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Land Use as a Predictor of Water Hyacinth (Eichhornia crassipes) Presence on the Entebbe Coast of Lake Victoria, Uganda

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SIT Study Abroad

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Abstract

Lake Victoria is shared amongst Tanzania, Kenya, and Uganda and has tremendous ecological, economical, and cultural significance. Within the lake system, there are several problems, including the proliferation of an invasive weed, water hyacinth (*Eichhornia* crassipes). Therefore, this study aims to assess several factors that may correlate with water hyacinth proliferation. The specific objectives are (1) to identify possible correlations of water hyacinth density and land use around Entebbe, Uganda, and (2) to identify annual trends in water hyacinth coverage, to better inform policy and conservation efforts. Entebbe has a coastline of six land cover types: flooded vegetation, trees, grasses, shrub/scrub, crops, and built area. It was hypothesized that coastal areas adjacent to agriculture have a higher density of water hyacinth due to agricultural nutrient runoffs and flooded vegetation and built areas have higher abundances of water hyacinth due to a high amount of waste.

The first specific objective employed a systematic sampling method, counting 41,615 water hyacinth around the coast of Entebbe, and was compared in QGIS with Sentinel-2 land use/land cover satellite imagery. The second specific objective employed remote sensing with a normalized difference vegetation index (NDVI). Twelve eMODIS satellite images were created on QGIS to map the percent coverage of water hyacinth in the Ugandan part of Lake Victoria.

Flooded vegetation was found to have the highest density of water hyacinth, followed by crops, trees, built area, grass, and scrub/shrub. Additionally, 94% of water hyacinth was found on the left side of Entebbe. The most intense water hyacinth blooms occurred during June and July reaching 10.7% coverage, following the rainy season and maximum annual temperatures.

The high densities within flooded vegetation and croplands are likely due to organic pollution runoffs. These results support previous research which found high temperatures and eutrophication to cause water hyacinth proliferation. This study theorizes that several unknown factors cause water hyacinth proliferation and thus control solely through mechanical, chemical, and biological means is treating a symptom, not the cause. Future research can explore this, adding to this study's sample size, analyzing the different water dynamics for each land cover type, and further assessing the observation that water hyacinth presence may act as an indicator of organic pollution runoff.

KEYWORDS: *Water Hyacinth, Lake Victoria, Invasive Plant, Eutrophication, Land Cover*

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CHAPTER ONE

1.0 Introduction

1.1 Background

Lake Victoria is a vital natural resource of East Africa, with tremendous ecological, economic, and cultural value as the second largest freshwater lake with an estimated area of 66,400 – 69,485 km^2 (Awange et al., 2018). Lake Victoria as a natural resource supports the world's largest inland fishery and is responsible for revenue estimated at the US $400 million annually (Güereña et al., 2015). Sadly, anthropogenic stressors such as climate change, pollution, overharvesting, and introductions of invasive species are changing Lake Victoria (Nyamweya et al., 2020). Moreover, the growing surrounding population is causing an increase in anthropogenic activities, which exacerbates eutrophication in the main body of the lake (Shayo & Limbu, 2018). This lowers dissolved oxygen content and causes hypoxia in marine wildlife, compounding the effects of overharvesting (Mwamburi, 2016; Shayo & Limbu, 2018).

With such importance, an understanding of lake health and ecological dynamics is imperative for economic stability. Unfortunately, water hyacinth (*Eichhornia crassipes*), native to the northern tropics of South America, has invaded Lake Victoria, altering the existing ecological dynamics, posing threats to livelihoods and biodiversity (Nyawacha et al., n.d.; Villamagna & Murphy, 2010). Water hyacinth is one of the most invasive weed species in the world, which can form mats that may block sunlight from reaching native photosynthesizers who serve as primary producers, lower the transfer of dissolved oxygen to the water column, raise evapotranspiration by a factor of 10, and block fishing grounds (Datta et al., 2021; Harun et al., 2021; Villamagna & Murphy, 2010). Effective management plans minimize economic costs and ecological damage, emphasizing the need to identify water hyacinth hotspots and areas of nutrient runoffs causing large blooms. The size and shared governance of Lake Victoria have limited research and are attributed to weak management strategies. Additionally, little research has assessed water hyacinth cover in the Ugandan part of Lake Victoria with ocular observation, missing valuable metadata.

1.2 Problem Statement

Natural ecosystems across the globe are facing anthropogenic challenges that threaten their proper functioning. Many ecosystems have either lost their quality or degraded to an extent that they can no longer provide ecosystem serveries as before (Awange et al., 2018). Such challenges among others include the human population, pollution of all forms, overexploitation of natural resources, climate change, and the introduction of invasive alien species (Harun et al., 2021; Shayo & Limbu, 2018).

Across continents, fresh water and/or marine ecosystems are among the most affected ecosystems, especially by solid and liquid pollution and invasive alien species. Lake Victoria is one of the most important lakes in the world both ecologically and economically (Nyawacha et al., 2021). According to IUCN (2018), 31% of Lake Victoria's biodiversity (decapods, fishes, mollusks, and odonates) is made up of endemic species (204 species), with 76% of those endemic species are threatened with extinction (155 species). Moreover, Lake Victoria supports the livelihoods of 42 million people by supporting various socio-economic activities that the locals partake (Awange et al., 2018).

Unfortunately, like the rest of the freshwater ecosystems in Africa, Lake Victoria is also prone to the above-mentioned anthropogenic challenges, specifically the South American plant, water hyacinth (*Eichhornia crassipes*), which has invaded Lake Victoria, altering the existing ecological dynamics, posing threats to livelihoods and biodiversity (Nyawacha et al., n.d.). While our knowledge on the ecological effects and competitive traits of terrestrial invasive alien species has grown incredibly for several decades now, a lot is still lacking with regards to the ecological effects, environmental factors, spatial distribution of aquatic invasive alien plant species (Villamagna & Murphy, 2010). With this knowledge gap, this study aims to assess the spatial distribution and annual trends of water hyacinth density in the Ugandan part of Lake Victoria on the coast of Entebbe, using a Geographical Information System (GIS) and Normalized Difference Vegetation Index (NDVI) to theorize a cause-and-effect relationship between water hyacinth proliferation, seasonal changes, and coastal land use.

1.3 General Objective

To assess the factors that cause water hyacinth proliferation.

1.4 Specific Objectives

i. To identify possible correlations between water hyacinth presence and land use.

ii. To identify annual trends in water hyacinth abundance.

1.5 Hypothesis

Coastal areas adjacent to agriculture have a higher density of water hyacinth present due to agricultural nutrient runoffs and downstream migration. Additionally, flooded vegetation and built areas have higher abundances of water hyacinth due to a high amount of waste.

1.6 Scope of Study

This study analyzed a water hyacinth around 29 km of the coast off Entebbe (Figure 1). The observational data necessary for the first specific objective was collected over three days: November 22nd, November 25th, and December 1st. These results were compared with land cover types of flooded vegetation, trees, crops, built area, grasses, and scrub/shrub. NDVI analysis considered water hyacinth coverage of the Ugandan part of Lake Victoria.

1.7 Significance and Justification

This study revealed a possible correlation between land use and water hyacinth presence on the Entebbe coast, the results of which may be indicative of Lake Victoria as a whole. This apparent correlation may also indicate that certain land uses have harmful nutrient runoff or are connected to a polluted tributary, thus aiding in prioritizing conservation efforts toward more affected areas. Additionally, knowledge of the environmental factors under which water hyacinth proliferates may enable land managers to make choices to slow down the water hyacinth's high reproduction to a rate at which conventional control methods can remove more water hyacinth than can be reproduced. Moreover, a remote NDVI analysis of water hyacinth coverage would reveal seasonal spikes and cover a much larger area of water, which systematic sampling along the coast would fail to address. Hopefully, future studies with similar methodology will increase the sample size and assess various water bodies connected to Lake Victoria to understand the dynamics of East African hydrology more completely, promoting cooperation from multiple governments to conserve this important and threatened natural resource.

CHAPTER TWO

2.0 Literature review

The effect of water hyacinth on water bodies is well studied having drawn attention from scientists across the world due to its prevalence and difficulty to control (Datta et al., 2021; Güereña et al., 2015; Mwamburi, 2016; Nyawacha et al., n.d.; Villamagna & Murphy, 2010). A review article by Villamagna and Murphy (2010) summarizes the ecological impacts of water hyacinth as preventing the transfer of oxygen from the air to the water's surface, blocking out sunlight for native primary producers, outcompeting more nutritious food sources, increasing evapotranspiration by a factor of 10 compared to open-water evaporation rates, and preventing fish from reaching breeding or nursery grounds. The economic losses of water hyacinth on transportation and fisheries on Lake Victoria are estimated at approximately US $350 million per year, with a 70% decline of economic activities in Kisumu port, Kenya, during a year of high water hyacinth bloom (Güereña et al., 2015). Economic losses from water hyacinth almost halve Lake Victoria's value, as Lake Victoria's income generation is estimated at the US $400 million (Güereña et al., 2015). Awange et al. (2018) estimated that Lake Victoria supports the livelihoods of more than 42 million people, with a surrounding population projected to triple by 2050, thus poverty created from the economic declines will be amplified by a growing population.

Water hyacinth prevention measures have also been studied; however, their efficacy is limited. In their article, Villamagna and Murphy (2010) describe the three kinds of control used for invasive plant species: mechanical, chemical, and biological. Mechanical control involves the physical harvesting of plants. This is ineffective for water hyacinth control, as removal is expensive and in-situ cutting accelerates eutrophication because of the nutrients released and oxygen used (Villamagna & Murphy, 2010). Chemical control involves the use of herbicides which are cheaper than mechanical control, however, herbicides are indiscriminate with which plants they kill and may introduce toxic chemicals to the environment. Finally, biological control involves introducing an insect species to predate the water hyacinth. This suffers from several downsides, including the long time necessary to be effective and the limited knowledge of long-term effects (Simberloff & Stiling, 1996). Species introduced for biological control may prey-switch to a native species and become invasive themselves after the targeted species declines.

Despite these risks, weevils were introduced to Tanzania in 1995 to biologically control water hyacinth, however, this has had little efficacy to date (Williams et al., 2007).

Because water hyacinth has been described as nearly impossible to eradicate, priorities have shifted from eradication to successful control (Harun et al., 2021). Yet continuous control methods are costly – causing conflict over who should pay in Lake Victoria, an internationally owned water body. A recent wave of papers has been assessing whether the harvesting of water hyacinth could be turned into a self-sustaining management strategy via the creation of biofuel and several value-added products such as cellulose, levulinic acid, shikimic acid, and more (Datta et al., 2021; Güereña et al., 2015).

For this macroeconomy around water, hyacinth to be successful and benefit Ugandans, an understanding of easily accessible, coastal water hyacinth coverage is imperative. Additionally, there is a lack of localized papers in Uganda regarding water hyacinth. Most studies covering water hyacinth in Uganda have been conducted remotely by western researchers, focusing on the health of Lake Victoria while ignoring the social significance and missing valuable metadata (Awange et al., 2018; Stager et al., 2009; Williams et al., 2007).

CHAPTER THREE: Methodology

3.1 Study Area

The study area is the Ugandan part of Lake Victoria off Entebbe, lying on the equator with the latitude of 0.01 degrees North and 32.29 degrees East respectively (Figure 1). Entebbe is home to roughly 70,000 residents with a coastline of around 27 km. Entebbe borders Lake Victoria, the world's second-largest freshwater lake, with an estimated area of 66,400 – 69,485 km^2.

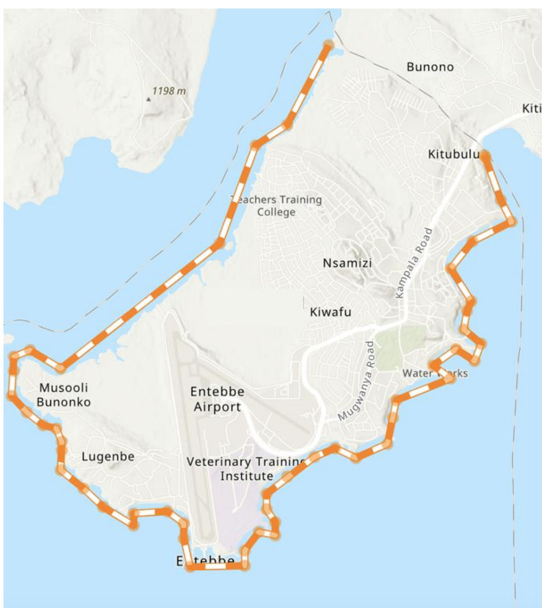
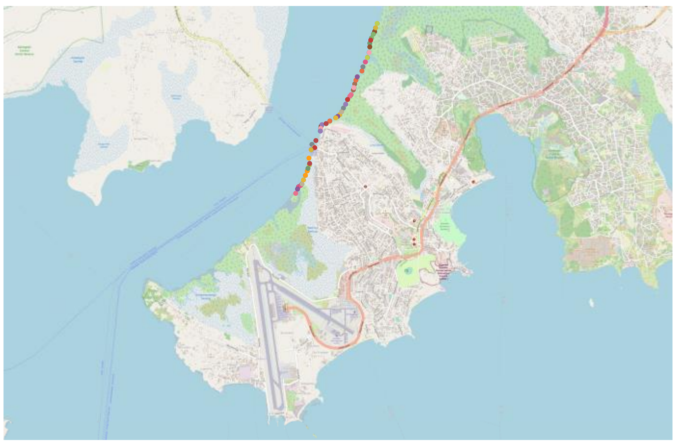


Figure 1. The 29.9 km route of data collection around Entebbeis shown by the white orange dashed line.

3.2 Methods

Systematic sampling of water hyacinth on the Entebbe coast

To systematically sample water hyacinth on the Entebbe coast, a motorized canoe was utilized for three days to drive around Entebbe. The canoe stayed 100 meters from the shore at a



speed of roughly 5.6 kilometers per hour, recording water hyacinth along different parts of the coast each day (Figures 2, 3, and 4).

Figure 2. Data were collected during Day #1 along half the right side of Entebbe. The location of the Nakiwogo docks is shown in Red

Figure 3. Data were collected during Day #2 along the bottom and left edge of Entebbe.

Figure 4. Data collected during Day #3 along the left half of Entebbe

The canoe left from Nakiwogo docks, on November 22, November 25, and December 1, at 10:30 A.M. (Figure 2). The investigator was accompanied by a boatsman to steer and a translator to guide and explain to the boatsman where the recording of was done data each day of data collection (Figure 5). Water hyacinths were only recorded when visible and bordering the coast. The recording was done on Gaia GPS, creating a keyhole markup language (KML) file titled with the raw counts and valuable metadata formats of water hyacinth. Water hyacinth was identified from its broad, rounded, and glossy leaves, which were a distinctively darker green than the surrounding aquatic grasses (Figure 6).

Figure 5. Photo of canoe used for data collection and translator, Bright.

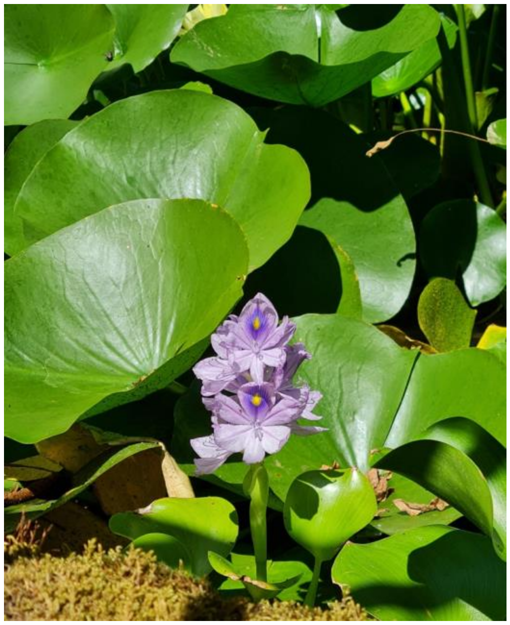


Figure 6. Water hyacinth (*Eichhornia crassipes*) flower and leaves. The water hyacinth's glossy and round leaves are helpful identifiers.

Data analysis

In this study, Sentinel-2 satellite imagery of land use/land cover for the year 2020 was used for data analysis of the first objective. The data resolution was 10 meters. The collected GPS data were converted from KML to shapefiles and manually shifted from the water to land to overlap the Sentinel-2 land use for data preparation. This allowed for the attribute table to be exported with both count data and land cover type for analysis in RStudio and Microsoft Excel.

Microsoft Excel was used to standardize the collected data, summing raw counts for each land cover type and the length of coastline that land cover type took. The summed counts were divided by the length of the coastline for each land cover type to standardize results. Because the collected data was non-normal distributed, a non-parametric Kruskal-Wallis test was chosen to be performed in RStudio to assess statistical significance differences of water hyacinth between the different land cover classes (Figure 7).

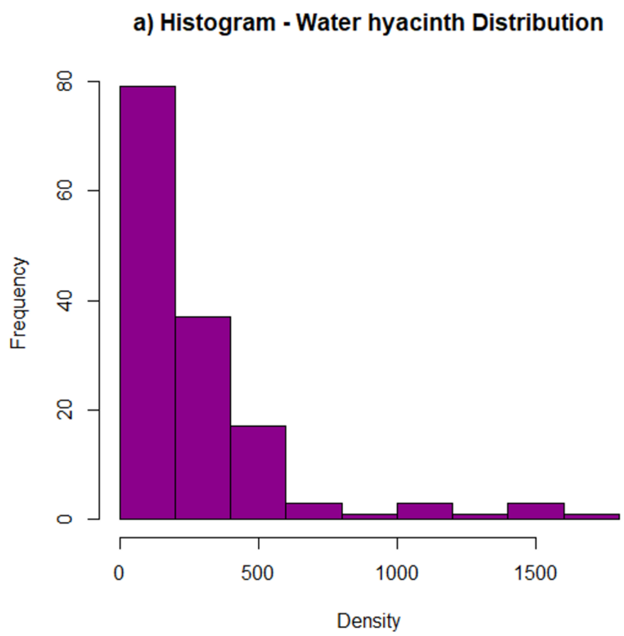


Figure 7. Histogram of collected water hyacinth abundance data distribution. The histogram shows a non-normal distribution of data.

The outcome of the Kruskal-Wallis test tells if there are differences among groups, but doesn't distinctlywhich groups are different from others. To determine which groups are different from others, post-hoc testing was conducted. A Dunn posthoc test was conducted in RStudio to determine if there was a significant difference in values in water hyacinth abundance between land cover classes (Annex-1).

NDVI Analysis

Twelve Normalized Difference Vegetation Index (NDVI) images were created for the Ugandan part of Lake Victoria to support the results from method #1. NDVI was extracted from NASA's eMODIS satellite, which measures the greenness of vegetation through the reflectance of red and near-infrared wavebands. (NASA, n.d.). Chlorophyll will absorb red light, while the mesophyll structure of a leaf will scatter reflected near-infrared light. Therefore, if the proportion of reflected near-infrared light is greater than the red light captured this represents a signal of vegetation. The images were downloaded from – United States Geological Survey Famine Early Warning Systems Network (USGS FEWS NET) Data Portal based at Earth Resources Observation and Science Center (https://earlywarning.usgs.gov/fews/datadownloads/East%20Africa/eMODIS%20NDVI%20C6). The data collected in the field a 148 GPS was used to classify water hyacinth area. The images were classified in QGIS for each month for the year 2020.

Ocular Observation

By taking thorough field notes and marking metadata for novel recordings on Gaia GPS, valuable metadata was collected to help describe results.

3.3 Study Design

This study adopted a correlational study design for the quantitative analysis of the first objective, which aims to identify a significant relationship between land use and water hyacinth abundance. Additionally, a spatial-temporal study design was employed for the remote NDVI data used for the second objective, which aims to identify seasonal trends in water hyacinth coverage of the Ugandan part of Lake Victoria.

3.4 Sampling Techniques and Procedure

Systematic sampling of water hyacinth on the coast of Entebbe was employed for this study to gather spatial data of water hyacinth abundance for the correlational analysis. The data will be collected along a predetermined path around Entebbe with consistent methodology and set rules of thumb.

3.5 Sample Size

In this study, 148 GPS recordings were made of water hyacinth abundance off the coast of Uganda, resulting in a total of 41,615 water hyacinth counted throughout the coast 29.87 km in length. Additionally, twelve NDVI maps were created for each month in 2020.

CHAPTER FOUR: Data Presentation, Analysis, and Results Interpretation

4.1 Objective 1: Relationship Between Land Use and Water Hyacinth Abundance

There were 148 recorded GPS points mapped in QGIS and ArcGIS Online displaying count data for clusters of water hyacinth. These clusters ranged from just ten individuals up to 1750, with a total of 41,615 water hyacinths recorded. This data was collected on a 29.87 km track of coastline with land cover types including trees, grass, flooded vegetation, crops, shrub/scrub (1.44 km), and built area (Table 1).

Table 1. Water hyacinth count data standardized for six land cover types.

Land Cover Type	Water Hyacinth Counted	Coastline (km)	Water Hyacinths/km
Trees	12405	6.99	1774.68
Grass	103	1.29	79.84
Flooded Vegetation	21795	6.88	3167.88
Crops	870	0.44	1977.27
Shrub/Scrub	51	1.44	35.42
Built Area	6391	12.83	498.13
Average of all land cover types:	41615	29.87	1393.20

From mapping collected data, it was found that the flooded vegetation land cover type had the highest water hyacinth abundance, and the shrub/scrubland cover type had the lowest (Figure 8). Flooded vegetation, trees, and crops were found to have water hyacinth densities above the average. Built areas, grass, and shrub/scrub land cover types were found to be lower than the average.

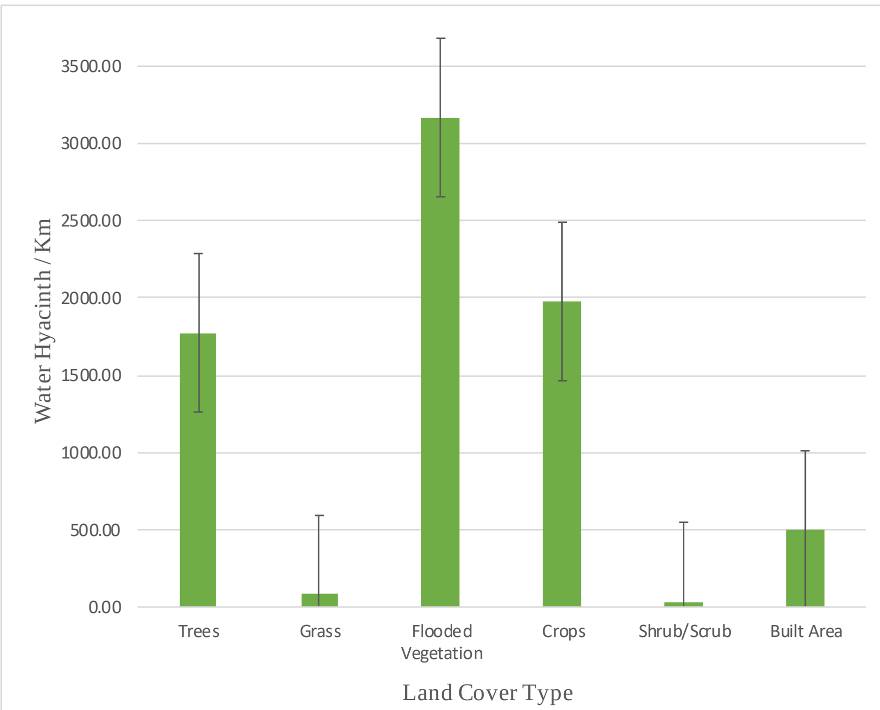


Figure 8. Water hyacinth count data grouped by land cover type and standardized by the length of coastline (n = 148).

Spatially, 94% of water hyacinths were located on the left side of Entebbe (39,290 recorded water hyacinth, with just 6% of recorded water hyacinth on the left side (2,325 recorded water hyacinth) located adjacent to the Entebbe Airport airstrip and the Kampala-Entebbe Expressway (Figure 9). There were roughly 30 records over the course of data collection of little egrets perching on top of water hyacinth mats. Additionally, the water quality was much poorer on the left side of Entebbe, with far less transparent water and thousands of cercaria-infected snails floating on the water, a sign of possible diseases for any who swim (Yampa Abraham, 2021). Finally, there were only four records taken of water hyacinth flowering during the data collection, all of which were found on the upper right side adjacent to the Kampala-Entebbe Expressway.

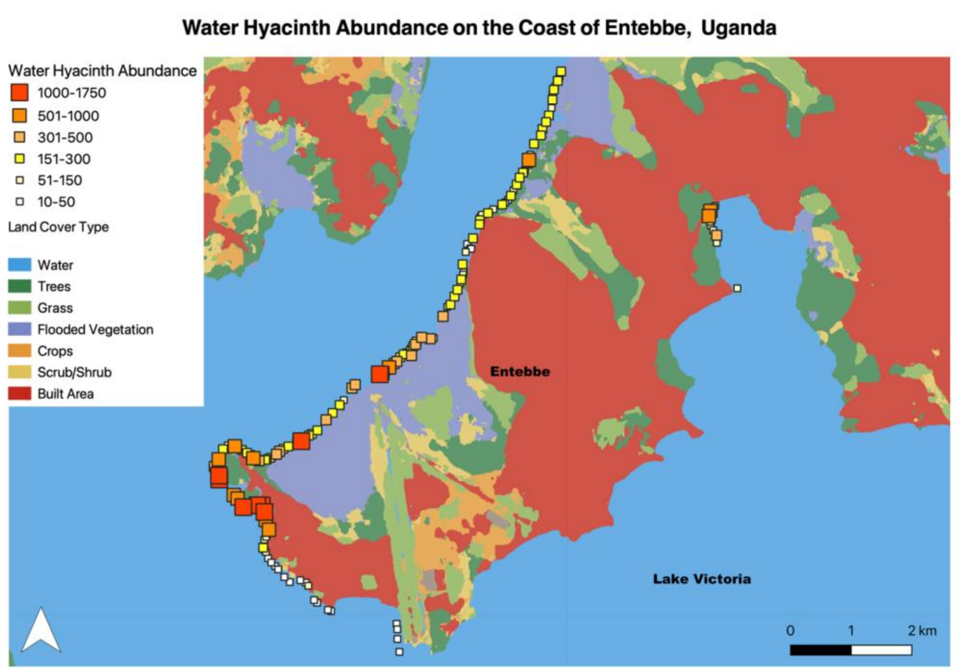


Figure 9. Map of spatial water hyacinth abundance on the Coast of Entebbe, Uganda.

Variability in water hyacinth density per land cover type was assessed in a boxplot (Figure 10), with the highest range of water hyacinth abundance within flooded vegetation and trees' land cover types. Crops were omitted, as there was no variability in water hyacinth mats due to only one record made within the 0.44 km stretch of the crops' land cover type.

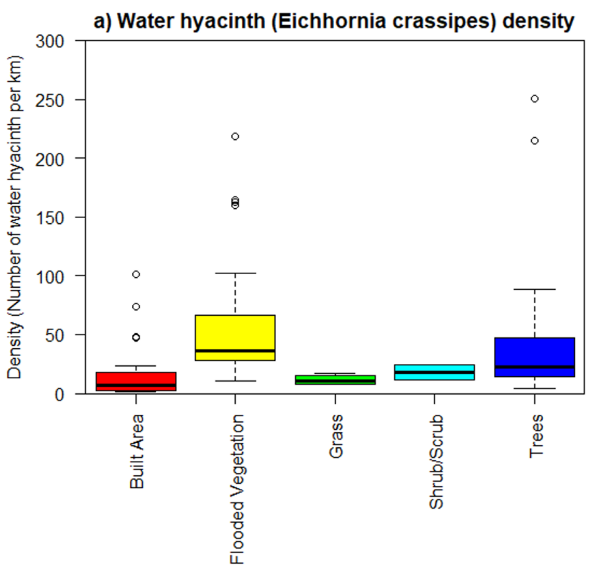


Figure 10. Water hyacinth density boxplot. Red represents built area, yellow represents flooded vegetation, cyan represents grass, blue represents shrub/scrub, and magenta represents trees.

The results from the Kruskal-Wallis test reject the null hypothesis and conclude that not all the group medians are equal. The test revealed a significant difference (Kruskal-Wallis chi-squared = 52.706, df = 4, p-value = 9.816e-11) in the water hyacinth density across the land cover. A -post-Dunn test indicated there were statistical differences between built area and flooded vegetation, flooded vegetation and grass, and built area and trees at alpha = 0.05. Table 2 summarizes the results.

Table 2. Dunn (1964) Kruskal-Wallis multiple comparison p-values adjusted with Bonferroni method. Courtesy of Dr. Mohammed Said.

	Comparison	z	P.unadj	P.adj
1	Built Area - Flooded Vegetation	-6.677896	2.42E-11	**2.42E-10**
2	Built Area - Grass	0.2728479	7.85E-01	1.00E+00
3	Flooded Vegetation - Grass 8.937303e-04	3.917767	8.94E-05	**8.94E-04**
4	Built Area - Shrub/Scrub	-0.5135184	6.08E-01	1.00E+00
5	Flooded Vegetation - Shrub/Scrub	1.4922205	1.36E-01	1.00E+00
6	Grass - Shrub/Scrub	-0.6088133	5.43E-01	1.00E+00
7	Built Area - Trees	-3.7969369	1.46E-04	**1.46E-03**
8	Flooded Vegetation - Trees	2.7053675	6.82E-03	6.82E-02
9	Grass - Trees	-2.4758661	1.33E-02	1.33E-01
10	Shrub/Scrub - Trees	-0.7262733	4.68E-01	1.00E+00

4.3 Objective 2: NDVI Analysis

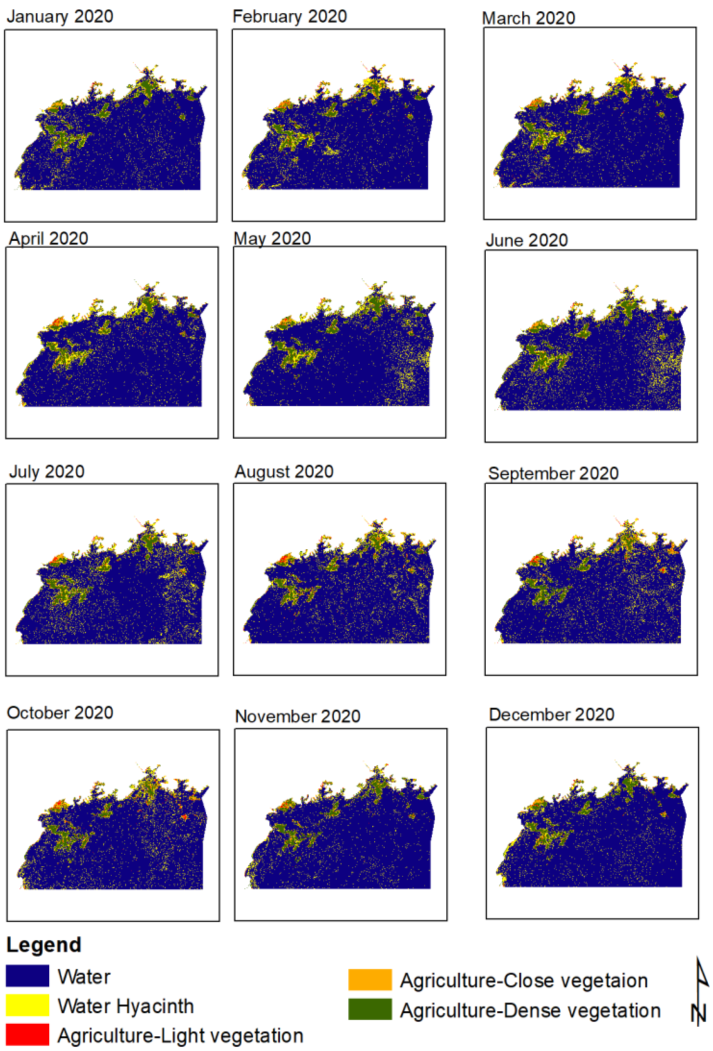


Figure 11. NDVI trends in the Ugandan part of Lake Victoria mapped for each month of 2020. Figure courtesy of Dr. Mohammed Said.

There were 12 NDVI maps created for each month in 2020 to assess water hyacinth coverage remotely (Figure 11). Water hyacinth coverage was highest during June and July. Spatially, the water hyacinth blooms during these months are concentrated along the coastline and around Buvuma Island and the Ssese Islands. Additionally, there is a high amount of free-floating water hyacinth on the left side of the NDVI maps, near the Kenyan-owned part of Lake Victoria. Water hyacinth coverage was lowest during November and December, the months within which this study's raw data was collected. Water hyacinth covered a maximum of 10.7% of the Ugandan part of Lake Victoria and a minimum of 6.0% (Figure 12).

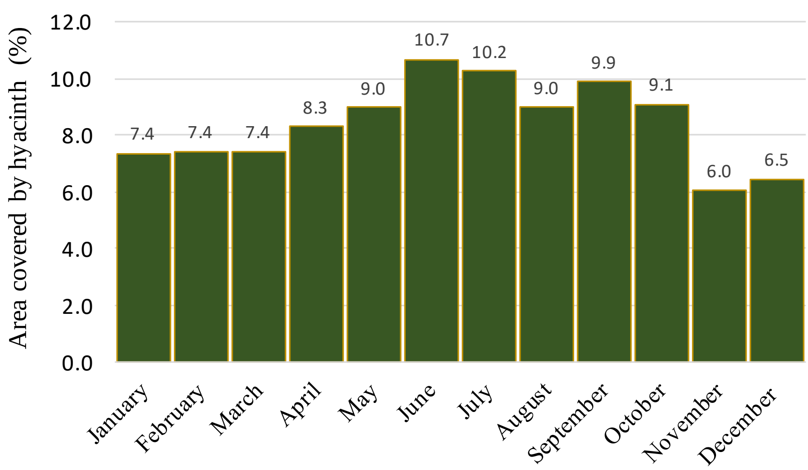


Figure 12. Histogram of water hyacinth coverage for each month in 2020, on the Ugandan part of Lake Victoria. Percent coverage was determined through remote sensing NDVI analysis. Figure courtesy of Dr. Mohammed Said.

4.3 Metadata: Conversation with Lwanga, Bright, and Yampa

Over the course of data collection, metadata was collected from conversations with the boatsman, Lwanga, and guides, Yampa and Bright, during the time used to travel to the data collection spots. Lwanga, Yampa, and Bright are Entebbe locals and shared some of their experience and knowledge with water hyacinth.

During the July blooms, travel is infrequent, as boats can become trapped away from shore due to water hyacinth mats, potentially being fatal for those who cannot swim (Bright, Personal Communication, 2021). The water changes to brown and children are not allowed to swim as the water can carry disease (Yampa, Personal Communication, 2021). Additionally, the only usage of water hyacinth for locals is as pig feed.

CHAPTER FIVE: Summary, Discussions, Conclusions, and Recommendations

5.1 Discussion

An understanding of the conditions in which an invasive species proliferates and is spatially distributed is imperative for guiding policymakers and land planners to not further exacerbate the problem. Water hyacinth is no exception, being a growing problem has spread to more than 80 countries over the past century (Datta et al., 2021). Because the ability to differentiate land cover on a large scale has only recently become available through modern satellite imagery, little research has focused on several coastal land cover types influencing water hyacinth proliferation. Therefore, the purpose of this study was aimed to assess possible factors that cause water hyacinth proliferation. The specific objectives of the study, which included identifying seasonal trends through remote sensing and identifying possible relationships between land cover and water hyacinth abundance, were accomplished.

5.1.1 NDVI Analysis

Through remote sensing NDVI, it was discovered that June and July have the highest abundance of water hyacinth. During this time, transportation is limited due to fatalities having occurred from water hyacinth trapping boats (Bright, 2021). This bloom is following the rainy season in April and May, where temperature and precipitation are highest (World Bank, n.d.). It is likely that the increased temperature contributed to this bloom, as high temperatures, eutrophic conditions, and other environmental factors have been found to promote the proliferation of water hyacinth in freshwater bodies (Harun et al., 2021). Moreover, there is a possibility that water hyacinth is controlled by a more biophysical feature, such as wind force, wind direction, and lake circulation than eutrophication (Nyawacha et al., n.d.) The high amount of precipitation may also have played a role, in increasing discharge in the lake which could dislodge water hyacinth from stationary mats to colonize other parts of the lake system. Additionally, the proliferation of water hyacinth in the Ugandan part of Lake Victoria may be due to land use.

5.1.2 Systematic Sampling

The systematic sampling of water hyacinth along the coast of Entebbe found flooded vegetation, crops, and trees land cover types as having the highest densities of water hyacinth along the coast (Figure 8). This coincided largely with the hypothesis, however, built areas did not have a water hyacinth density higher than the average. This is likely due to waste being disposed into areas of flooded vegetation or burnt, rather than thrown directly into the lake. Additionally, the built areas may have a local garbage management system aimed at preventing pollution from damaging locally important natural resources.

The highest abundance of water hyacinth was found in flooded vegetation areas and may be explained in three ways. First, existing aquatic vegetation may trap free-floating water hyacinth due to existing plants acting as physical barriers. Papyrus and other aquatic grasses within the swampland disrupt the water’s current and cause still water, which may trap water hyacinth and result in large build-ups. Second, these swamps likely have high levels of organic pollution, as much trash is thrown into swampland due to no municipal garbage disposal, causing eutrophication which causes blooms of water hyacinth (Harun et al., 2021). Finally, the flooded areas are located on the left side of the coast in a concave manner, potentially trapping free-floating water hyacinth due to the shape of the coastline rather than the land cover type. Likely, the high density found within this land cover type is due to a combination of these three factors rather than just one.

The crops' land cover type had the second-highest water hyacinth abundance, however also had the least data, with only one water hyacinth GPS recording within the 0.44 km of crop coastline. I would attribute this result to fertilizer runoffs causing eutrophication, supplying extraneous nutrients, such as nitrogen, phosphorus, or potassium to the lake, causing water hyacinth proliferation. Increased nutrient inputs into Lake Victoria had previously been found to result in decreased water transparency, increased water hyacinth infestations, and hypoxia within deep waters, which have been observed in this study (Shayo & Limbu, 2018). Similarly, the trees' land cover type had a higher-than-average water hyacinth abundance, likely due to runoff of soil with high nutrient contents. To support high biomass plants the soil within the trees' land cover type must have high nutrient contents which may act as organic pollutants. This same reasoning applies to the low water hyacinth abundance found in grass and shrub/scrub land cover types. In those land cover types, the soil cannot sustain high biomass, likely due to lower nutrient content, and thus soil runoff would not result in as dramatic a water hyacinth bloom as trees, crops, and flooded vegetation.

The built area land cover type covered almost half the coastline, with two distinct hotspots of water hyacinth along the Kampala-Entebbe Expressway and between two areas of flooded vegetation at Nakiwogo Harbor (Figure 9). The first hotspot may be explained by pollution from the highway and the concave shape of the coastline in that spot, which leaves nowhere else for the water hyacinth to go. The second hotspot in Nakiwogo Harbor was far less intense than the first and is likely the result of two factors. The first contributing factor to this hotspot is Nakiwogo's location, being bordered by flooded vegetation. Additionally, the high amount of traffic and population stemming from the harbor may release pollutants from boats and waste from passengers, fueling eutrophication.

5.1.3 Implications for the Future

These results may suggest that an increasing population, like that of Entebbe, would result in an increasing amount of water hyacinth in Lake Victoria. A previous study conducted in Zimbabwe analyzed urbanization causing land cover changes, with the proliferation of aquatic hyacinth. Water hyacinth abundance was found to increase with increased urbanization, which the authors theorized to be attributed to organic pollutant runoffs into the lake (Dube et al., 2018). This adds to the theory that waste is a significant contributor to water hyacinth proliferation, thus a higher coastal population would result in more water hyacinth. However, this is contrary to my found results, as-built areas had a lower density of water hyacinth than natural land cover types, such as flooded vegetation or trees. The process of changing different land cover types likely causes organic wastes from the clearing of trees, grass, shrubs, and soil, which then decompose in the water body introducing nutrients for water hyacinth blooms. In addition, land covered by crops would increase to accommodate the larger population, requiring more fertilizer which can runoff and cause eutrophication. By this reasoning, Entebbe will have more intense water hyacinth blooms in the future.

The prediction that water hyacinth will increase over time with a growing population has little recent historical data for support. A study analyzing Winum Gulf in the Kenyan part of Lake Victoria found that water hyacinth coverage was direst in 2020, but dropped by approximately 50% in 2021, likely due to scaled-down industrious activities from the COVID-19 pandemic (Nyawacha et al., n.d.). Once urban growth resumes to pre-pandemic levels, the correlation between water hyacinth and urban land cover change will likely present itself again, at a scale that would inhibit transportation, reduce the already overharvested fish stocks, and decrease water quality further. This would result in increased food insecurity, job losses, cultural losses, increased diseases, and crime among locals, as a water hyacinth infestation in Kisumu, Kenya leads to an increase in petty crime and unemployment (Güereña et al., 2015). These future risks make it imperative to gain as much knowledge possible about water hyacinth to combat if such issues arise.

5.2 Conclusions and Recommendations

The results of this study have shown that:

i. There is a relationship between water hyacinth density and land cover type.
    i. Densities were highest in areas of flooded vegetation, croplands, and trees.
    ii. Densities were lowest in grasses and scrub/shrub.

ii. Water hyacinth has the highest bloom in June and July following the warmest annual temperatures and rainy season.

iii. Locally, removal efforts should be concentrated on the left coast and bottom edge of Entebbe.

iv. There may be harmful runoffs from the Kampala-Entebbe Expressway and the trash thrown into flooded vegetation.

This study is useful to visually map the areas around Entebbe infested with invasive water hyacinth and lays the groundwork for future studies connecting land cover type to water hyacinth proliferation. This will inform policymakers on how decisions that change the land cover may influence water hyacinth, and where removal efforts should be concentrated.

Additionally, it can be helpful to view water hyacinth as an infection. Large and stationary water hyacinth mats act as reservoirs, with individuals breaking away to infect other parts of the lake. This study's results suggest that water hyacinth proliferation is a symptom of a larger issue of water quality and runoff. Further understanding the exact reasons why water hyacinth was much more prevalent on the left side of Entebbe's coastline and almost non-existent on the right may enable policy and management to improve water quality to levels equal all along the coast. This would only occur if the conditions under which water hyacinth proliferates are fully understood and minimized to lower the reproductive rate of water hyacinth enough for mechanical invasive plant control methods to be effective. This could work in conjunction with the recent waves of scientific papers assessing the efficacy of creating macroeconomies centered around turning water hyacinth into biofuel and products to fund its removal (Datta et al., 2021; Güereña et al., 2015; Waweru et al., 2019).

5.2.1 Future research:

To further this study's results, the same methodology applied to different study sites on the coast of Lake Victoria would add to this study's dataset and strengthen the results, especially if conducted during June and July, to account for when water hyacinth abundance is highest. Additionally, an additional sample of coastline with a larger stretch of crops and shrub/scrub land cover types, which were narrowly represented in this study, may reveal significant relationships in the post-hoc Dunn test. Additionally, long-term monitoring could reveal differing results, especially around croplands where land inputs change seasonally. Moreover, the use of radio telemetry on free-floating water hyacinth mats could determine whether the high abundance of water hyacinth on the left side of Entebbe's coast is due to its concave shape trapping free-floating water hyacinth.

Further study of the differing water dynamics (discharge, present nutrients, dissolved sediments, etc.) off the coast of each land cover type may give insight into this study's results and support the theory that water hyacinth abundance is tied to soil nutrient content. In addition, an experimental study where stretches of coastline are designated to a specific land cover type and monitored continuously may establish causation. Furthermore, a water quality study around the same area with a focus on the parasite cercaria as well as water hyacinth may assess the correlation between these two problem species.

5.2.2 Limitations:

There were several limitations during the process of this study. The first limitation in this study was the use of unassisted ocular observation to count the water hyacinth abundance. Large mats of water hyacinth were difficult to count accurately, requiring a strategy where a fraction of water hyacinth within a mat was counted and multiplied by a number to make that fraction a whole. Additionally, counts were limited by visibility, with tall aquatic grasses obscuring presumably higher abundances of water hyacinth within the flooded vegetation land cover type. The land cover types of crops, grass, and scrub/shrub made up only 10% of Entebbe's coastline despite being half of the land cover types considered in this analysis introducing error from the small sample size. In addition, the raw data collected cannot show temporal trends such as agricultural seasons, rainfall, or temperature.

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ANNEXES

(1) RScript

```
###########################################################################
#################################################################
#Land Use as a Predictor of Water Hyacinth (Eichhornia crassipes) presence on the Entebbe
Coast of Lake Victoria, Uganda
#R-Script Program Written on 8th December 2021
#Zachary Hoffman, Gettysburg College
#Major: Environmental Studies
#Submitted in partial fulfilment of the requirements for Tanzania-Uganda: Wildlife
Conservation and Political Ecology,
#SIT Study Abroad, Fall 2021

###########################################################################
#################################################################

library(FSA)
library(lattice)

hyacinth <- read.csv("C:/2021/Mweka/Lake-Victoria-Study/Statistics/RawData1.csv")
names(hyacinth)

# Test for normality
hist(hyacinth$density)
hist(hyacinth$rawdata)
hist(hyacinth$logdensity)

# Display colored figures for variations based on land use land cover
boxplot(hyacinth$logdensity~hyacinth$landcover, ylim=c(0,5), cex.axis=0.75, tck=-.01,
las=2, cex.lab=1, xlab=" ", ylab="Density (Number of hyacinth (log10) per km)", main="a)
Water hyacinth (Eichhornia crassipes) density", col=rainbow(6))

###########################################################################
#################################################################

# Kruskal Wallis Test One Way Anova by Ranks
kruskal.test(hyacinth$density~hyacinth$landcover) # where y1 is numeric and A is a factor

###########################################################################
#################################################################
#Dunn test for multiple comparisons
#If the KruskalWallis test is significant, a post-hoc analysis can be performed to determine
which
#levels of the independent variable differ from each other level.  Probably the most popular
test for
```

#this is the Dunn test, which is performed with the dunnTest function in the FSA package.
#Adjustments to the p-values could be made using the method option to control the familywise error rate
#or to control the false discovery rate. See ?p.adjust for details.

#Zar (2010) states that the Dunn test is appropriate for groups with unequal numbers of observations.
#If there are several values to compare, it can be beneficial to have R convert this table to a compact
#letter display for you. The cldList function in the rcompanion package can do this.

dunnTest(hyacinth$density~hyacinth$landcover,method="bonferroni")

---

(2) Work Plan

Date	Activity
November 15	Arrive in Entebbe
November 15-19	Dealing with outstanding details (finding a boat, guide, and interviewees)
November 20	Data Collection Begins
November 30	Write-Up/Data Analysis
December 4	Arrive in Kampala
December 13-14	Final ISP Presentation
December 15	Final ISP Submission

(3) Work Budget

Expenses	Quantity	Cost Per (UGX)	Total Cost (UGX)
Housing (Breakfast Included)	20	45,000	900,000
Food	20	20,000	400,000
Transport	15	8,000	120,000
Advisor	15	10,000	150,000
Travel (to Entebbe & Kampala)	2	10,000	20,000
Boat and Boatsman	4	100,000	400,000
		Total:	1,990,000