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Assessment of Macrophyte Populations in Lake Naivasha, Kenya; Using GIS and Remote Sensing

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Abstract

Exotic aliens, *Salvinia molesta* (floating water fern) and *Eichhornia crassipes* (water hyacinth) encroachment in Lake Naivasha are associated with deteriorating water conditions. This Paper presents findings of a study designed to assess the distribution and quantify the extent of the macrophyte population in Lake Naivasha between February and March 2017. High-resolution optical Earth Observation (EO) data and in-situ data were used to assess the extent and quantify the macrophytes and other Aquatic invasive weeds in lake Naivasha, Kenya. Mapping of distribution and extent of macrophytes was done using remotely sensed imagery Sentinel-2 acquired on 28th February 2017, 20th March 2017 and 30th March 2017. The images were geo-referenced and geographically rectified. The datum was set to WGS 84 and referenced to Universal Transverse Mercator (UTM) zone 36 North. Image compositing using both false colour and natural colour band combinations was conducted including image enhancement, and clipping the images based on the extent of the study area. The image interpretation was done at a scale of 1:50000, while Ground truthing was undertaken to provide supplemental details of actual information in the field. Maps were produced and the macrophytes quantified in terms of distribution and coverage using different spectral signatures. Kappa Index of agreement was used to assess the accuracy of the maps of 28th February 2017 and 30th March 2017. Multi temporal analysis of the satellite images (28th February 2017, 20th March 2017 and 30th March 2017) showed there were two major types of macrophytes that could be identified and quantified. It also showed that the area covered by water hyacinth had increased significantly from (940 Ha) to (1480 Ha) between the study dates, while the area under papyrus had also increased from 570 Ha to 590 Ha. The overall findings indicate that the coverage of papyrus remained relatively stable both in terms of distribution and area covered on the other hand, the coverage of water hyacinth was dynamic both in terms distribution and coverage.

Keywords: Lake Naivasha; Earth Observation; Macrophytes; Water Hyacinth; Papyrus; Distribution; Coverage

Introduction

Lake Naivasha is one of Kenya's 'urban' lakes by its strategic location next to Naivasha Town. The lake, which is an internationally recognized Ramsar site, sits in the eastern rift valley of Kenya (0° 46'S, and 36° 20'E) at an altitude of about 1890 m above sea level and covers a surface area varying between 120 km^2 in the dry spell and 150 km^2 in the wet spell [1-3]. It is a shallow freshwater body, with mean depth varying between 4m and 6m. Its freshness is mainly maintained by the inflows from the catchment area, biogeochemical sedimentation and the underground seepage [4].

As one of the most important freshwater resource in Kenya, the hydrology of Lake Naivasha and its biological communities have been studied for more than 40 years. The Lake Naivasha basin comprises of 3 distinct catchments that drain into the Northern part of the lake: the Malewa (1750 km^2) which rises in the Nyandarua (Aberdares) range to the east and north at an elevation of almost 4000 m, the Gilgil (420 km^2) in rift highlands due north, and the Karati (70 km^2) on the Kinangop plateau to the west. Many small basins with a total size of 1000 km^2 drain the southern and western part of the basin. The rainfall distribution has a bi-modal character. The long rains from April to June and the short rains during October and November. The spatial distribution of the rain varies from approx. 600 mm at Naivasha town to approx. 1700 mm at the slopes of the Nyandarua Mountains. The inter-annual variability of rainfall is high with a mean of 600 mm/year At Naivasha town the maximum temperature is 37 °C and the minimum 5 °C, mean around 16 °C. Long cycles with wetter or drier conditions occur regionally and are the driving force behind the fluctuations of the lake. The lake level fluctuations have attracted analysis because their dependence upon the high-altitude rainfall makes them dependent upon large-scale climatic influence.

Around the lake, the dominant vegetation appears to have been Acacia *xanthophloea* (Benth) woodland, followed by a narrow fringe of Papyrus (*Cyperus papyrus*) covering most of the shoreline, the floating Nile cabbage (*Pistia stratiotes*), Wolffia arrhiza and water lily (*Nympha acaerulea* and *Nymphaea nouchalii*) and, the submerged *Potamogeton spp., Najas horrida, Ceratophyllum demersum*, and macro-algae *Chara spp.* [5,6]. The diversity of these plant species was dependent upon hydrological fluctuations, which created a series of dynamic vegetation zones through the land-water ecotone, thereby regulating incoming materials, especially soluble and particulate nutrients as per classical ecohydrological principles and they may act as natural water purifiers [7-10].

Over the years, the environmental conditions in Lake Naivasha have changed markedly due to spatial and temporal dynamics of the water quality parameters [11]. The lake has become eutrophic and a functioning swamp ecotone, with no protection whatsoever from surface run-offs and negative inputs originating from its catchment area [12,13]. Environmental pressures ranging from introduction of alien species, catchment deforestation, overgrazing and erosion, over-abstraction, and sewage from unplanned settlements have resulted in an increased load of nutrient concentrations acting upon the lake [14]. Continued land use changes have resulted in the loss of the dominant papyrus including native aquatic plant species in the lake ecosystem processes, resulting in increased eutrophication and an observed shift from clear water, to macrophyte infested turbid conditions with periods of water hyacinth regeneration [12,15,16].

To establish sustainable management of Lake Naivasha and its aquatic resources, up-to-date information about the distribution and coverage of selected macrophytes and other invasive weeds at several scales will be required. This can be achieved through remote sensing techniques that can monitor the change in macrophyte area and assess the percentage cover of the species.

Remote sensing has long been used to complement information normally collected by conventional tedious, time-consuming ways that may sometime be inapplicable due to poor accessibility [17]. The technique involves gathering data regularly about the earths features without actually having to be in direct contact with those features, allowing for continuous monitoring due to its repeat coverage and its digital data can be easily incorporated into a Geographical Information System (GIS) database for more analysis, which is less costly and less time-consuming [17-22]. While both multispectral (Landsat TM, SPOT imagery) and hyperspectral remote sensing techniques have been used to discriminate and map wetland vegetation species, the use of multispectral data could be challenging due to spectral overlap between species and lack of spectral and spatial resolution of multispectral data whereas hyperspectral data allows for discriminating and mapping vegetation species more accurately and precisely as a result of having contiguous bands and narrow ranges [17,22-25]. With a few previous attempts using multispectral remote sensing techniques having proven to be promising and successful, the study aimed to assess the distribution and coverage of macrophytes and other invasive weeds on Lake Naivasha and to recommend guidelines on possible management scenarios for the sustainable use of Lake Naivasha aquatic resources.

Materials and Methods

Study Area

Lake Naivasha is situated at 00° 45' S and 36° 20' E in a closed basin at an altitude of 1890 m above sea level in the Eastern Rift Valley of Kenya (Figure. 1), and covers an area of approximately 160 km^2 [26]. It is the only freshwater lake in the Rift Valley without a surface outlet but with a substantial exchange with groundwater [27].

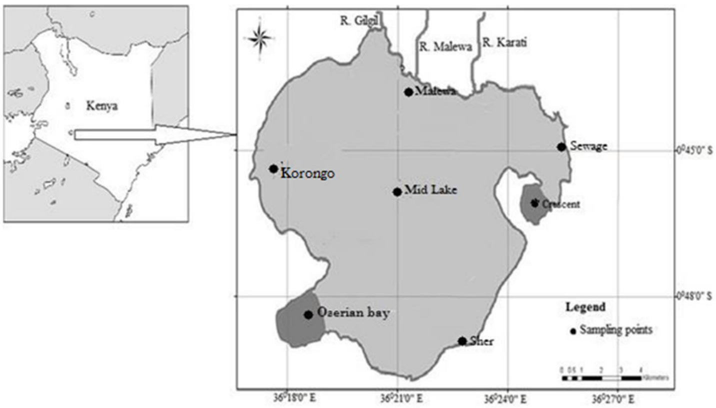

Figure 1: Map of the study area (Lake Naivasha)

Field data collection

Identfication of macrophytes and invasive weeds

The most common macrophytes and invasive weeds in the area were identified to the lowest possible taxononomy possible with an experienced ecologist using field observation techniques. The species were then recorded based on their densities and estimated percentage cover and, their photos taken.

Data acquisition

Multi-date very high-resolution satellite imagery Earth Observation (EO) and in-situ data covering the Lake Naivasha were acquired from the Regional Centre for Mapping and Resource Development (RCMRD) and LocateIT Ltd. Macrophyte distribution maps were derived from the Sentinel-2 satellite images acquired on 28th February 2017, 20th March 2017 and 30th March 2017. In-situ data collection was scheduled and undertaken on the same day of the Sentinel-2 overpass to ensure minimal mismatch between the locations of the macrophytes on the lake and on the satellite image and ground positions collected using Garmin GPS 76CSx before the data was downloaded using Garmin Basecamp 4.2.2.0 software (Figure 2).

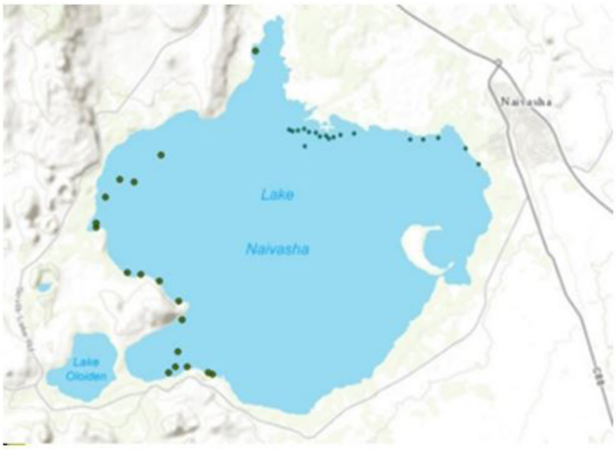

Figure 2: Location and distribution of field sample points for macrophytes and invasive weeds collected in Lake Naivasha

Data processing

Data analysis

Digital image processing techniques that included image geo-referencing and ortho-rectification, noise filtering, mosaicking, clipping, feature extraction, etc. were used to analyse the satellite images. The datum for the satellite images was set to WGS 84 and referenced to Universal Transverse Mercator (UTM) zone 36 North. The images were digitized based on false colour composite bands (3, 4, and 8) and clipped based on the extent of the shoreline of Lake Naivasha. The bands were re-sampled and classified using object oriented classification methodology. The classification methodology entailed the following steps:

- Digitizing the shoreline of Lake Naivasha based on a false colour composite image (Bands 3, 4, 8)
- Clipping all the eight Sentinel-2 image based on the shoreline digitized
- Resampling bands 5, 6, 7 and 8A from 20m to 10m
- Carrying out object-oriented classification by
    - Creating a segmentation file
    - Creating training data derived using field data
    - Creating signature files from the training data
    - Running a classification procedure using the maximum likelihood module
    - Carrying out accuracy assessment using a separate set of segments derived using field data
    - Carrying out cartographic design and layout of the macrophytes map produces
    - Computing area under each type of macrophyte mapped in ArcGIS

Accuracy assessment

Kappa Index of agreement was used for the accuracy assessment for the macrophytes maps of 28th February 2017 and 30th March 2017. The fieldwork data collected on 28th February 2017 were used in the classification derived from the Sentinel-2 image of 28th February 2017 (Table 1). Accuracy assessment was leveraged on field data collected on 10th March 2017 (Table 2) with care taken to only include sample points (9 sample points) that were in locations in the lake where the macrophytes were relatively immobile. Finally, the dominant categories were used to compute the accuracy assessment (Table 3) against the final map of macrophytes by way of error matrix (also known as confusion matrix). The Overall Kappa Index attained from the accuracy assessment for the macrophyte maps of 28th February 2017 and 30th March 2017 was 0.913978 and 0.9013 respectively – implying an accuracy of about 91.4% for the macrophytes maps of 28th February 2017 and 90% for that of 30th March 2017 (Figure 3 and 4).

Result

Satellite images showed physiognomic vegetation types of Lake Naivasha. The dominant macrophytes recorded included Cyperus papyrus, stranded Eichhornia crassipes (water hyacinth) and Salvinia shoots that were deposited on the shore during the high Lake levels.

Longitude (X)	Latitude (Y)	Elevation (m)	Macrophytes Present	Dominant	2nd Dominant	3rd Dominant
36,34886	-0,72269	1887	Papyrus, Water hyacinth, Grasses	Water hyacinth	Papyrus	Grasses
36,35026	-0,72319	1890	Papyrus, Water hyacinth, Grasses	Papyrus	Water hyacinth	Grasses
36,35227	-0,72303	1892	Papyrus, Water hyacinth, Grasses	Water hyacinth	Papyrus	Grasses
36,35491	-0,72870	1893	Water hyacinth, Grasses	Water hyacinth	Grasses	
36,35458	-0,72248	1895	Papyrus, Water hyacinth	Water hyacinth	Papyrus	Grasses
36,35648	-0,72358	1893	Papyrus, Water hyacinth, Grasses	Water hyacinth	Papyrus	Grasses
36,35916	-0,72394	1896	Papyrus, Water hyacinth, Grasses	Water hyacinth	Papyrus	Grasses
36,36073	-0,72525	1894	Papyrus, Water hyacinth	Papyrus	Water hyacinth	
36,36288	-0,72501	1895	Papyrus, Water hyacinth, Grasses, Sedge	Water hyacinth	Papyrus	Sedge
36,36405	-0,72593	1894	Papyrus, Water hyacinth	Papyrus	Water hyacinth	
36,36575	-0,72543	1893	Papyrus, Water hyacinth, Grasses	Water hyacinth	Papyrus	Grasses
36,36843	-0,72473	1894	Papyrus, Water hyacinth, Grasses	Papyrus	Water hyacinth	Grasses
36,37364	-0,72419	1894	Papyrus, Water hyacinth, Grasses	Papyrus	Water hyacinth	Grasses
36,39500	-0,72608	1893	Papyrus, Water hyacinth, Grasses	Water hyacinth	Papyrus	Grasses
36,40017	-0,72625	1893	Papyrus, Water hyacinth, Grasses, Shrubs	Water hyacinth	Papyrus	Grasses, Shrubs
36,40578	-0,72553	1893	Papyrus, Water hyacinth	Water hyacinth	Papyrus	
36,41639	-0,72919	1893	Papyrus, Water hyacinth, Acacia	Papyrus	Water hyacinth	Acacia
36,42117	-0,73475	1896	Papyrus, Water hyacinth, Acacia, Grasses	Papyrus	Water hyacinth	Acacia, Grasses

Table 1: Data of field points of 28th February 2017 used in accuracy assessment

Longitude (X)	Latitude (Y)	Time	Wind	Sample Size (m)	Macrophytes Present	Dominant	2nd Dominant	3rd Dominant
36,29853	-0,81651	9:38 AM	Light winds	90x200	Papyrus, Water hyacinth, Shrubs, Acacia	Water hyacinth	Acacia	
36,29348	-0,81183	9:58 AM	Not windy	100x200	Papyrus, Water hyacinth, Shrubs, Acacia	Water hyacinth	Papyrus	Acacia, Grasses, Shrubs
36,32607	-0,81541	10:24 AM	Not windy	10x100	Papyrus, Water hyacinth,Grasses	Papyrus	Water hyacinth	Grasses
36,32947	-0,81606	10:33 AM	Not windy	90x100	Papyrus, Water hyacinth, Acacia	Papyrus	Acacia	Water hyacinth
36,33276	-0,82072	10:47 AM	Light winds	100x200	Papyrus, Water hyacinth,Grasses	Acacia	Water hyacinth	Papyrus, Grasses, Shrubs
36,34334	-0,82582	10:58 AM	Light winds	100x200	Papyrus, Water hyacinth, Acacia	Papyrus	Water hyacinth	Acacia
36,35447	-0,82909	11:13 AM	Light winds	50x200	Papyrus, Water hyacinth, Grasses, Shrubs, Trees	Water hyacinth	Shrubs	Trees, Grasses
36,38518	-0,81227	11:48 AM	Light winds	100x100	Papyrus, Water hyacinth, Shrubs, Grasses	Acacia	Acacia	Shrubs
36,40636	-0,78822	12:45 PM	Light winds	200x500	Water hyacinth, Shrubs, Acacia, Crops	Grasses	Acacia	Crops, Shrubs

Table 2: Data of all field points sampled on 10th March 2017

Longitude X	Latitude Y	Elevation	Dominant	2nd dominant	3rd dominant
36.298530	-0.816510	1891	water hyacinth	acacia	
36.293480	-0.811830	1892	water hyacinth	papyrus	acacia, grass, shrubs
36.326070	-0.815410	1897	papyrus	water hyacinth	grass
36.329470	0.816060	1894	papyrus	acacia	Water hyacinth
36.343340	-0.825820	1897	papyrus	water hyacinth	acacia
36.354470	0.829090	1895	Water hyacinth	shrubs	trees, grass
36.344300	-0.783776	0	water	none	none
36.363977	-0.784375	0	water	none	none
36.278112	-0.813795	0	water	none	none
36.340631	-0.715722	0	water	none	none
36.415193	-0.738217	0	water	none	none
36.344523	-0.754991	0	water	none	none
36.408117	-0.815646	0	no data	none	none
36.273967	-0.786363	0	no data	none	none
36.263729	-0.747416	0	no data	none	none
36.402673	-0.833811	0	no data	none	none

Table 3: Data of field points of 10th March 2017 used in accuracy assessment

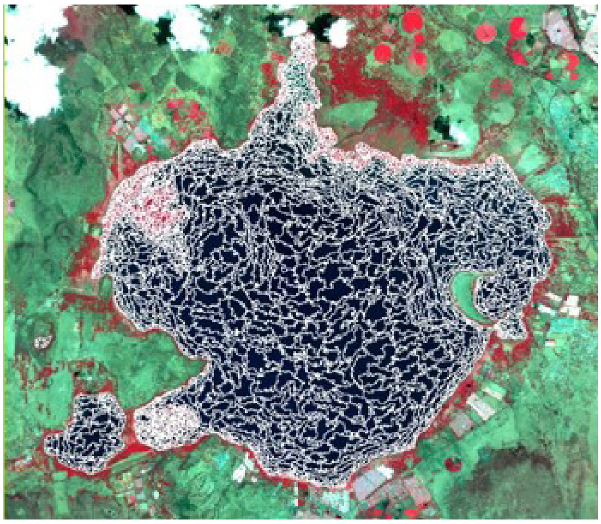

Figure 3: Segments used in the object-oriented classification of macrophytes and invasive weeds in L. Naivasha based on the Sentinel-2 satellite image acquired on 28th February 2017

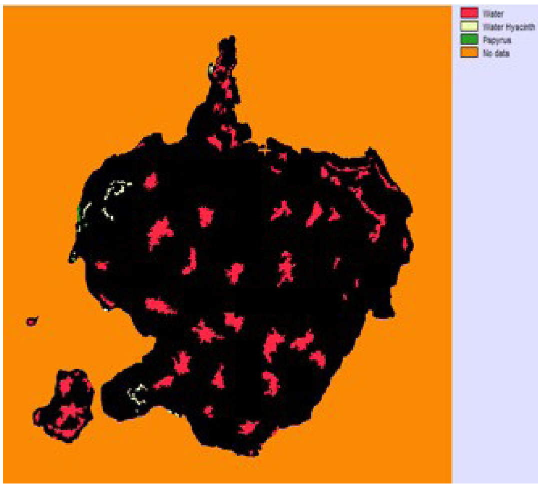

Figure 4: Training sites derived from the Segments for use in object-oriented classification for the Sentinel-2 satellite image of 28th February 2017

Macrophytes distribution

The findings from the study indicate that there are mobile and stationary mats of water hyacinth. In February water hyacinth mats occupied the southern, southwestern, northwestern and northern parts of the lake with the larger percentage located within Oserian Bay and around Korongo. Parts of the weed plants broke away and floated about, finding themselves occupying the north western and northern parts of the lake (crescent and Malewa River mouth) a month later, but they were often returned by diurnal winds to the nearest shoreline within a given sheltered bay. The well-sheltered bays of the south stored most of the weed biomass produced. During the survey a permanent strip of the water hyacinth along the southern shoreline was observed. Papyrus was also permanently distributed along the northern and northwestern shoreline part of the lake, near Korongo and Malewa (Figure. 5).

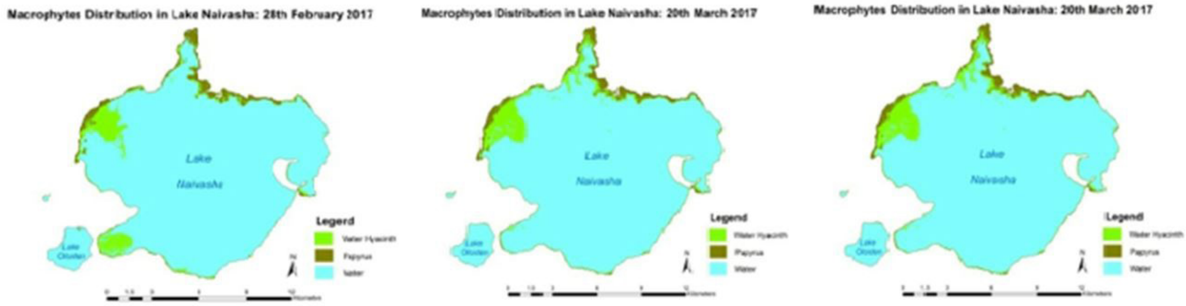

Figure 5: Location and distribution macrophytes and invasive species on Lake Naivasha

Macrophytes coverage

The findings from the study indicate that water hyacinth coverage has increased significantly in terms of location / distribution coverage from 9.4 Km^2 in February 2017 to 14.8 Km^2 in March 30th 2017. Stationary weed mats were also observed along the shoreline, expanding beyond the sheltered bays of Oserian, Crescent and Korongo, while the area covered by papyrus increased slightly from 5.7 Km^2 in February 2017 to 5.9 Km^2 on March 2017 before decreasing back to 5.7 Km^2 on March 30th 2017 (Figure 6).

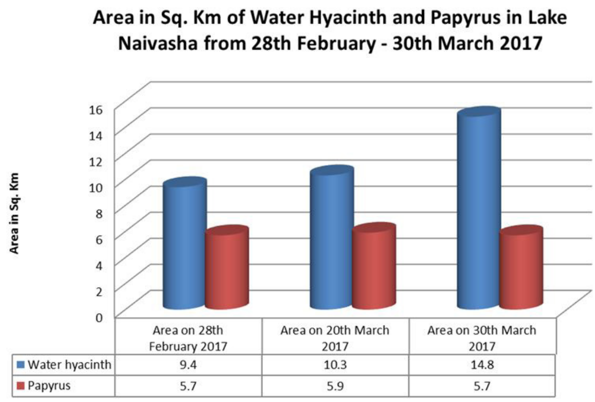

Figure 6: Area of water hyacinth and papyrus in Lake Naivasha on 28th February, 20th& 30th March 2017

Discussion

The overall findings of the study indicate that the coverage of papyrus is increasing significantly both in location and distribution. This could be attributed to intense clearing of papyrus vegetation for construction of jetties, cultivation and extensive trampling by herds of cows, buffaloes etc (per observation).

Studies have shown that extensive swamps, reefs and floating islands of Papyrus existed in Lake Naivasha until the 1980s, with lagoons of the submerged aquatic plants *Potamogeton spp., N. horrida, C. demersum* and the macro-algae *Chara spp*. under 'carperts' of floating-leaved N. anouchalii (Water Lilies) [5, 28]. From 1983 to 1987 the water level dropped by 3m and much of the papyrus was cleared, with only 2 km^2 left in 1987 [28]. However in 1988, the lake water level rose by 1m and seedlings of papyrus re-established resulting in a 12 km^2 expanse of papyrus on the lake, with 80-90% of the lake periphery lined with the species. The previously dominant Papyrus reduced significantly from 2600 ha in 1988 due to a decline in lake water levels, anthropogenic activities and extensive trampling by herds of *Syncerus caler* (Buffalo) to 1160 ha in 2017 [29]. In general, papyrus left on dry ground by a receding lake dries up, but if that area is re-flooded the papyrus regeneration can be swift. However sudden rise in lake level can also 'kill' papyrus by "drowning" the rooted areas.

Water hyacinth *Eichhornia crassipes* on the other hand is seen to be dynamic both in terms of coverage and distribution, generally increasing from 9.4 Km^2 on 28th February to 14.8 Km^2 on 30th March 2017 (Figure 6). The rapid spread of water hyacinth around the shores of Lake Naivasha seems to have been facilitated by a combination of wind patterns including the diurnal land and sea breeze; various local winds and water currents and nutrients enrichment (eutrophication).

The Water hyacinth (*Eichhornia crassipes*) that was first recorded in Lake Naivasha in 1988, where it occurred in protected bays and estuaries did not spread throughout the lake due to unfavourable water conditions then [5]. Currently, the water hyacinth covers about a third of the lake, exerting considerable influence on the ecology and water chemistry. Nutrients especially phosphorus are known to drive proliferation of water weeds [30]. Indeed it is often said that the appearance of the water weed especially water hyacinth in a water system is an indication of enrichment with nutrients. Attempts should be made to understand the link between environmental factors especially the main limiting nutrients and the proliferation of water hyacinth in the Lake Naivasha basin.

Conclusion

The present findings show that the lakes' water surface has been filled in their place by exotic aliens; first *Salvinia molesta* (Floating Water Fern), *Eichhornia crassipes* (Water Hyacinth) and many semi-aquatic species of grasses and sedges. However, in view of the relatively limited quantity and distribution of the species of grasses, Nile cabbage and *S. molesta* which in most cases were subdued by the reflectance of water hyacinth, and considering the limitations occasioned by the spatial resolution of Sentinel-2 (10m), the species of grasses were not mappable, even though these were observed in the field. Therefore, there is a need to employ the use of higher resolution satellite images such as the Quickbird to enable isolation and mapping of all macrophytes currently found on the Lake surface. Furthermore, research to identify sources, routes and dynamics of the essential nutrients that trigger macrophyte regeneration is essential to the formulation of the sustainable nutrient management strategies. Early warning surveillance mechanisms for the possible resurgence or invasion of the water hyacinth and other water weeds need to be developed through public private partnerships. There is need for continuous monitoring of the invasive water plants to be able to determine their impact on the fishery and other resources of Lake Naivasha. There is need to understand the dynamics of the water hyacinth infestation; its distribution, proliferation and impact modalities and the development and implementation of appropriate weed control strategies and options. Studies on the environmental factors that trigger the resurgence of the water hyacinth and other weeds be undertaken as key to improved management practises upstream and downstream.

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Data Availability Statement

All datasets generated or analysed during this study are included in this published article and are available from the corresponding authors on reasonable request.

Disclosure

The authors declare there is no conflict of interest regarding the publication of this paper.

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