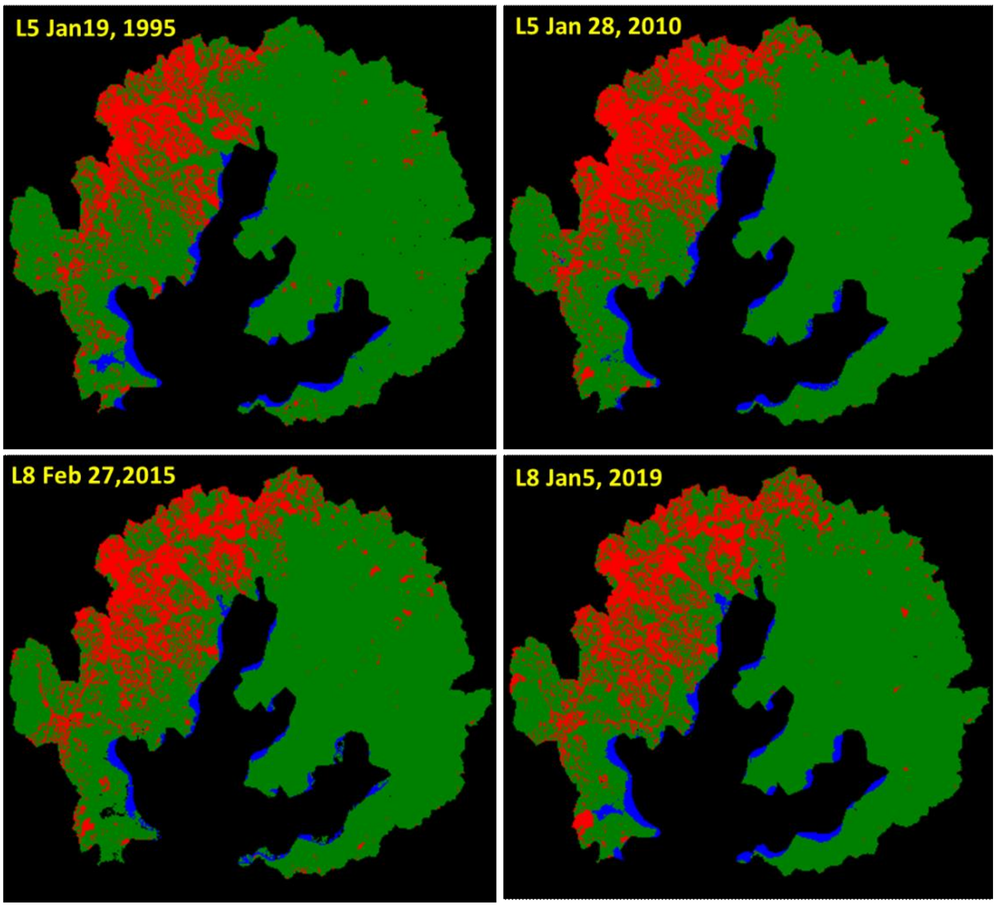

Figure 3: *The unsupervised classification images of the study area where the areas covered with vegetative surface, impervious surface and water are shown in green, red and blue, respectively. The impervious surface areas increased at the expense of the vegetative cover during the period of 1995-2019.*

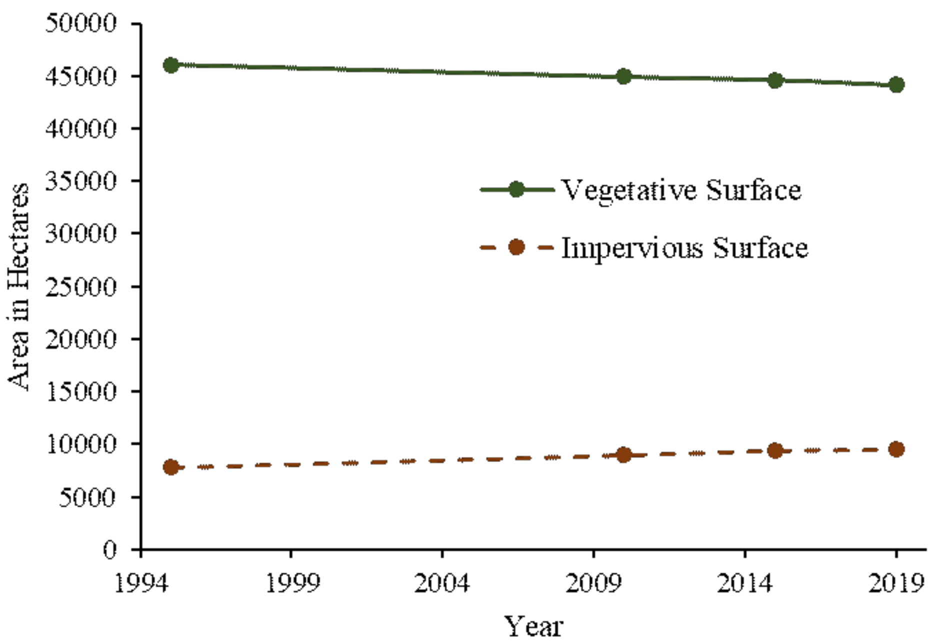

Figure 4: *Change in the acerage of impervious and vegetative suface over the period of 1995-2019 in the Murchison Bay Watershed (MBW).*

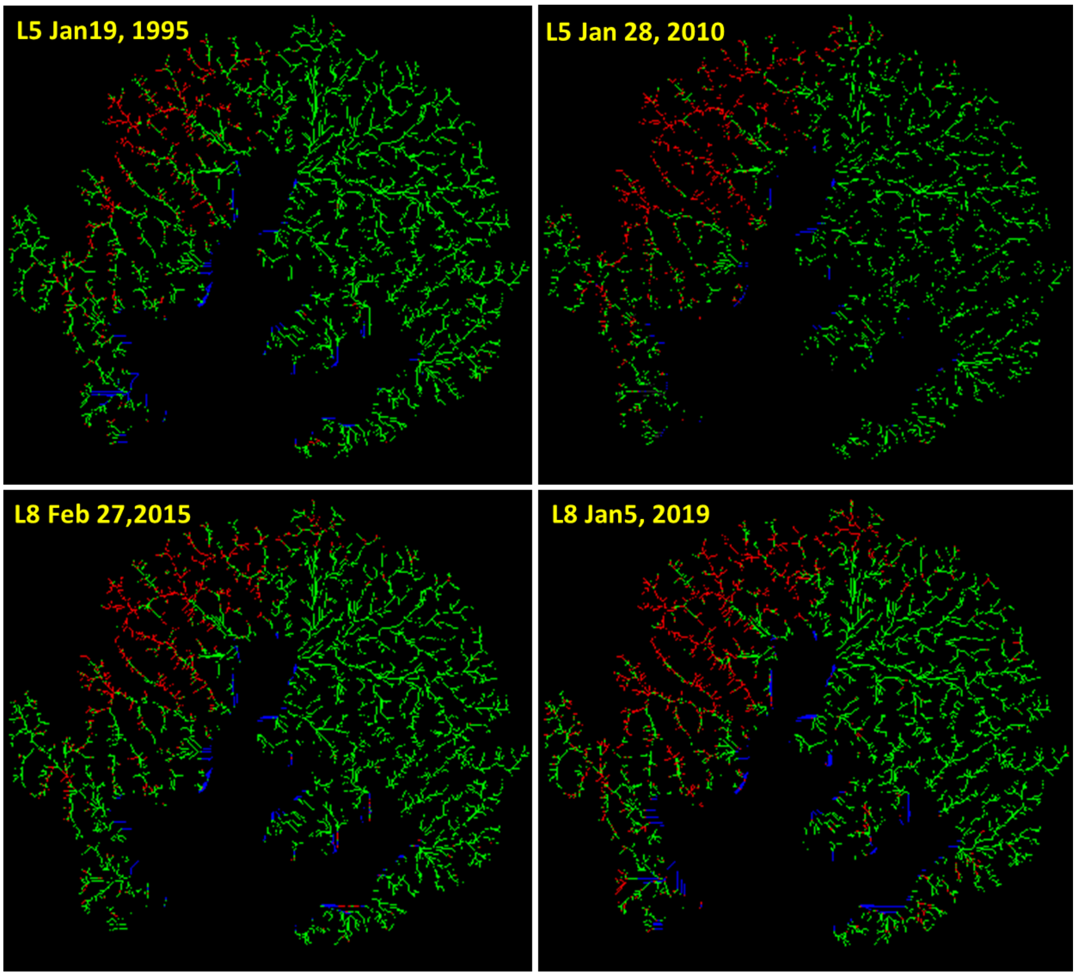

Figure 5: *The unsupervised classification images of the study area along the stream buffers within the watershed where the areas covered with vegetative surface, impervious surface and water are shown in green, red and blue, respectively. The impervious surface areas along the stream buffers increased at the expense of the vegetative buffers during the period of 1995-2019.*

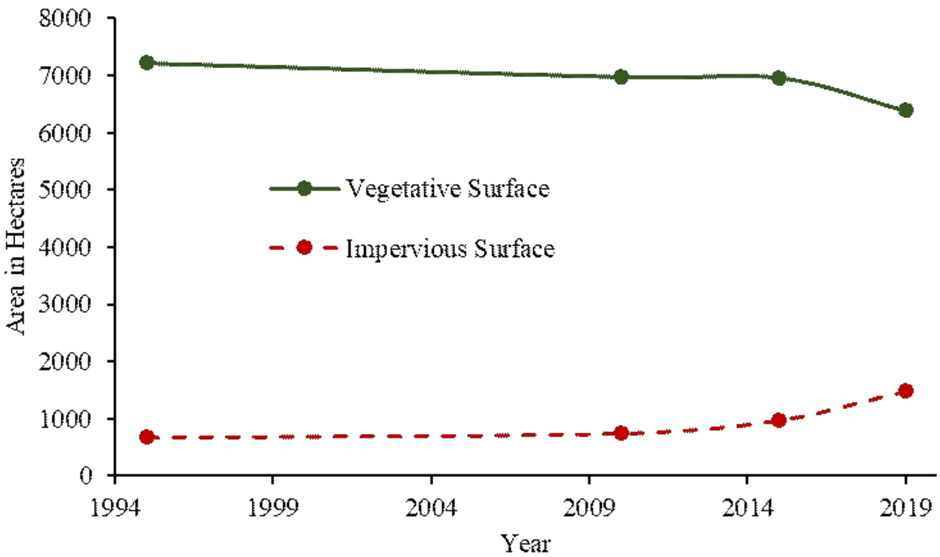

Figure 6: *Change in the acerage of impervious and vegetative suface along the strem buffers in the Murchison Bay Watershed (MBW) over the period of 1995-2019.*

The phosphorus concentration in the MB and GB are at more than the recommended maximum level of 100 ppb for the surface water. The Total P in the range of 10 to 75 ppb is the appropriate level to control the nuisance algal blooms in fresh water (USEPA, 2002). This high P concentration in the bay can be attributed mainly to the domestic and municipal waste and waste water disposal as well as intensification of agricultural and industrial activities within the watersheds draining into Murchison Bay, which causes lake eutrophication resulting in massive algal blooms and consequently spread of aquatic weeds such as water hyacinth (Selman et al., 2008). Water hyacinth affect the lake ecology by changing the habitat, interrupting the nutrient cycle, causing fish kills, and affecting the water transportation networks (Brendonck et al., 2003; Toft et al., 2003; Coetzee et al., 2014; Wasige et al., 2013; Thamaga et al., 2018).

Phosphorus also serves as an essential nutrient promoting algal growth such as cyanobacteria (*Microsytis*), which produce microcystin, a hepatotoxin, which impacts the human and animal health upon consumption of water contaminated with microcystins. From time to time, Murchison Bay and several other parts of Lake Victoria experience widespread algal blooms across the lake. Murchison Bay is heavily eutrophic (Haande et al., 2011; Ssebiyonga et al., 2013) and a major improvement can only be expected if the P inputs into the lake are controlled and the total P concentrations are brought down. Also the Murchison Bay is the water withdrawal point of the water treatment plant for the distribution of potable water for Kampala City. In recent years, with increase in surface runoff, industrial and municipal waste and sewage effluent into the bay, the water withdrawal points were extended to deeper and further portions of Lake Victoria (Akurut et al., 2017). The ammonia concentration in the surface waters of the bay is above the recommended standard criteria of 0.06 ppm (Richard, 2009), which also contribute the production of algal blooms along with the increase in P concentrations. The increase in the concentration of the algal blooms over the bay is clearly evident during the last three decades (Figure 7), which can be attributed to increase in the nutrient run off into the bay.

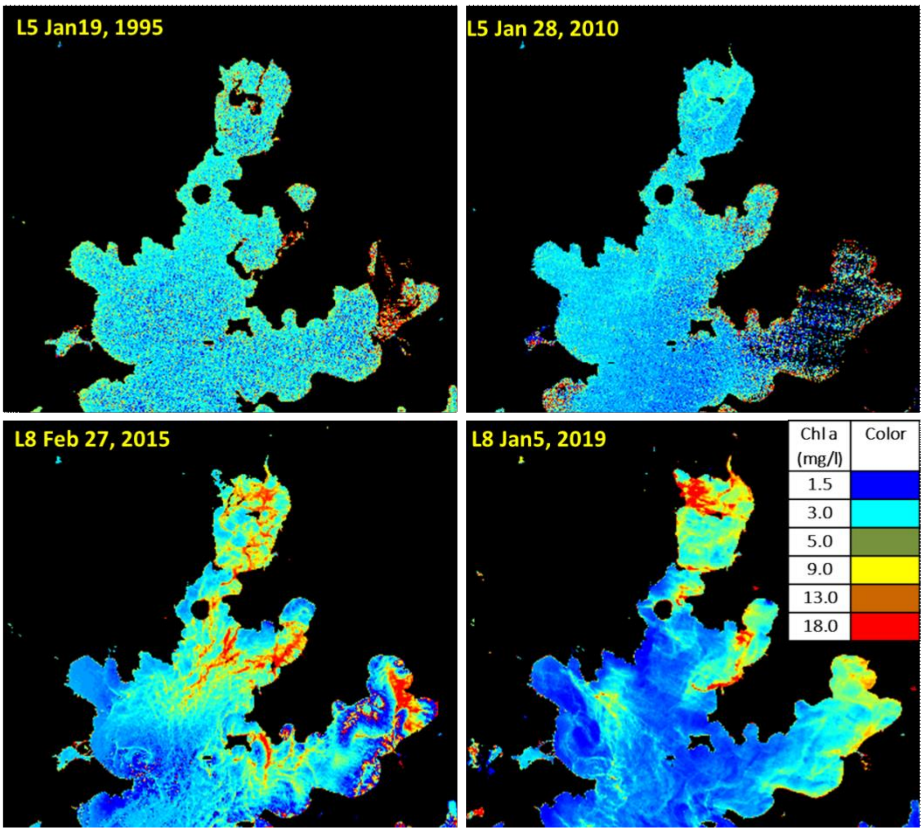

Figure 7: *The changes in the Chlorophyll a concentration in the Murchison bay water during the period of 1995-2019. The Chlorophyll a concentration increased significantly and covered most of the bay with time.*

The concentration of As in MB is significantly higher compared to other locations and is also higher than the general range of As in natural water which is 1-2 ppb (Hindmarsh and McCurdy, 1986; USNRC, 1999; WHO, 2011a). Long term exposure of high As concentration in drinking water increases the risk of cancer to the skin, lung, bladder and kidney (IPCS, 2001). The concentration of Pb in MB and MuB are getting close to the proposed maximum critical limit of 10 ppb which is higher than the average Pb levels of 2.8 and 2 ppb found in drinking water of US (WHO, 2011b) and Canada (Dabeka et al., 1992). High concentration of Pb over 10 ppb in water is poisonous affecting the health of infants, children and the fetus of pregnant women. The high concentration of metal and nutrient concentration in Murchison bay can be attributed to the presence of several large and small-scale industries within the drainage watershed. The partially treated or untreated effluents from upstream flows into the Nakivubu Channel, which further drains into the Murchison Bay (Richard, 2009). Apart from this, waste disposal from several systems such as pit latrines, waste water treatment plants and agricultural activities make its way into the bay (Richard, 2009).

The land cover change analysis revealed that the impervious surface increased by 21.9 % and the vegetative surface decreased by 4.2 % in the watershed areas during the period of last three decades. According to Akurut et al. (2017) the pollutant loading into streams of MBW has tremendously increased due to rise in population, wetland conversion, commercial growth, and industrialization in Kampala City. Urban sprawl, population increase and wetland loss around Murchison Bay is leading to land degradation and thus increasing the sediment and nutrient loading into the lake system from point and non-point sources of pollution (Machiwa, 2003). Pollutants originating from non-point sources was reported to be higher than that of point sources around Murchison Bay (Banadda et al., 2009) due to decrease in vegetation along the stream buffer zones and reduction in the wetlands. This claim can be justified by our land cover analysis along the 100 m stream buffers within the watershed where the vegetative cover decreased and impervious surface increased at a faster rate of 12% and 119%, respectively, than the rest of the watershed (Figure 5; Figure 6). Land cover change due to human activities is an important parameter that impacts the global environmental and ecological change by changing complex biophysical processes at global, regional and local scales (Wasige et al., 2013; Wu et al., 2003).

4. Conclusions

We compared and analyzed the Landsat satellite imagery of the last three decades (1995 to 2019) to identify the land cover changes of the Murchison Bay Watershed (MBW) and found that the vegetative surface decreased by 4.2 % and the impervious surface increased by 21.9 %. The land cover changes along the 100 m stream buffers within the watershed showed that the vegetative surface decreased and impervious surface increased by 12% and 119%, respectively, which is more intense than the rest of the watershed within the same period time. The increase in impervious surface of MBW is contributing to more surface water runoff and nutrient load into Murchison Bay resulting in more algal blooms. Consequently, the Chlorophyll a concentration increased significantly and covered most of the bay during the course of time in the last three decades based on the satellite imagery. Our water quality analysis reveal that the P, As and Pb concentrations were higher in Miami Beach (MB) followed by Ggaba Beach (GB) and Mulungo Beach (MuB), which are aligned accordingly in the north to south direction along which the influent water flows into the Murchison Bay. The chemical and image analysis data indicates that the nutrient and Chlorophyll a concentration increased along the gradient from the Outer Murchison Bay (OMB), to the Inner Murchison Bay (IMB), which are geographically located in the south and north of the Murchison Bay, respectively. This study improves the understanding of the land cover change in MBW which is recognized as a critical gap in the knowledge of wetland and forest loss, soil and water degradation, and eutrophication of Murchison Bay. Further research involving the use of high resolution satellite and aerial imagery along with a comprehensive water analysis for extensive inorganic and organic contaminants covering the entire bay will be greatly beneficial. Urban growth with environmental sustainability is key to the future economic growth in the region where urban development should be planned by conserving the natural resources.

Conservation of the wetland areas, reducing the inflow of domestic sewage and industrial effluents, developing and preserving the vegetative buffer strips around the drainage streams, along with the control of point and non-point source pollution is crucial to prevent the decline in the water quality of Murchison Bay and to reduce the proliferation of harmful algal blooms and floating aquatic weeds.

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