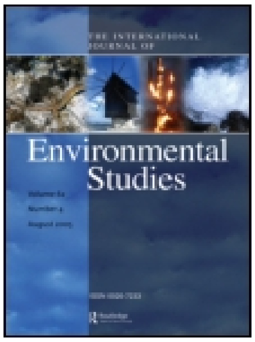

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Dynamism and abundance of water hyacinth in the Winam Gulf of Lake Victoria: evidence from remote sensing and seasonal-climate data

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Aquatic plant infestations impede lake traffic through navigable waterways, block ports and passenger ferry terminals. Timely, accurate information on aquatic plant dynamism, distributions and density is required both by public agencies and by private companies engaged in aquatic plant control efforts and the local population whose economic livelihood depends on the lake. This study combined the interpretation of remote sensing and climatic variability data in understanding the seasonal dynamism and abundance of water hyacinth in Winam Gulf of Lake Victoria. The results showed a direct relationship between the hyacinth geographic and density distribution and seasonal-climatic patterns. Gentle currents, moderate rainfall and modest but stable temperatures propagated the rapid blooming and aggregation of the hyacinth mats especially in the sheltered bays. Relatively high rainfall and high temperatures do not favor the proliferation of the weed; hence disintegration and mobility as the strengths of the currents increase in magnitude.

Keywords: Remote sensing (RS) data; Water hyacinth; Seasonal climate data; Lake Victoria; Winam Gulf

1. Introduction and background

Lake Victoria was invaded by the water hyacinth *Eichhornia crassipes* (Ponteridiaceae) in 1989. Control of this tropical aquatic weed, of South American origin, presents an enormous challenge in the East African region. The weed has disrupted commercial and subsistence fishing and boat transport. It has affected infrastructure facilities including water supply intake points, port facilities and the hydroelectricity power generation plant at Owen Falls, Uganda [1]. The weed is also associated with increased incidences of water-borne diseases. In Lake Victoria, ideal environmental conditions caused by man-made environmental degradation and the lack of biological control agents such as phytophagous insects, mites and microbial pathogens were responsible for rapid growth and spread of the water hyacinth during the last decade. Further details on the origin and evolution can be found in [2,3].

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Unmanaged water hyacinth populations create serious impacts. Effects of the infestations in the region and worldwide are varied and well documented [4–7]. These impacts include: impeding irrigation and drainage water in canals and ditches; hindering navigation; interfering with hydroelectric schemes, increasing sedimentation by trapping silt particles, decreasing human food production in aquatic habitats (fisheries, crops); decreasing the possibilities for washing and bathing; and adversely affecting recreation (swimming, water-skiing, angling) [3]. Additional effects include hindering the processing and delivery of municipal and industrial water supplies, threatening structures such as low bridges and pipelines, creation/aggravation of human health hazards (harboring bilharzia, venomous snakes, and possibly cholera), the transformation of aquatic habitats into wetland or terrestrial habitats through succession by other plant species, and displacement of native flora and fauna not able to compete or survive in infested environments. With the increasing threat to the lake the water supply continues to dwindle. Without detailed and proper studies of water ecological systems and climate changes for conservation-management-action-plan purposes, Kenya faces a ‘dark water’ future.

*1.1. Water hyacinth (*Eichhornia crassipes*)*

The aquatic weed, water hyacinth is an erect, free-floating, stoloniferous, perennial herb. It grows to 1 m in height with buoyant leaves, which vary in size according to growth conditions. Figure 1 shows water hyacinth in Lake Victoria. Besides being bio-indicators of pollution, they efficiently remove minerals from the sediment nutrient pool and thus assist in pollution abatement, by acting as nutrient pumps and serving as biological sinks. Water hyacinth propagates and multiplies vegetatively; vegetative propagation is rapid. Two plants of water hyacinth could multiply to 120,000 in 120 days, while 30 offspring could be

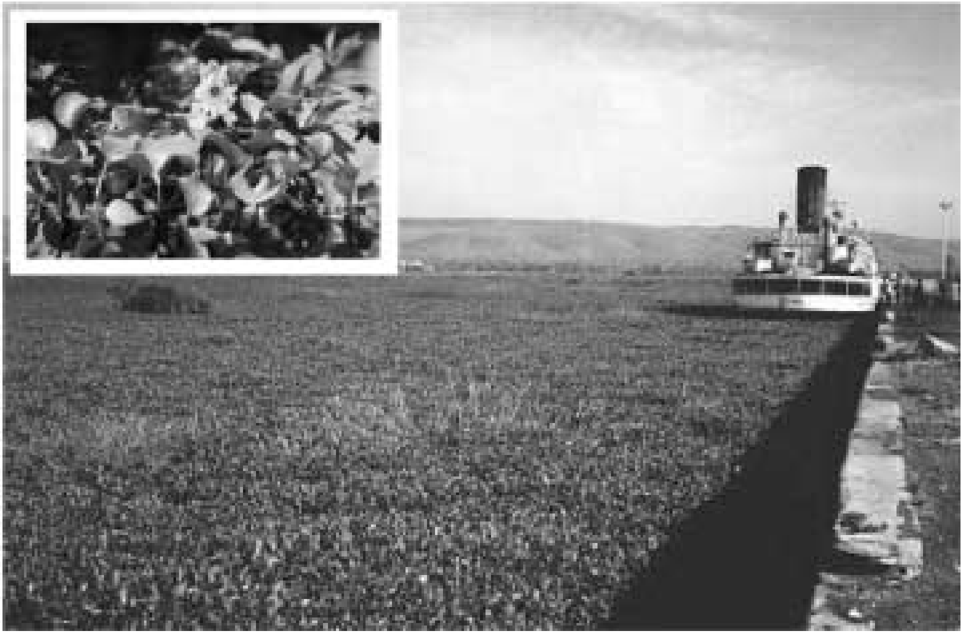

Figure 1. Water hyacinth blocking the port of Kisumu. Inset is a photograph of water hyacinth plant.

produced from two parent plants within 23 days. The rate of organic-matter production by water hyacinth is so high that the dead organic matter accumulates in the water body. The rate of decomposition of dead plants depends on the water quality. The hyacinth takes nutrients from minerals dissolved in the water, the principal nutrients being nitrates, phosphates and potassium, which are available as pesticides from agricultural run-off, sewage and industrial effluent.

In Figure 1, the steamer cannot move due to the blockage by the dense hyacinth mat around the Kisumu bay, which is also one of the most economically significant ports in the East African region. During this period, all transport services were stalled or alternatives methods had to be sort, e.g. using smaller boats to dock on shallower and non-infested water hyacinth areas. Interestingly, the distribution and location of the water hyacinth can be predicted based on seasonal climatic variations. That is, high and low concentrations are observable in particular geographic locations and specific seasons/moths of the year if they are not mechanically or otherwise removed. Thus observed climatic and quantified hyacinth distributions via satellite data can be correlated to understand the seasonal-climatic dynamisms, and subsequently derive information system for advising the stakeholders: transportation, lake management and fishing industries. During the survey, dwellers of riparian communities also pointed to many social, health and economic problems resulting from water-hyacinth infestations. These include emigration of fishers to other water bodies, difficulties in accessing riverbanks, protein deficiency resulting from the unavailability of fish, and obstruction of boat and sites where fishing boats land and unload fish. Perennial water shortages continue to affect Kisumu city as all the intake points have been blocked by the weed. A further point is that the local people – the Luo – are traditionally fish eaters.

1.2. Water hyacinth distribution patterns – a RS perspective

Obtaining information on the distribution and extent of water hyacinth is crucial in order to understand the evolution of the invasion, to determine affected areas, to relate water hyacinth abundance with environmental parameters and to gauge the efficacy of control measures and management actions. The two primary objectives of a monitoring program are to: (1) assess the suitability of monitoring tools, including remote sensing and geographic information systems (GIS), within the riparian regions; and (2) apply these tools to document the invasion of water hyacinth in terms of distribution and extent in Lake Victoria, focusing more so on the inherently ‘hot-spots’. The goal of this study is to provide a survey of the qualitative and spatially explicit information on the distribution and extent of water hyacinth in Lake Victoria over a 12-month’s period and analyze this information in relation to potentially influential seasonal-climatic factors, based on quick view 30 m resolution Landsat data (http://edcsns17.cr.usgs.gov/EarthExplorer/) and actual Landsat imagery of the scene acquired in 2003.

Aerial photographs are the most commonly used form of remote sensing data collection for mapping aquatic vegetation [9], although other kinds, such as satellite, video and airborne multispectral scanner data, have also been widely used [10–16]. The advantages of aerial photography is related to its good spatial resolution and flexible data acquisition. One disadvantage is the poor spectral resolution, especially compared to a airborne multispectral scanner data [17]; another is that aerial photographs contain considerable brightness variations caused by light falloff effects and bi-directional effects [17]. On the other hand, methods for correcting these effects in frame format data have been developed further than those for airborne scanner data, for instance. The causes of brightness variations, their effects and the available correction methods are presented in detail in [18–20]. Remote sensing studies have indicated that aquatic vegetation yields spectrally distinct signals governed by the density of the vegetation, the openness of the canopy and the amounts, forms and orientations of the leaves [21–25]. Multitemporal remote sensing data can provide valuable information on changes that have taken place in a given area. [10,11,16] for example, detected changes in wetlands and areas of aquatic vegetation with the aid of remote sensing data.

While aerial photography and remotely sensed imagery have been used to map and monitor seasonal and yearly changes in the *extent* of aquatic plant cover [23,26–29], few studies have attempted to address quantitative estimation of aquatic plant cover based on spectral reflectance [30,31]. By calibrating remotely sensed multispectral data with ground measurements of cover, density, biomass or leaf area, vegetation condition measured at sample points can be then extrapolated across a large geographic region [10,30]. Traditional field-based mapping and monitoring of the extent and density of aquatic plant infestation present several challenges:

(1) Areas may be inaccessible to field sampling: dense mats of vegetation can block boat access, and aquatic plant infestations can cover large geographic areas, necessitating extensive travel to ensure adequate sampling.
(2) Rapid changes in aquatic plant extent and density: invasive aquatic plants species typically have high growth rates. Water hyacinth, for example, can double its biomass and number of plants within six to 12 days. Extensive mats of vegetation are often free-floating, and can change position rapidly owing to currents or wind action.
(3) Seasonal and inter-annual changes: the extent and density of aquatic plant infestations can rapidly change within a growing season and from year to year as a result of high growth rates, movement of vegetation mats, and effects of weather on plant growth rates.

1.3. Research aim

Given the limitations of traditional methods of assessment, coupled with the wide geographic distribution of the aquatic plant infestation problem (affecting water-based transportation in numerous states and countries) and the need for up-to-date information on aquatic plant distribution and density, the objective of this project is to develop a strategy for mapping and monitoring the aquatic plant in the Lake Victoria over a 12-month period as a means of developing an early warning system based on seasonal-climatic indicators. In the present study an attempt has been made to use satellite remote-sensing images to identify the area of water body covered by water hyacinth. Our objective in this phase of the study is to demonstrate the capability of time-series satellite image analysis, particularly that from medium spatial resolution (30 m) Landsat data to record the seasonal patterns of spatial distribution (spatio-temporal) of water hyacinth. The advantage of Landsat data series is that it acquired twice a month for the same scene and with its 15m panchromatic band (in ETM+) much better spatial resolution can be achieved via data fusion methods.

Most studies have concentrated on using remote sensing data for mapping the water hyacinth abundance (area coverage) in Lake Victoria (e.g. CLEAN LAKES Inc. [http://www.cleanlake.com/]; USGS [http://edcintl.cr.usgs.gov/waterhyacinth2.html]). Others have concentrated on the impacts of the water hyacinth on the lake water quality (LVEMP publications [www.lvemp.org/Kenya.htm]). Our present study focuses on the integration of climatic factors with remote sensing data observations in explaining the dynamism of water hyacinth spatial–temporal distribution and concentration in the Winam Gulf of the Lake Victoria from 2000 to 2004.

2. Study site, data and materials

Lake Victoria with an area of 68,800 km^2 is the second largest freshwater lake in the world. The lake is shared between Kenya, Uganda and Tanzania (figure 2) in the ratios 6, 45 and 49% of the surface area, respectively. It is thus an international water body. It stretches 412 km from north to south between 0° 30′ N and 3° 12′ S and 355 km from west to east between 31° 37′ and 34° 53′ E. It lies across the equator at an altitude of 1135 m above sea level. The lake is relatively shallow, with a recorded maximum depth of about 80 m and an average depth of 40 m. It has a water volume of about 2760 km^3. It has a long (about 3500 km) indented shoreline, enclosing innumerable small, shallow bays and inlets. It contains numerous islands [32]. The Winam Gulf, which is the study area (Kenyan portion of Lake Victoria), is shown in figure 3.

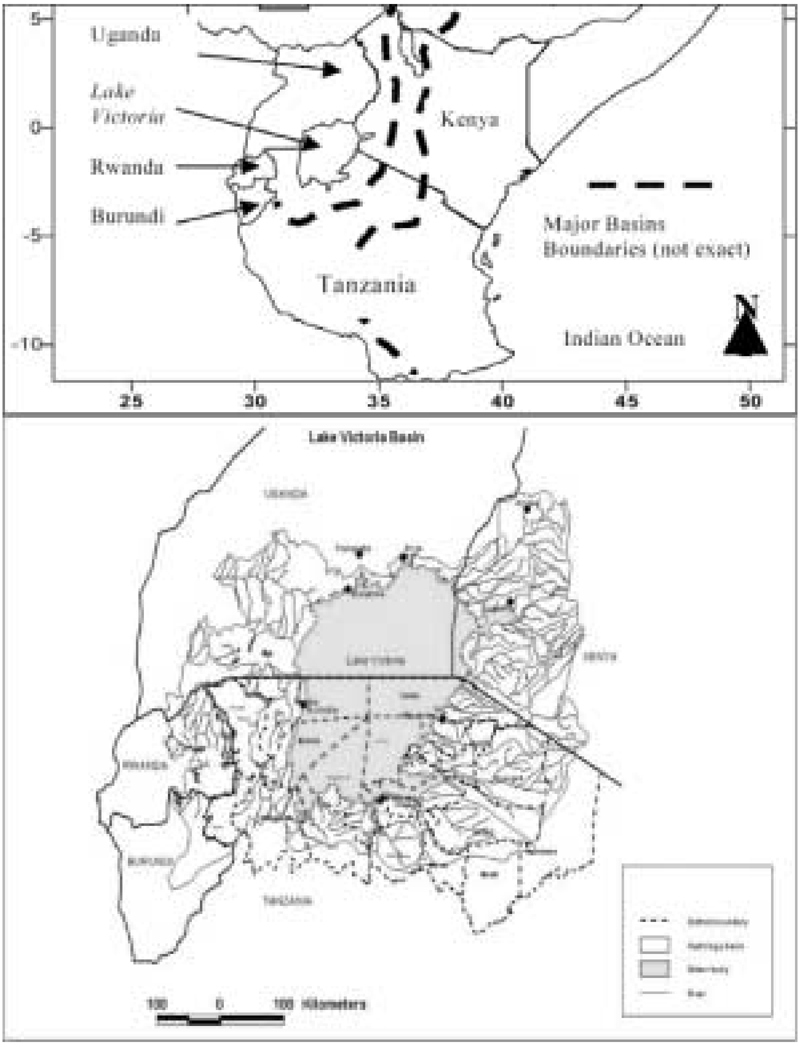

Figure 2. Map showing division of Lake Victoria among the riparian countries and the Lake Victoria and its basin.

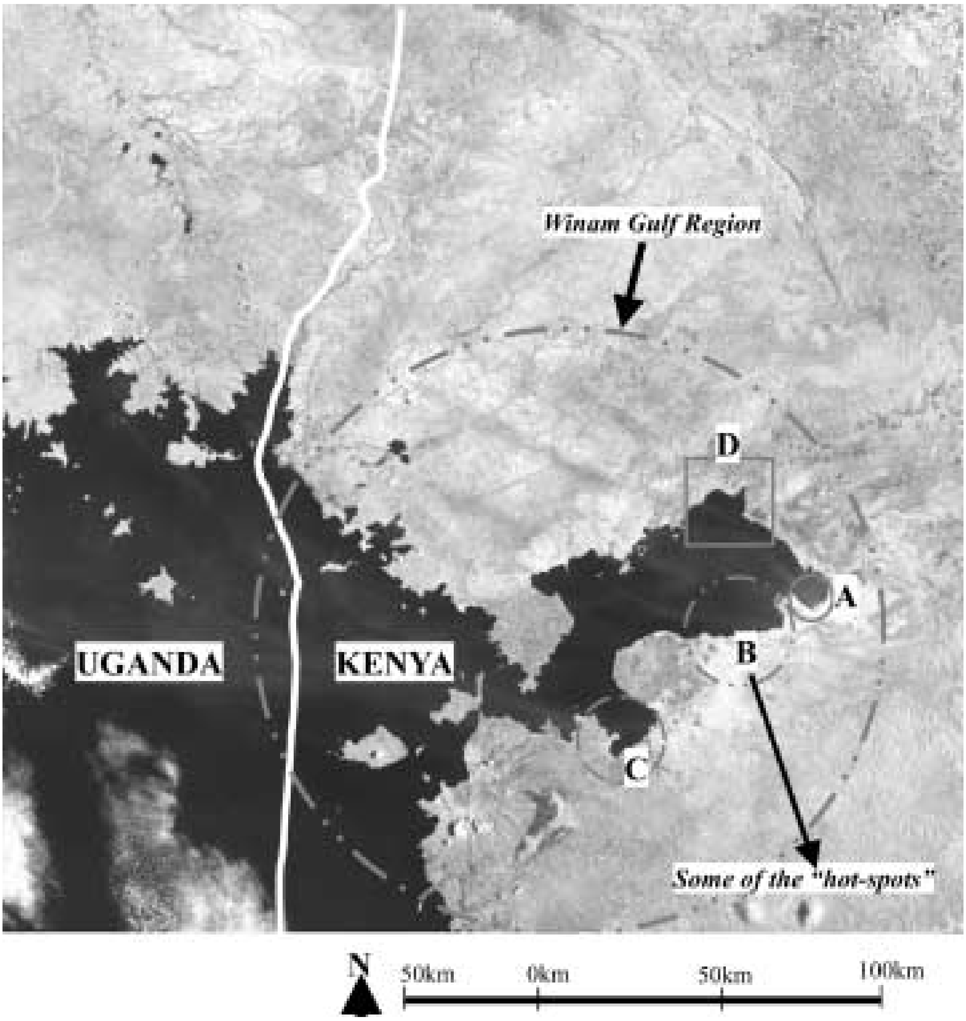

Figure 3. Location of Winam Gulf in Kenya on 2000-Landsat ETM+ – path 170, row 060. The sections correspond to: (A) Nyakach Bay; (B) Kendu and Osodo Bay; (C) Homa Bay; and (D) Kisumu Bay.

The data used are divided into two: first is the multitemporal satellite data from Landsat quick view images (USGS), only for visual interpretation. The data selected for the visual study span from 2000–2004 (5 year duration). For actual image processing and quantification, Landsat ETM+ data of 2003 and 1:50,000 topographic maps of the study area were used. Because of poor weather conditions at the time of satellite sensor observation, some scenes were not suitable for analysis. Figure 3 shows the Winam Gulf on 2000 March with the some of the 'hot-spots' highlighted for this research. The second data type integrated with the remote sensing data for analysis is the climatic data taken at specific months as seasonal representatives. The climatic data included wind and current spends, temperature and rainfall on the lake, in 2003.

In order to obtain comprehensive season-climate investigations, we chose three strategically located months of the year 2003 (March, July and November). These are the months within which we conducted field surveys and *in situ* measurements such as wind and current speed measurements over and within the lake. Ideally, the seasons can be grouped into the following months: DJF (December, January, February); MAM (March, April, May); JJA (June, July, August); SON (September, October, November). However, the three real climatic seasons are wet (rainy) and dry (very minimal rain) and an in-between scenario. These three seasons are best reflected in March, July and November. For purposes of this study we divide or name the seasons as: season 1, season 2 and season 3, respectively.

3. Methodology

The methodology is summarized in figure 4. The first step involved the field reconnaissance to ascertain/identify and map the water hyacinth 'hot-spots'. These regions are infested annually; but the climatic reasons for the abundance in these regions have not been studied in detail. Of course there are many other areas infested, but we concentrated on the areas with consistency and large mats of water hyacinth e.g. harbor/bay areas. The next phase involved the measurement of: (1) average current and wind speeds of and over the lake; (2) temperature; and (3) rainfall at different stations of the 'hot-spots'. Most of the climatic data like rainfall were only verified from the local municipality/district meteorological offices (Kenya Marine Authority and Kisumu Municipality). The final phase of the methodology involved the quantitative analysis of the three data sets viz: RS data and climatic aspects in relation to the spatio-temporal dynamism of water hyacinth in this region of the lake.

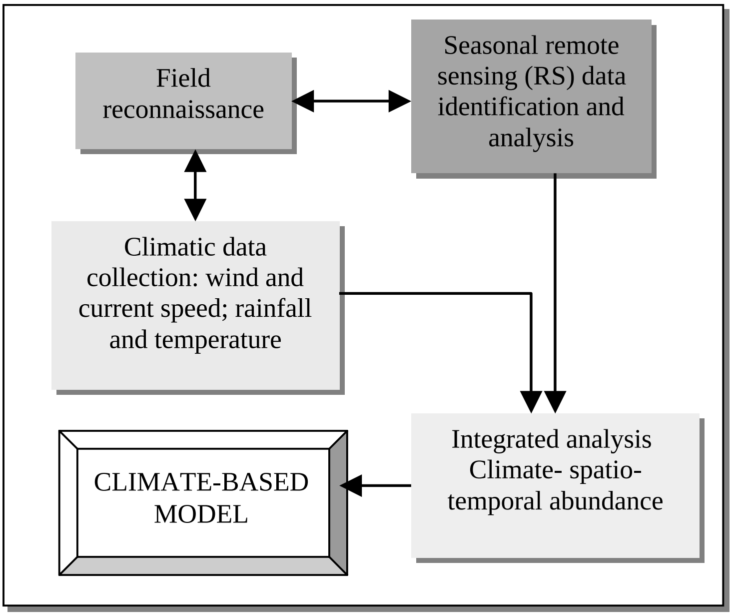

Figure 4. Research framework.

3.1. Water hyacinth identification on RS data

In order to quantify the availability of hyacinth on RS data, we first of all delineated the Winam Gulf region from the 1:50,000 map via digitization. This was then geo-referenced to the UTM-Zone 37 projection system to form a vector map. The most clear (cloudless) representative Landsat images for 2003 were used to assess the amount and distribution of water hyacinth. The images were subset using the vector map.

For mapping and quantifying the hyacinth, unsupervised ISODATA (Iterative Self-Organizing Data Analysis Technique) clustering (ERDAS Imagine software) was used to separate hyacinth and water. The objective of unsupervised classification is to determine the naturally existing spectral clusters within a scene. Since we do not know *a priori* all that may be within the scene, setting the minimum and maximum possible class numbers made unsupervised classification a good choice. The applied classification detects clusters of pixels in feature space and categorizes the pixels to the clusters based on the minimum distance criterion. For that purpose the ISODATA algorithm was used. With this approach, the optimal number of spectral clusters is automatically determined by iteratively applying split and merge operations while performing the following steps:

(1) A number of parameters have to be initialized by the operator. These parameters are the desired number of clusters, the minimum number of iterations, the minimum number of pixels in a cluster, the minimum standard deviation to initiate cluster splitting, and the maximum distance in feature space between cluster centers to initiate cluster merging.
(2) Each pixel is assigned to one of the predefined clusters by a minimum distance criterion.
(3) All clusters containing fewer members than a predefined number of pixels are eliminated.
(4) New cluster centers are computed from the pixels assigned in step (2).
(5) Aggregated clusters are split, if the standard deviation is larger than the specified threshold. Neighboring clusters are merged, if the pair wise distance is smaller than a predefined parameter and if the maximum specified number of clusters has not been reached.
(6) The algorithm is terminated, if the maximum number of iterations is reached, else it is continued with step (2).

For computational reasons, only a certain percentage of pixels (for example only the pixels of each 10th row and column) are used for cluster formation in step (2). After the stop criterion is reached, the detected cluster centers are used to classify the entire image based on the minimum distance criterion. Finally, the feature classes are interpreted and combined to realistic thematic classes or object classes in an interactive step. The results of the ISODATA algorithm of course depend on the quality of the input data. If the data in feature space is distributed in almost isolated natural groups, these clusters can be detected very reliably. Using 10 clusters and six iterations, two of the classes were combined to determine water hyacinth class while the rest were combined via the class combine module, into water only class. The results for the classified imagery are presented in figure 5. These were supported visually interpreted USGS-quickview multitemporal data.

The following observations were made:

(1) In the first season (represented by March), a consistent concentration of water hyacinth along the western banks of the lake is observed (regions A and D). This season manifested the least quantity of water hyacinth during all the three seasons as seen in figures 5(a), 5(b) and 5(c).

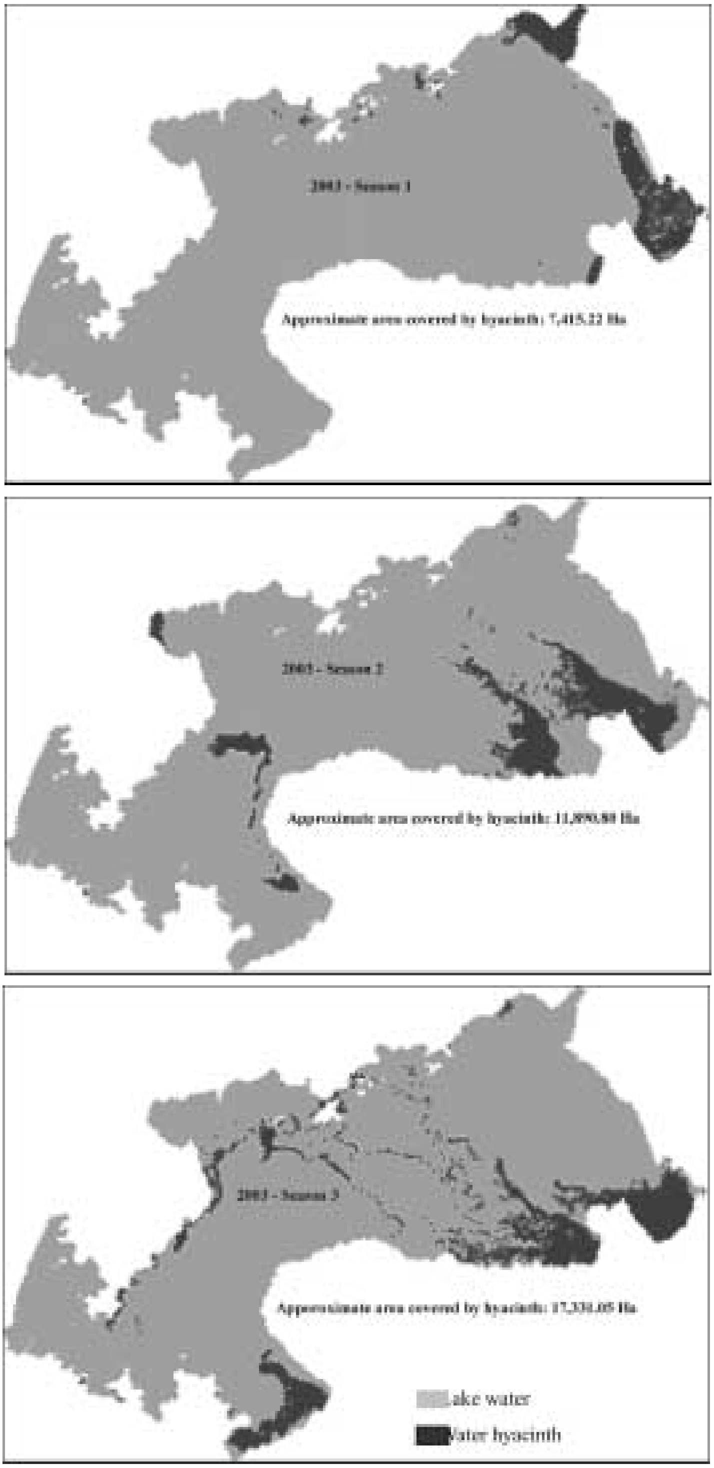

Figure 5. Distribution and quantification of water hyacinth represented over three seasons. The very dark areas represent the water hyacinth: (a)–(c) seasons 1—3, respectively.

(2) In the second season, the quantity observed had increased by nearly 4450 ha compared to season 1. The geographic locations had also shifted evidently in the easterly direction i.e. from regions A and D towards B and C.
(3) The third season registered the highest quantity of the weed, more than twice that in the first season. It is clear that the motion that was offset by the currents in season 2 is now settled at strategic positions in season 3. The mats have moved farthest east, multiplied and settled. Those that were not swept by the currents due to their being at sheltered positions are still in their season 1 positions.

From the three seasons observations, the best trend can be seen in 'hot-spot' zones A, B and C. D is a harbor, and here as such the hyacinth is constantly removed. We have observed that as the seasons changes (in months increasingly) every year, the shift tends towards the western sides after around the month of March, which is after season 1. There is also evidence of disintegration of the mats in the process. Towards the end of the year, around October/November, there is observed slow re-integration (aggregation) and rapid bloom, such that by March of the next year a peak at the same geographic location is observed. In between, season 2, mobile disintegrated concentrations are observed to the western sides. This is a kind of *reverse backward–forward* mobility. We conclude from the analysis of the multitemporal satellite data that apart from the widely researched hyacinth–water quality impacts and human induced influences on the hyacinth distribution and dynamism, other factors like seasonal climatic variations are also very strong contributors. Man-induced effects are mostly localized i.e. industrial disposals and other pollutants. These will not create a seasonal mobility kind of circle observed in the multitemporal satellite imagery.

3.2. Climatic factors

In this section we present the results from surveys and meteorological data collected from different public authorities within the region. Regional climatic factors dictate the local climatic conditions, especially in a local active region such as Lake Victoria. The impacts of climate changes on the hyacinth dynamism are of paramount interest even if nothing can be done to control the climatic conditions and whatever their contributions to the proliferation of hyacinth. It is necessary to understand the effects or contributions of climate in the scientific sense and as an early warning system for economic reasons (fishing, transportation etc.).

3.2.1. Local rainfall patterns and water hyacinth distributions. The annual patterns of rainfall and evaporation over Lake Victoria are similar and bimodal. For the study period, the mean annual rainfall total over the lake was at 1176.8 ml depth. In figure 6, we correlate the amount of rainfall and quantity of water hyacinth. Evidently moderate rainfall amounts around season 3 can be said to be most optimal for water hyacinth amounts propagation. Very high and very low rainfall seasons 1 and 2 show a slower proliferation.

The impacts will vary according to the direction and magnitude of precipitation change and the hydrological characteristics of the lacustrine and any associated fluvial system. Endorheic (closed) and exorheic (open) lakes depend on the balance of inflows and evaporation and may be very sensitive to change in either. Increases in precipitation, unless offset by higher evaporation, will increase lake inflows and lake levels, if extreme precipitation events increase in frequency this will lead to greater frequency of riparian flooding. The extent to which lake level fluctuations and change affect lake productivity and biodiversity varies according to local conditions of the lake and its catchment. Drier conditions, exacerbated by

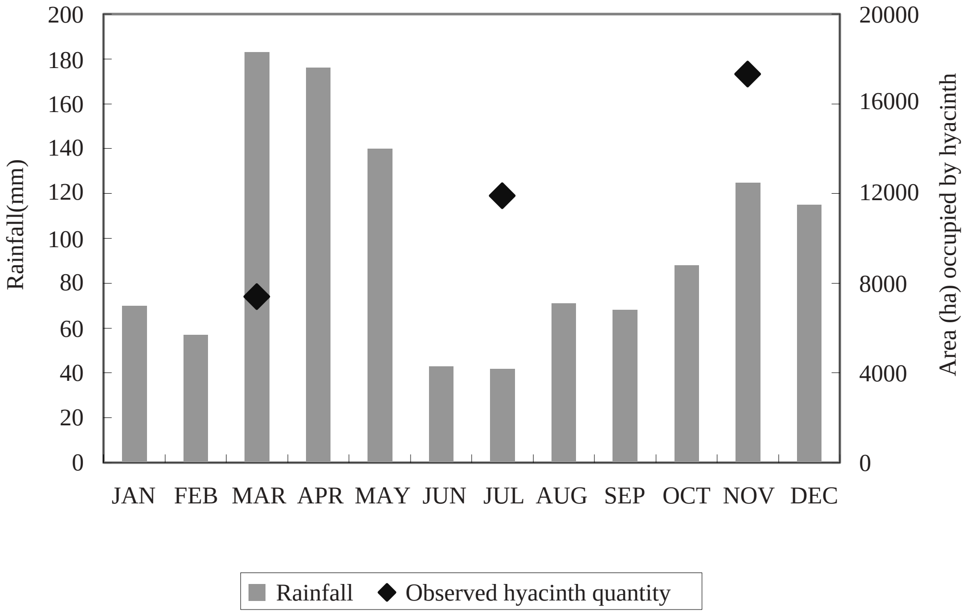

Figure 6. Monthly rainfall and seasonal hyacinth amount estimates.

greater evaporation, will reduce lake inflows and lake levels. Water quality, productivity and biodiversity are likely to be reduced.

3.2.2. Lake depth–temperature profile. We divided the studied 30 m depth into three bands as D1 (0–7 m), D2 (7–15 m) and D3 (15–30 m), figure 7 and defined the surface (0 m) to around 1.5 m below the surface as the critical depth band. The critical depth band is where the lake weed directly derives its nutrients. Temperature measurements, based on depth profile, were taken with the results shown in figure 7. It is observed that below 15 m, the temperatures were nearly within the same range. But, above 15 m (shallower), disparity in the months starts to be evident.

For the month of November, the temperatures were near stable ranging 30–10 m. Small changes are observed between 10–6 m. A large shift of about 0.5°C was noted between the 6 m and 5 m range. Then stability with less than a 0.1° C change was observed between the lake surface and water at 5 m. The stability phenomenon observed in the SON season indicates that steady and consistent activity can be achieved, i.e. accumulation of nutrients and propelling of the re-aggregation and multiplication process of the hyacinth mats, particularly so in strategic positions of the lake. A maximum of about 26.7°C was observed in November and a minimum of approximately 26.1°C.

A more dramatic change in temperature was observed between July and March as compared to November, especially the D1 depth band. In July, from 10 to 3 m, a near stable temperature average of 26.4°C was observed. This suddenly increases by 0.2°C within 1 m depth difference (2–3m) and by 0.7°C between 1–2 m depth range and stable at the 0–1m depth. In July the most sensitive depths are not very dynamic, in fact stable between 0–1.5 m just as was found November, but very unstable between 1.5–3.0 m. So far July was observed

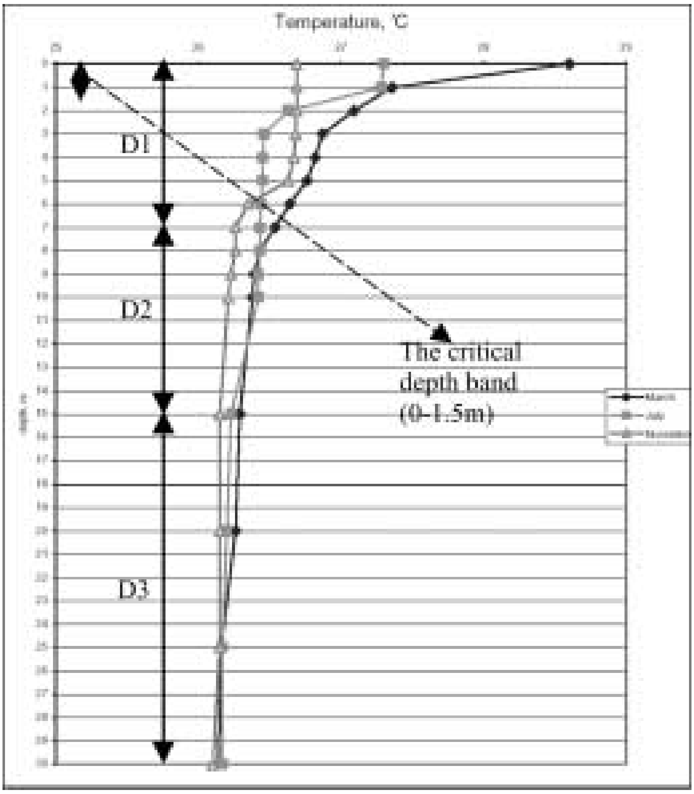

Figure 7. Depth–temperature profile of Lake Victoria.

to be warmer than November on average. In March, a steady rise in temperature with decreasing depth is noted from 10 m (26.3°C) to 1 m (27.4°C); jumping to 28.6°C on the surface. The three bands D1, D2 and D3 exhibit the most radical temperature shifts, with the most radical in the first band (D1). The critical question here is the meaning of the temperature variations for the dynamism and proliferation of the hyacinth in the 0–1.5 m critical zone. We seek to understand this in comparison with other fundamental climatic variables.

3.2.3. Lake wind and current speeds and their directions. Current speeds refer to the average lake water motion (waves). The most significant depth speed is near the surface (0–2 m). The wind speeds are the average air speeds and they influence not only the current speeds, but also the mobility of the hyacinth on the lake. Since the hyacinth floats on water, current and wind directions and their magnitude (vector) directly influence their location in a given season. In March, the lowest current and wind speeds of 8.5 and 12.2 m/s are recorded (figure 8). In July, the current and wind speed increases to 12.1 and 14.3 m/s, respectively. November registered the strongest speeds of 17.6 m/s wind speed versus 13.2 cm/s current speed.

While the speeds change, the directions they take dictate their contributions and influences. At the time of sampling in March, a surface current towards the southeast was observed and a northwesterly wind. In July, current was towards southwest and a northeasterly wind was observed. A similar surface current and wind was observed in November.

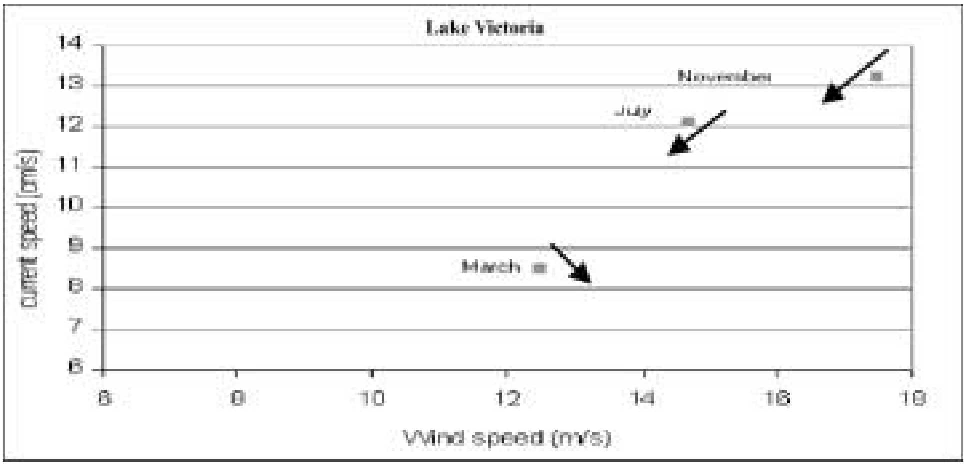

Figure 8. Average surface current and wind speed. The arrows show the current directions.

Current and wind direction corresponded with the general westerly and easterly winds characteristic for the climatic (rainy and dry periods) season in the Winam Gulf water catchment. The strongest/highest speeds were observed in November (SON season). This probably accelerates growth of the hyacinth, resulting in disintegration and spread over the direction of the currents, as compared to the relatively calmer MAM seasons.

3.2.4. Temperature–precipitation interaction. A direct qualitative and quantitative relationship can be derived from the precipitation–temperature interaction as shown in figure 9, for the two extreme climatic seasons, DJF and JJA. For the DJF period, the trend is such that higher rates (increase) of the temperature changes depict lower rates of precipitation changes.

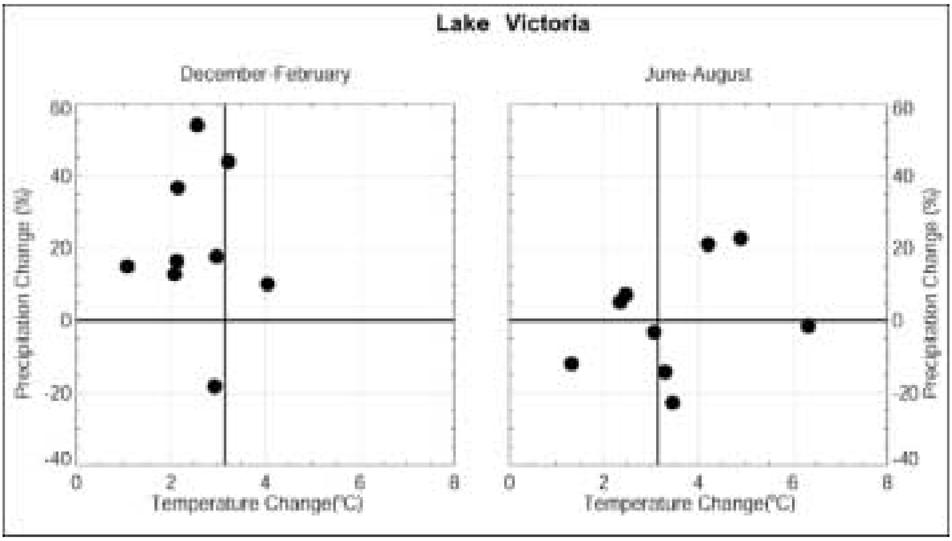

Figure 9. Temperature–precipitation change interaction.

Between 1–3°C, the precipitation increases by between 15–55%. This season shows high rainfall with generally low precipitation changes.

In the June–August season, a temperature change of between 1–3°C reflects a negative (decrease) in precipitation changes. The water temperature change range in June–August is wider than that found in the December–February range. Thus higher precipitation rates above 10% of increase are observed in December–February and mostly negative percentages in the June–August.

Rising air temperatures will increase surface water temperature and influence thermal stratification in lakes. Warmer 'winters' may affect mixing and nutrient-recycling rates in temperate lakes as reduced seasonal cooling, which causes breakdown in the thermal density contrast, may be reduced. Higher frequency of extreme temperatures in 'summer' (with possible exceeding of critical thresholds) and reduced winter freezing in certain lakes are likely to affect thermal stratification and species composition. Higher surface air and water temperatures will increase open water evaporation rates and lead to a fall in lake levels unless offset by increases in precipitation or changes in other factors that affect evaporation rates. These changes impact on the lake's ecosystem.

4. Results and discussions

In order to characterize the functioning of the lake's ecosystem, it is essential to study the lake's physical limnology, including the large-scale movement of water both horizontally and vertically. This is especially important since the nutrients in the surface waters (where the light and thus photosynthesizing plankton are) are insufficient for maximum primary production. The nutrient concentration increases with depth, and water temperature decreases with depth. Thus primary production will be maximized when cold nutrient rich water from the metalimnion layer is brought upwards to mix with warmer, phytoplankton rich surface waters of the epilimnion; either in large-scale upwelling events or during periods where the lake surface temperature is close to that of the deeper waters, and thus the thermal barrier to mixing is minimized.

Combining the geographic location mobility knowledge derived from satellite imagery with the observed climatic variations, we have observed the following seasonal–climatic variations:

(1) The distribution of the weed on the lake depends on various factors such as the variations in the different positions of the lake, physical features of the various bays and location vis-à-vis wind activity (southeasterly and northeasterly), the local and diurnal land and lake breezes, among others.

(2) By distribution classes, the weeds were of two groups; resident and mobile mats (not an ecotype taxonomy). Resident hyacinth, as can be seen in part of region A, occurred in sheltered shallow bays of the various wetland ecotones. Mobile water hyacinth existed in a variety of mat sizes, from solitary plants to huge concentrations tossed about the waves by diurnal and seasonal winds. These mats could be lodged or dismantled anywhere along the shoreline by wind.

(3) The convoluted formation of some portions of Lake Victoria's shores enabled the weed to establish itself easily both in the littoral and sub-littoral zones. The 'hot-spots' are predominantly shallow, sheltered and mostly papyrus-fringed bays and inlets. These provided shelters for rapid growth with minimal interruption from winds and currents (e.g. regions A and C).

(4) The hyacinth can increase the drag of the wind and thereby increase the current. If the wind blows over a long period of time and is blowing towards the shore, it can push the plant into a dense mass. When the water hyacinth cannot move anymore, the wind blows over the hyacinth with very little drag on the water and the current reduces. On the other hand, if the wind is blowing towards the main lake, it can increase the current speed.

(5) In the season 1 observations, corresponding to DJF season, the satellite imagery mapped the high bloom and aggregation of large mats of the weed in the easterly end of the lake (regions A and D). The highest rainfall characterized this period, highest lake surface temperatures, high rates of changes in precipitation against low temperature changes and sharp temperatures changes within the critical depth. This season shows the least quantity of hyacinth. This is apparently because the high rainfall and highly unstable temperatures in the critical depth in this season do not provoke the blooming of water hyacinth. Due to the slow current speeds during this season, and the fact that the hyacinth concentrate in the eastern sheltered parts of the lake, it is concluded that currents are only significant in this season in concentrating the weed to the east.

(6) In the season 2 observations, the lowest rainfall is recorded, moderate temperatures that are lower than those of season-1 are observed, the winds move fairly faster in the south westerly direction and increase the water hyacinth mats. It is concluded that all this causes disintegration of the hyacinth mats, and they tend to move quickly in the east-to-west direction. The southwesterly movement is rampant towards the non-sheltered lake portions like from A to B to C. This season reflects the lowest rainfall amounts, medium wind speeds with slightly stable and moderate temperatures. The mats are highly mobile and tend to disintegrate faster. We can conclude that the slightly stable temperatures in the critical depth favor the proliferation of the hyacinth, even though rainfall is lowest.

(7) In season 3, the lowest but stable temperatures are observed with moderate rainfall. The winds and currents are in the same direction as in season 2, but stronger. This condition shifts the mats further southwesterly where they begin to re-integrate, as seen in region A, B and C. Stronger winds/currents also spread the mats further. The change in current speeds, rainfall and temperature as the season nears DJF shifts the randomness to stability. The stable and fair temperatures and medium rainfall favors accelerated growth of the hyacinth mats during this season.

(8) So far the current-winds-rainfall-temperatures all act together to influence the hyacinth dynamism. We can conclude that the rainfall and temperatures directly influence the ecological functioning within the lake, which in turn affects the health status of the hyacinth. The current-wind factor influences the mobility and hence geographic positioning from time-to-time on the lake. Weak mats will be displaced faster if they are not in strategic sheltered shores. The changes in wind/current directions and speeds create a *backward–forward* (southwesterly to southeasterly) mobility within the seasons.

5. Conclusion

Seasonal–climatic data has been shown directly to affect the spatio-temporal dynamics of the water hyacinth in the Winam Gulf of Lake Victoria. Remote sensing data provided useful information on spatial and temporal changes in water hyacinth in Lake Victoria. The use of historical images permitted the assessment of long-term changes of aquatic vegetation even in cases where no field data prior to a lake management project exist. The results show the integrated interpretation and applicability of the remote sensing and climatic data for detecting changes in emergent and floating-leaved aquatic vegetation. This is a useful component of hydrological information system, which can serve as an early warning and planning system for hyacinth management and provide for continuity in the socio-economic activities and benefits of the lake. The concept can be extended to the entire lake so as to derive an overall picture within the riparian countries.

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