TEMPORAL AND ENVIRONMENTAL CONDITIONS REGULATING BIOMASS DYNAMICS IN WATER HYACINTH AND ITS EFFECTS ON WATER QUALITY IN LAKE NAIVASHA, KENYA

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DECLARATION AND RECOMMENDATION

DECLARATION

This thesis is my original work and has not been submitted or presented for examination in any other institution.

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RECOMMENDATION

This thesis has been presented for examination with our approval as official university supervisors.

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DEDICATION

I dedicate this work to all the young scholars, those that struggle but financial uncertainties threaten what should be a bright and productive future for all. In the scorching sun and in the freezing cold they seek knowledge without proper shelter, food nor clothing. Folks, your lives are an inspiration to me.

ABSTRACT

The influence of the water hyacinth mats on the physico-chemical characteristics of the underlying water is important in understanding the potential impacts on the aquatic organisms and human uses. The objective of the study was to determine the temporal and environmental conditions regulating biomass dynamics in water hyacinth and its effects on water quality in Lake Naivasha, Kenya. Field measurement and experimental set up were used to generate research data. Field research was carried out in three selected sites in Lake Naivasha; off Sewage, Malewa River inlet (both with hyacinth cover) and an open water site without water hyacinth cover. Field measurements and water sample collection was carried out once in a fortnight for five months (September 2011 to January 2012). Physico-chemical variables were measured *in situ*. The water samples from the lake and experimental buckets were analyzed for N, P and total suspended solids (TSS). The density and dry weights of live and senesced *E. crassipes* per square metre was determined using a 0.5×0.5M quadrat in triplicates per site. In all the statistical analyses, 95% level of significance was used as the critical point (P= <0.05). The water column below water hyacinth mats had three times lower dissolved oxygen concentration as compared to the open water, with values below 1mg/l recorded in some cases. In sites with water hyacinth, water transparency was two times lower with twofold higher total phosphorous concentration compared to the open water. Temporal variation of hyacinth biomass was observed in the lake. The number of juvenile plants increased fourfold within a month during the rainy season. By the end of the rains (two months after the onset), the juvenile population had reached thirteen fold increase. The results from the experiment indicated that juvenile plants are capable of taking up to 2.5 times more P and N per unit area than the mature ones. The development of a new plant in 9 days in 3.20 mg P/L and 25.60 mg N/L of nutrient enrichment was the fastest multiplication rate. The highest rates of change in plant biomass recorded were 1.48 and 3.69 Kg/m^2/week (fresh weight) for the young and mature hyacinth respectively grown in 3.20 mg P/L and 25.60 mg N/L of nutrient enrichment. This was achieved between the 33rd and 47th day. In conclusion, increase in N and P concentrations in the water column resulted to increase in water hyacinth growth which in turn influences the water quality both positively through nutrient uptake and negatively by organic matter rain-down from decaying biomass. Management strategies that limit nutrient input into the lake should be enforced.

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
APHA	American Public Health Association
DO	Dissolved Oxygen
EARP	East African Regional Programme of IUCN
EC	Electrical Conductivity
ELC	Environmental Law Center of IUCN
EOIA	Earth Observation and Integrated Assessment
GOK	Government of Kenya
IUCN	International Union for Conservation of Nature
IWHC	International Water Hyacinth Consortium
KARI	Kenya Agricultural Research Institute
LSD	Least Significance Difference
LRNA	Lake Naivasha Riparian Association
SRP	Soluble Reactive Phosphorous
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solids
WWF	World Wide Fund for Nature
ICAR	Indian Council of Agricultural Research
ICLARM	International Center for Living Aquatic Resources Management

CHAPTER ONE

INTRODUCTION

1.1 Background information

Lake Naivasha is one of the Rift valley lakes in Kenya. It was designated as a Ramsar site (no. 724) in 1995. The Lake has a catchment area of approximately 3, 400 km^2 and stretches from the Aberdares mountain ranges in the north and north east to the Olkaria, Longonot mountains in the south and south east. It is bounded by the Mau Escarpment in the west, Eburu Escarpment to the North and the Kinangop plateau in the East (WWF, 2011). The lake surface area is approximately 140 km^2 (Bercht *et al*., 2006).

Lakes Naivasha are Baringo are the freshwater rift valley lakes of Kenya. Lake Naivasha is both ecologically and economically important. It has diverse flora and fauna as it provides a variety of habitats for a plethora of mammals, birds and fish. The lake and its surrounding has a high economic value as it provides water for agricultural production for export and domestic markets and is a major hub for tourism and recreation industry. Most importantly, a population of about 250,000 people in the vicinity of the lake gets their domestic water from the lake or its waterways (IUCN, 2003). Despite the absence of a surface outlet like many other Rift Valley lakes, Lake Naivasha has remained a freshwater lake and this is of great ecological and economic significance. According to Gaudet and Melack (1981), Lake Naivasha has remained fresh due to the presence of underground seepage routes, ions exchange with the sediment and dilution of lake water by rain and river inputs. There is also the effect of the macrophytes especially papyrus which stores significant amount of ions in the littoral zone through bio-uptake; thereby, keeping the water relatively fresh.

In spite of all these, the lake has been subjected to all kinds of adverse environmentally degrading activities including overfishing, introduction of alien invasive species, upstream diversion of water in the streams feeding the lake, abstraction of water for irrigation along the lake shore, wetland reclamation by clearing of papyrus vegetation and agricultural and urban pollution (Njuguna, 2002). Eutrophication of the water has been reported (Kitaka *et. al* 2001) and is evident to date from the persistent proliferation of nuisance floating aquatic macrophytes such as *Salvinia molesta* and *Eichhornia crassipes*. *Eichhornia crassipes* is currently the most common and notorious species of the genus *Eichhornia* which is commonly referred to as ‘water hyacinth'. Water hyacinth is thought to have been brought to East Africa as an ornamental. Its presence was reported in L. Victoria in 1989 (Ochile *et al*., 2001) and in L. Naivasha in 1988 (Adams *et al*., 2002; Mironga *et al*., 2011). In the last twenty years, hyacinth has gradually increased its dominance in Lake Naivasha, despite the various attempts to control its spread. By 1999, it had covered about 25 per cent of the lake water surface (Njuguna, 2002). Lake Naivasha is much smaller compared to Lake Victoria and if favorable growth conditions are achieved; water hyacinth can easily cover much of the lake surface with devastating ecological and economic consequences. Significant amount of studies have been done on water hyacinth growth, its effects and control efforts in Lake Victoria unlike in Lake Naivasha. This justifies the demand for more research on the dynamics and factors influencing growth conditions of water hyacinth in Lake Naivasha.

The ecological and economic effects of water hyacinth overgrowth are often quite dramatic with severe consequences. Its ecological effects include; competitive displacement of native plant communities (particularly submerged plants), restriction of phytoplankton production due to shading, and interference with atmospheric oxygen exchange with the water through surface coverage. Severe depression of dissolved oxygen do occur in water column underlying dense waters hyacinth mats due to the effects of rapid deposition of organic matter from senescing leaves (Joyce, 1985). Development of anoxic conditions under water hyacinth can directly lead to exclusion of fish and other oxygen-dependent organisms, thereby radically changing the structural composition of faunal communities (Schmitz *et al.,* 1993). In addition, livelihoods are often adversely affected through restricted navigation, loss of fisheries access, and siltation of drainage systems is associated with substantial water hyacinth cover in a water bodies (Gopal, 1987). The aforementioned ecological pressures on the lakes native plants, phytoplankton and animal communities in turn affect the economic functions of the lake. The poor population living in slums and peri-urban centers around the lake as a consequence to enormous growth in horticultural sector relies on the lake water for their domestic use, and the same time fishing forms one of their important economic activity. The fish from the lake is a major source of protein. Heavy infestation with water hyacinth in the lake, which is likely to influence fishery negatively becomes a major threat to livelihood.

Lake Naivasha being an economic hub both locally and globally, its management and sustainable resources utilization fits well in the long-term national development plan (Kenya Vision 2030). According to GOK (2007), vision 2030 looks at a selected number of salient and emerging issues that need to be considered to achieve the Vision's goals and targets. One of the key issues is the protection of the country's water sources that feed hydropower, support fisheries, wildlife and tourism destinations, irrigate both export and small holder farms, and nurture grazing areas. In order to achieve these goals, the following strategies are integral: promoting environmental conservation to help achieve the Millennium Development Goals (MDGs); improving pollution and waste management through proper design and application of economic incentives to empower Kenyans and increasing biodiversity especially for lake Naivasha which is a Ramsar Site (GOK, 2007). A wide range of policy, legal and institutional frameworks such as the Convention on Biological Diversity (CBD) are relevant in the management of Lake Naivasha basin (WWF, 2012). CBD focuses in conservation and sustainable use of biodiversity, both terrestrial and aquatic resources, of which Lake Naivasha is included.

1.2 Statement of the problem

Eichhornia crassipes is considered as the most nuisance floating aquatic weed species because of its potential of rapid multiplication; forming thick mats covering the water surface commonly in rivers, lakes and reservoirs. The negative impacts of extensive hyacinth mats on the lake environment, such as the obstruction of fishing, navigation and irrigation are well documented. Its response to nutrient fluxes and the subsequent impacts on water quality, especially in Lake Naivasha, need to be established. There is need to know the extent to which different nutrient concentrations particularly nitrogen and phosphorous are likely to affect water hyacinth growth. There is need to establish whether nutrient loading into the lake from the catchment through River Malewa, River Gilgil and River Karati together with influence of municipal wastewater from the Naivasha sewage treatment plant have enhanced the establishment and proliferation of water hyacinth in the lake, especially in the northern shores. There is evidence that the weed's problems have intensified over the last two years (2010 and 2011) with local fishermen complaining of navigation and landing difficulties. Adequate and recent information on the effects of water hyacinth biomass accumulation and degradation on the lake's water quality has been lacking.

1.3 Objectives

1.3.1 General objective

To determine the temporal and environmental conditions regulating biomass dynamics in water hyacinth and its effects on water quality in Lake Naivasha

1.3.2 Specific objectives

1. To compare the effects of water hyacinth biomass dynamics on the physico-chemical parameters of underlying water in different parts of the lake.
2. To determine the uptake rates of nitrogen and phosphorous by different growth stages of water hyacinth.
3. To evaluate the effect of varying concentrations of nitrogen and phosphorous on water hyacinth biomass change under experimental conditions.

1.4 Hypotheses

1. There is no significant difference in the effects of water hyacinth biomass dynamics on the physico-chemical parameters of underlying water in different parts of the lake.
2. There is no significant difference in the uptake rates of nitrogen and phosphorous by different growth stages of water hyacinth.
3. There is no significant difference in the change in biomass of water hyacinth grown under different concentrations of nitrogen and phosphorous enrichment.

1.5 Justification

Lake Naivasha is a Ramsar site and plays a significant role in supporting livelihoods. The lake is increasingly becoming eutrophic; thereby, compromising its ecological and socio-economic roles. The data generated in this study provides information that relates the effects of nutrient input into the lake from the catchment and Naivasha Municipal wastewater discharge on water hyacinth biomass accumulation and degradation and the consequence to physico-chemical parameters of lake water. The nutrient requirement threshold for water hyacinth was determined, using data from the water hyacinth propagation experiments. Consequently, the half saturation coefficients (concentration of nutrients, when growth rate is ½ specific maximum growth rate) for N and P were established. Each aquatic ecosystem has its half saturation coefficients which consequently determines the rate at which biomass accumulates leading to various ecological and socio-economic problems associated with excessive biomass. The information from this study will contribute to science based aquatic weeds management strategies in Lake Naivasha, by formulating and implementing policies that will target minimization of water hyacinth multiplication through reduced input of nutrients into the lake.

CHAPTER TWO

LITERATURE REVIEW

2.1 Classification and morphology of water hyacinth Water Hyacinth is a monocotyledonous, vascular and flowering aquatic plant that belongs to the family Pontederiaceae. Some of the species in the genus *Eichhornia* include: *E. azurea* (Anchored Water Hyacinth), *E. crassipes* (Common Water Hyacinth), *E. diversifolia* (Variable leaf Water Hyacinth) and *E. paniculata* (Brazilian Water Hyacinth). Mature plants of water hyacinth (*Eichhornia crassipes*) consist of long, pendant roots, rhizomes, stolons, leaves, inflorescences and fruit clusters. The plant may grow up to 1 m high, although 40 cm is the usual height. The inflorescence bears 6-10 lily-like flowers, each 4-7 cm in diameter. The stems and leaves contain air filled tissue, which gives the plant considerable buoyancy (Herfjord *et al*., 1994).

2.2 Global and local distribution of water hyacinth

Water hyacinth (*Eichhornia crassipes*) is a prolific aquatic plant widely distributed in most of the tropical and subtropical countries. It is native to South America, particularly to the Amazonian basin and its worldwide distribution started as an ornamental plant first introduced into the USA in 1884 (Edwards, 1980). It reached Australia in 1895, India in 1902 and Malaysia in 1910. However, the time when the weed invaded or was introduced into Africa is uncertain, but it is thought to have begun to proliferate in Egypt during the later years of the 19th century. It started proliferating on Lake Kyoga in Uganda before 1987, when researchers sighted the weed on the lake (Twongo, 1988).

Botanists and gardeners carry plants with them in their travels, and experts suspect that this is how the water hyacinth came to East Africa. Since its flowers are beautiful, it was probably brought to East Africa as an ornamental for garden ponds (United Nations News, 2000). In 1989, Lake Victoria was invaded by water hyacinth and its presence in the Kenyan part was confirmed in 1992. The origin of the infestation is presumed to be the River Kagera Basin in Rwanda (Ochiel *et al*., 2001; Ambrose, 2008). The interdependence of the networks of African waters in the neighboring states has facilitated its spread to new aquatic environments. Its proliferation is attributed to lack of its natural enemies, an abundance of space, suitable temperature conditions, and abundant nutrients in the water bodies (Opande *et al*., 2004). According to KARI (2001), *Eichhornia crassipes* was first recorded growing as an ornamental plant in Kenya in 1957. It is currently found in Lake Victoria, Lake Naivasha and other water bodies including river systems. Wind movements and currents help to disperse the plant throughout the waterways.

Adams *et al*., (2002) and Mironga *et al.* (2011) stated that water hyacinth was first noticed in Lake Naivasha, in 1988. It subsequently spread throughout the entire lake in the 1990s but was particularly prevalent in northern shallow inshore waters. Earlier, the lake was infested by *Salvinia molesta* which first appeared in the lake in 1961. In 1989 over 75% of littoral zones were covered by *Salvinia* and by 1993 only 5% of the same sites surveyed supported the same density. At that time, *E. crassipes* had reached over 75% cover of the lake edges (LNRA, 1993). According to IUCN (2003), *E. crassipes* was reported in 1999 to be widely distributed in the lake with an overall frequency of 80% within the littoral fringes and scattered in open water where it formed patches. It rarely covered more than 5 % of the lake open water during that time. Plants in open water were generally less healthy than those in more sheltered fringes which grew vigorously and rooted in sediment forming mats especially in the absence or scarcity of emergent plants and more open shoreline (IUCN, 2003).

2.3 Factors that influence the establishment and proliferation of water hyacinth

The level of available nutrients is one of the most important factors that affect the establishment, growth and productivity of water hyacinth. Nutrients are taken up and used for reproduction and to build-up biomass. Nitrogen and phosphorous are the most important factors limiting growth (Wilson *et al*., 2001). Nitrogen is identified as limiting if total nitrogen concentration is less than seven times that of the phosphorus concentration (Wilson *et al*., 2005). Water hyacinth half saturation co-efficients for nitrogen and phosphorous are significant as they denote the concentrations of these nutrients at which, the growth rate of water hyacinth is at half the maximum growth rate. The half-saturation co-efficient for water hyacinths grown under constant conditions have been found to range from 0.05-1 mg/l for total nitrogen and 0.02-0.1 mg/l for phosphates. Below the lower limits, growth is likely to reduce drastically. Aziz (1981), in a study to determine the effect of the source and concentration of nitrogen on productivity of water hyacinth grown in a series of 0, 1, 2.5, 5 and 10 N mg/L found that the greatest productivity was obtained when the N concentration was 10 mg/ L. The growth rate of water hyacinth is strongly dependent upon the concentration of dissolved nitrogen (N) and phosphorus (P) within which it grows (Reddy *et al*. 1989, 1990). Reddy & Tucker (1983) found that rates of N and P uptake were correlated directly with growth. Sato and Kondo (1981) reported that the maximum growth rate of hyacinth can be achieved at 28 mg/L of total N and 7.7 mg/L of total P. However, such high levels of N and P may not be found in natural systems like Lake Naivasha.

Cultural eutrophication of lakes is a major problem around the world and can amplify the problem of nuisance floating plants. Weed growth can expand rapidly if the concentration of nutrients such as nitrogen and phosphorus increases in the aquatic systems. In Africa there are many examples of eutrophication leading to elevated weed biomass and the subsequent problems that this brings. In Zambia water hyacinth on the Lower Kafue River has been directly attributed to anthropogenic nutrient loading (Williams and Teckey, 2005). In Lake Victoria, water hyacinth was particularly abundant in Speke Gulf, Tanzania in the 1990s. This was most likely as a result of discharge wastes from Mwanza Town (APS, 1991). Likewise in Murchison Bay, Uganda where nutrient levels are typically 10 times higher than that found in open water, as a result of inputs from the city of Kampala, weed proliferation was and it's still greater than in many other areas of the lake (Williams and Teckey, 2005). Kitaka *et al*. (2001 & 2002) classified Lake Naivasha as eutrophic using different parameters. Eutrophication resulting from agricultural and urban run-off within Lake Naivasha catchment has aided the invasion of these aquatic weeds (Harper, 1992).

Other prevailing conditions in the atmosphere and water column may hasten or limit the establishment and proliferation of water hyacinth. According to Wilson *et al.*, (2001) salinity, temperature, disturbance and natural enemies limit the growth rate and population density of water hyacinth. Olivares and Colonnello (2000) reported that water hyacinth can survive in salinities of 1.3-1.9 parts per thousand in the Orinoco (South America), while Kola (1988) reported that the plant grew well at salinities below 1 ppt. Water hyacinth is known to thrive in all types of low salinity, lentic and lotic aquatic systems. It is believed that the relatively warm climates in the tropical fresh water bodies favour the establishment and proliferation of water hyacinth. Low temperatures limit the plant's establishment in temperate areas and prevent it from reaching high levels of growth rate and biomass accumulation in the sub-tropics. Imaoka and

Teranishi (1988) suggested that the intrinsic growth rate, r, increases exponentially with ambient temperatures in the range of 14-29 ºC and that growth ceases below 13 ºC. Frost is a major cause of leaf mortality in temperate regions. Wilson *et al.* (2005) examined the role of temperature and nutrient level on the growth of water hyacinth by applying mathematical modeling. They set up the minimum (Q min.), optimum (Q opt.) and maximum (Q max.) temperatures for water hyacinth as 8 ºC, 30 ºC and 40 ºC, respectively. The model predicted a linear recession in specific growth rate with density. In Lake Naivasha, the mean monthly temperature ranges between 20 and 23 °C (Oyugi *et al*., 2011). This is below optimum temperature required to achieve maximum growth of water hyacinth.

Other environmental factors that affect the growth of water hyacinth are humidity and natural disturbances. Low air humidity, ranging from 15-40 percent relative humidity limits growth. Natural disturbances, especially stochastic events like floods and strong currents can destabilize water hyacinth growth. Flooding can break up large mats of water hyacinth and leave plants stranded on land (Wilson *et al*., 2001). Wave action may limit growth by directly damaging plants and by forcing the weed to maintain aerenchymatous tissue. The five main factors limiting the growth rate and carrying capacity of water hyacinth are salinity, temperature, nutrients, disturbance and natural enemies (Wilson *et al*., 2001). Since Lake Naivasha is a fresh water system and humidity is optimal; thus, the main factors that are likely to limit the maximum growth of water hyacinth are temperature, nutrients and disturbance.

2.4 Efforts to control water hyacinth in Lake Naivasha

Water hyacinth control in Lake Naivasha has been focused upon biological control measures. Attempts to control the weed began in 1995. This was necessitated by the fact that enormous floating mats of the weed interfered with boat navigation, fishing, and even clogged up irrigation canals around the lake (Adams *et al*., 2002). Based on the data by Harper *et al*. (2011) water hyacinth had covered approximately 35 km^2 (25% of the lake) by 1995. According to IUCN (2003), a control method was instituted and involved two insects, *Sameodes albiguttalis* and *Orthogulma terebrantis* which failed to establish on/in *E. crassipes*. After that, two Curculionid beetles, *Neochetina bruchii* and *N. eichhorniae* were introduced, but by 1998 they had not started affecting the growth of the weed significantly. Kenya Agricultural Research Institute (KARI) imported water hyacinth weevils, *Neochetina bruchii* and *N. eichhorniae*, from the Plant Health Management Division of the International Institute for Tropical Agriculture in Benin in 1993 (Ochiel *et al*., 2001). The coverage reached approximately 38 km^2 (27 % of the lake) in 2000. After the weevils had established, the coverage by water hyacinth declined to a low of 5 km^2 (3.6 % of the lake) by 2005. An attempt to manage the weed using biological control involved the release of a large number of weevils at different sites around Lake Naivasha had a major impact upon the hyacinth (Mailu, 2001). However, after 2005, the coverage of water hyacinth increased steadily to approximately 28 km^2 (20 % of the lake) by 2010. *E. crassipes* and water hyacinth weevil populations have been oscillating in a 'classic' predator-prey cycle (Harper D., unpublished data, cited by Harper *et al*., 2011). The presence of *E. crassipes* and its coverage trend in Lake Naivasha from 1988 to 2010 has had a major influence in the biomass of other lake native plants as shown in Figure 1.

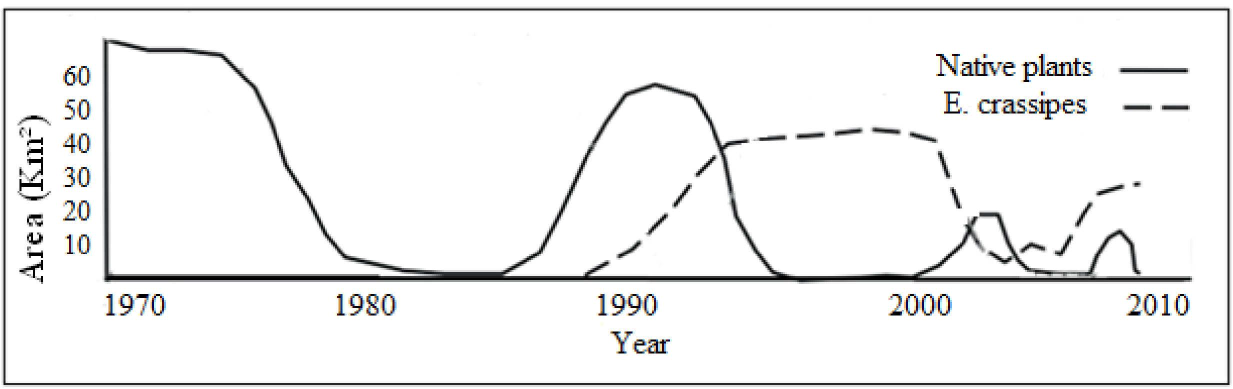

Figure 1: Temporal trends of native plants and *E. crassipes* cover in Lake Naivasha (Harper *et al*., 2011).

According to Gouder de Beauregard *et al.* (1998) cited in Harper *et al*. (2011) *Nymphaea nouchalii* var. *caerulea*, submerged *Potamogeton schweinfurthii, P. pectinatus, Najas horrida* and *Utricularia* sp. are some of the native plant species of Lake Naivasha that have become rare. Their population has been affected by invasive plants such as *Eichhornia crassipes* and *Salvinia molesta*, as well as cray fish (*Procambarus clarkii*), which was introduced in the Lake in 1970 (Harper *et al*., 2002a, Cited in Harper *et al*., 2011).

2.5 Reproduction and growth rates of water hyacinth

Water hyacinth can propagate vegetatively by use of stolons and sexually through seed production. Vegetative reproduction takes place with a rapid growth rate under preferential conditions (Herfjord *et al*., 1994). Water hyacinth produces an inflorescence with blue/white to violet flowers. Up to 400 minute seeds may be produced from fruiting capsules which develop from the inflorescence. These seeds usually sink and remain dormant in periods of stress, for instance drought. Upon flooding the seeds germinate. However, reproduction is mainly through vegetative propagation and growth rate is greatly enhanced by high nitrogen, phosphorus and potassium levels. Water hyacinths can double its mass in 6-15 days. A number of researchers have found that, under ideal conditions, water hyacinth is more prolific than any other known vascular plant (Gopal, 1987). The extremely high productive potential permits water hyacinth to grow quickly and outcompete other plant species (Schmitz *et al*., 1993), particularly in ecosystems affected by elevated nutrient levels and other forms of anthropogenic disturbance (Gopal, 1987).

The submerged roots and emergent leaves of water hyacinth make it to be a tremendously productive plant. Shoeb and Singh (2002) reported that under favorable conditions water hyacinth can achieve a growth rate of 17.5 metric tons per hectare per day while Coche (1983) reported a yield of 750 tons ha^{-1} $year^{-1}$ in irrigation canals in China. However, many of these reported yields are extrapolated. It may therefore not be possible to obtain the higher calculated productivities on a large scale, since it would be difficult to maintain high rapid growth rates obtained on a small experimental scale throughout the year (Edwards, 1980). Edwards further proposed that an annual production of 200 tons $ha^{-1}year^{-1}$ can be realized in eutrophic waters in the tropics. However, productivity varie**s** widely from place to place and it is dependent on the environmental conditions under which the plant grows as is evident in table 1.

Table 1: Production by water hyacinth in different aquatic environments

Aquatic environment	Biomass production (tons/ ha/year)
Fertile ponds in Thailand	15-200
Fertilized pond with sewage effluent	75.6-191.1
Irrigation canals in China	212-657
Nutrient non-limiting water of Florida, USA	400-750
Man-made lakes of central Java, Indonesia	106
	255

Source: Edwards (1980); Little and Muir (1987)

2.6 Ecological effects of water hyacinth

Water hyacinth has impacts on the physico-chemical characteristics of the underlying water which in turn influences the productivity and species composition of the system. Ecosystem surveys indicate that various aquatic plants such as water hyacinth, water lettuce, and *Hydrilla* spp. provide attractive habitat for crayfish, apple snails, amphipods, fish and other springs' fauna at moderate levels of coverage. However, as their mats thicken and enlarge over the water surface, more negative consequences are likely to arise. Herfjord *et al.* (1994) suggested that the rate of water loss due to evapotranspiration by water hyacinth can be as much as 1.8 times, that of the same water surface free of the plants.

Water hyacinth and water lettuce release allelopathic compounds capable of suppressing the growth of a number of algal taxa (Jason, 2006). Extensive growth over the open water surface is known to cause reduction on productivity of a lake's phytoplankton since the weed shade out the photoautotrophs (both phytoplankton and also submersed macrophytes) beneath them (Scheffer *et al*., 2003; Zimmels *et al*., 2007). A report by Harley *et al.* (1997) stated that where water hyacinth is prolific in growth, other aquatic plants have difficulty in surviving. This causes an imbalance in the aquatic micro-ecosystem and often leads to a negative influence on a range of fauna that relies on a diversity of plant life for existence. Mironga *et al.* (2011) in a study in Lake Naivasha, revealed that phytoplankton productivity is reduced when water hyacinth is present, suggesting that the water hyacinth is not only a nuisance but that it can also alter the ecology within the lake by changing species composition and biodiversity. The diversity of fish stocks is often affected with some benefiting due to increase in breeding and feeding sites while others suffer from the proliferation of water hyacinth through degradation of habitat and reduction in water quality. In addition, the roots of the water hyacinth have been found to provide favourable habitat for gastropods that are intermediate hosts of the waterborne parasite that causes schistosomiasis (Masifwa, 2001).

2.7 Effects of water hyacinth on water quality

According to Villamagna (2009), the effects of water hyacinth on water quality are similar worldwide but the magnitude of the effects is dependent on the percentage cover and partially on the configuration of water hyacinth mats. Degradation of dead plant matter under the water hyacinth mats by aerobic bacteria take up oxygen. This leads to decline in oxygen under the water hyacinth mats (Ntiba *et al*., 2001). Randomly selected sites with hyacinth in Lake Chivero, Zimbabwe, were more turbid with low oxygen concentration, low pH and nitrate values and high levels of COD (Rommens *et al*., 2003). People often complain of localised water quality deterioration in hyacinth infested waters (Harley *et al*., 1997).

Water hyacinth's nutrient uptake capacity and the subsequent effect on water quality has been validated in several field studies. It has a high nutrient uptake rate compared to other macrophytes (Rodríguez-Gallego *et al.*, 2004); therefore, it has the potential to significantly reduce nutrient concentrations in a water body through uptake and storage in biomass depending on the extent of cover and density (Pinto-Coelho and Greco, 1999). Overall, nutrient uptake is thought to vary by season, with greater uptake in the summer when temperatures are higher and more favorable for plant growth (Rommens *et al.*, 2003; Rodríguez-Gallego *et al.*, 2004). Reddy and Tucker (1983) investigated productivity and nutrient uptake rates of water hyacinth in systems receiving urea and methane digester effluents. They observed that under the most favorable conditions, maximum N and P removal rates were 2,161 mg N m^{-2} day^{-1} and 542 mg P m^{-2} day^{-1}. Rommens *et al*. (2003) found out that maximum values of 0.1% of Nitrogen and 0.025% of Phosphorous were taken up daily by water hyacinth from total nitrate and phosphate stocks, respectively. According to Kutty *et al*. (2009) water hyacinth effectively removed approximately 81% of ammonia, 67% of phosphorus and 92% of nitrate from municipal waste effluent. Its potential to strip off nutrients and heavy metals from the water column lowers the concentration of these substances; hence, improves the quality of water with regards to nutrients and heavy metals. However, upon senescence plants release nutrients back into the water column (Rodríguez- Gallego *et al.*, 2004), thereby negating the benefits of nutrient removal from highly eutrophic systems (Giraldo & Garzon, 2002). Bacterial decomposition of dead water hyacinth contributes to mineralization, hence increasing the oxygen demands (Bianchini *et al*., 2008).

CHAPTER THREE
MATERIALS AND METHODS

3.1 Study area

The study was carried out in Lake Naivasha, Kenya. The lake which lies on the floor of Africa's Rift Valley, is located at $0^{o}45'$S, $36^{o}20'$E with an altitude of 1890m above sea level, and covering approximately 140km^2 (Bercht *et al*., 2006). It is the second largest fresh water lake in Kenya and one of a series of twenty three lakes in the Eastern arm of Africa's Great Rift Valley spanning latitudes from approximately 7^{o}N to 5^{o}S (Bercht *et al*., 2006). Lake Naivasha is a shallow endorheic lake basin and has two perennial inflowing rivers namely; Malewa River and Gilgil River and an intermittent River Karati as shown in Figure 2.

According to Mireri (2005), Lake Naivasha is located in the rain shadow of the Aberdare Range with a mean annual rainfall of about 650mm. The mean annual rainfall in the Aberdare Range is 1350mm. Most of the upper parts of the catchment are considered semi-humid and are suitable for rain-fed agriculture, whereas the area around the lake is classified as semi-arid. The lake itself is located in the south east of the catchment and consists of four lake basins; the main lake, Crescent Island, Oloidien and Sonachi Crater Lake. Sonachi Crater Lake is situated in the south west of the main lake and is completely detached, while Oloidien is located to the south of the main lake and it is influenced by the main lake level fluctuations making it either part of the main lake during high water levels or separate completely at low water levels, at different times of the year (WWF, 2011).

Lake Naivasha is currently under intensive scrutiny over concerns about how its environmental integrity can be maintained whilst still supporting a valuable and growing economy and society. Agricultural activity in the basin has expanded dramatically in terms of both the rural smallholder farmers in the upper catchment and the high value exported commercial horticulture around the lake anchors a local economy that supports almost 650 000 people (WWF, 2011), however the influence of this in the lake's hydrology should not be ignored.

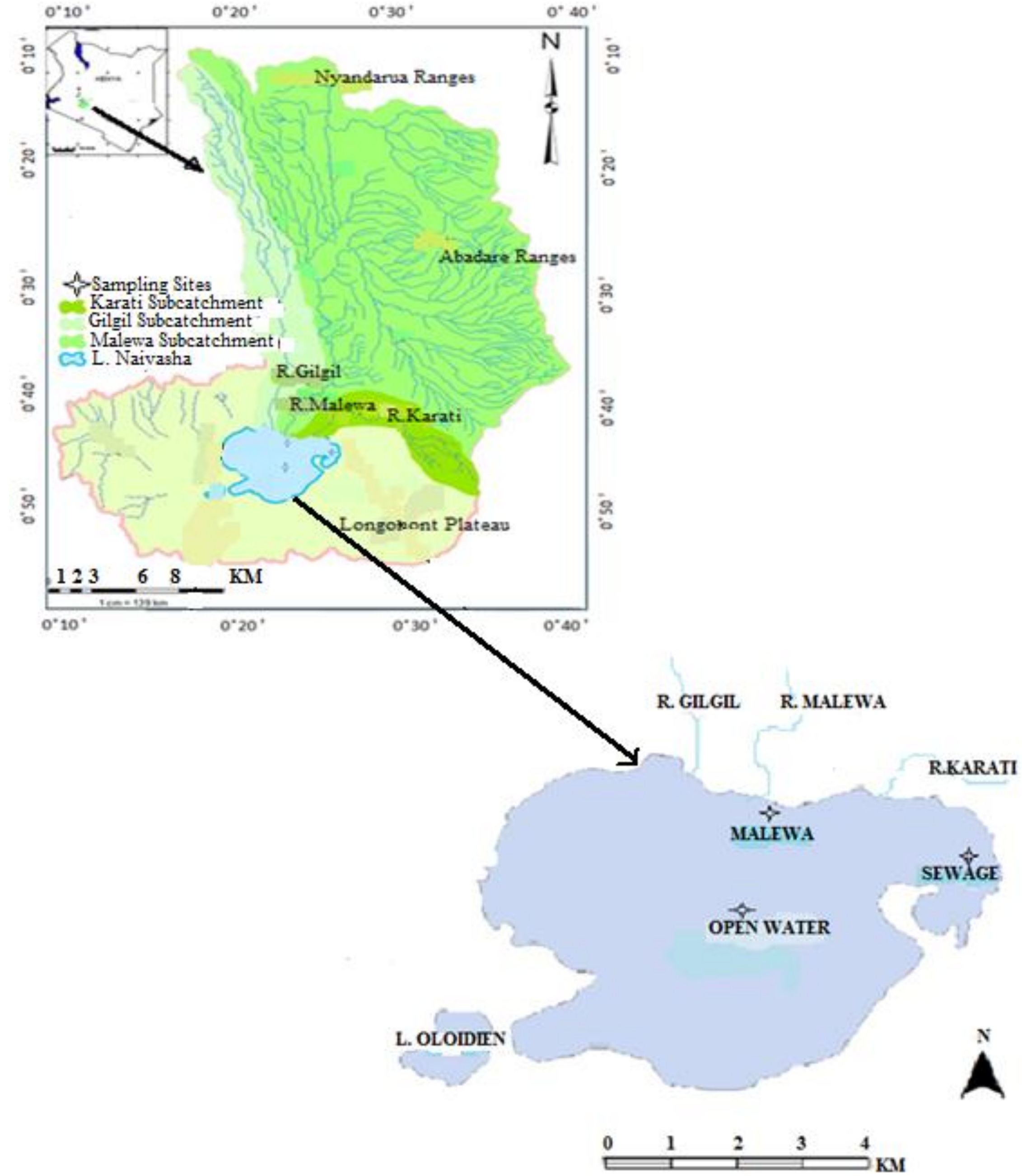

Figure 2: Map of Lake Naivasha and its catchment showing the sampling sites.

3.2 Study design

3.2.1 Description of sampling sites

The study was carried out in three selected sites in Lake Naivasha; the point off the Naivasha municipal wastewater treatment plant, Malewa River inlet (both with hyacinth cover) and pelagic zone (mid-lake) without water hyacinth cover as the water quality control site. The site situated off Naivasha Municipal wastewater will there after be referred to as "Sewage" whilst Malewa River inlet site will be refered to as referred to as "Malewa" in the rest of the text. The study sites were located at 00° 46' 21.1" S, 36° 24' 48.9" E for the Sewage, 00° 43' 39.60" S, 36° 21' 17.85" E for Malewa and 00° 48' 40.5" S, 36° 20' 40.8" E for the open water site. The two sampling sites with hyacinth are shown in Plate 1.

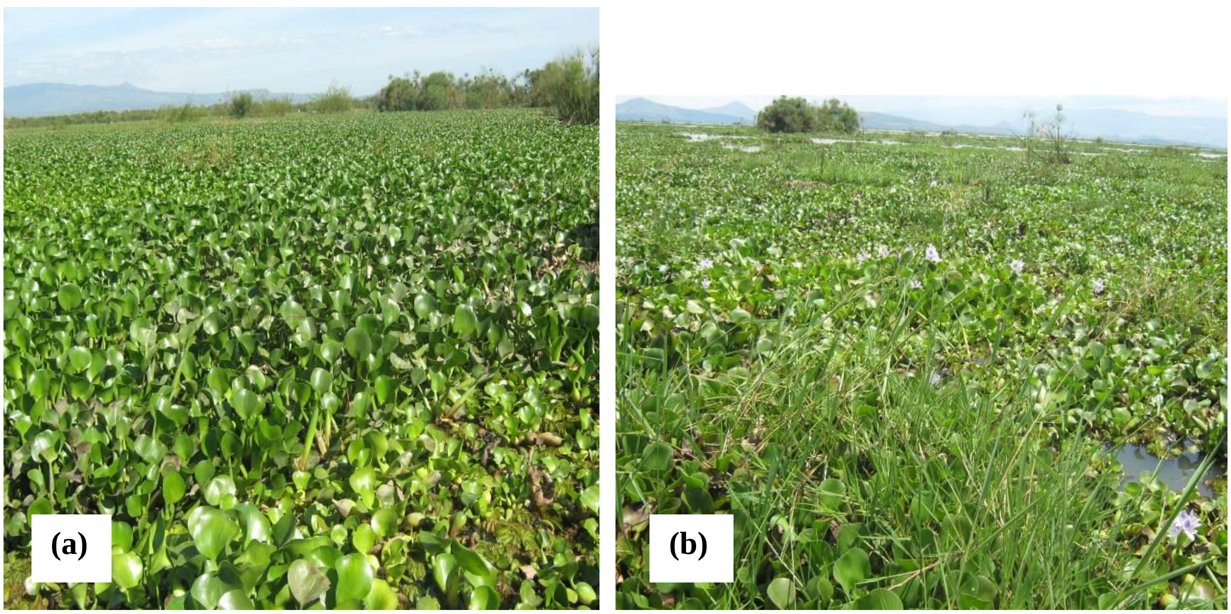

Plate 1: Sites with water hyacinth; (a) off municipal wastewater treatment station (Sewage) and (b) Malewa River inlet station (Malewa).

Sewage and Malewa were chosen due to the prevalence of water hyacinth in the two sites with the later situated in the nothern shores of the lake and potentially receiving nutrient input from Rivers Malewa, Gilgil and Karati and sewage off shore the Naivasha Municipality wastewater treatment plant. The choice of this two stations targeted the difference in water hyacinth biomass dynamics and physico-chemical parameters. The open water site situated in the mid-lake region, away from direct nutrient input from either point or diffuse sources via the adjacent land. This station was used as the control site, especially with reference to the physico-chemical parameters of the underlying water.

3.2.2 Sampling of water and measurement of physico-chemical parameters

Sampling was done twice a month for a period of five months (September 2011 to January 2012). The sampling time was between 9.00 am and 12.00 pm, when the lake was calm to avoid the effects of the afternoon winds induced turnover. In the areas with water hyacinth cover, water samples were obtained below the pure water hyacinth dense mats. Intergrated water samples were taken along a depth profile in the water column; at the surface, in the middle and at the bottom using a schindler sampler. The mid-point of the water column was established by first determining the total depth of the water. The collected water samples were transfered into clean acid washed 500 ml plastic bottles. Water samples were placed in a cool box and transported to Egerton University, Department of Biological science laboratory where the samples were analysed in the laboratory for TSS, NH_4^+, NO_3^-, NO_2^-, SRP and TP on arrival. At each sampling point and sampling depth, dissolved oxygen concentration, electrical conductivity, temperature and pH were measured *insitu* using a multimeter (HACH model HQ40d) and appropriate probes. The probes used were LDO^{TM} for dissolved oxygen concentration and temperature, CDC401 for conductivity and PHC101 for pH. Water transparency was determined using a black and white Secchi disk of 20 cm diameter. In places with high floating plant density, secchi depth measurements were achieved by first pushing aside the plants to give space (0.5 m^2) for the lowering of the secchi disc.

3.2.3 Sampling of water hyacinth

Sampling was done in the same period and frequency as the physico-chemical parameters. Random sampling was done in triplicate per site, with a distance of approximately 50 m between the sampling points, within each of the sites. Using a 0.5m × 0.5m wooden quadrat, the density of *E. crassipes* per square metre was determined by counting the number of offshoot plants within the quadrat. The number of juveniles (newly developing shoots) within the population was also determined. Live plants from each quadrat were taken for the determination of the dry weights biomass. Dead plants were removed from the quadrat for the determination of senesced biomass. Hyacinth was packed in polythene bags and transported to Egerton University, Department of Biological science laboratory for analysis on arrival.

3.2.3 Experimental setup for determination of the effect of nutrient treatment on growth of *E. crassipes*

An experiment was set up in November, 2011 at the Kenya Marine and Fisheries Research Institute station located at 00^o 46' 28.3"S, 36^o 25' 41.9" E and about 1km from the lake shore. The choice of the experimental site was to ensure that the experiment was safe from external disturbances and also to avoid introducing additional variability that would arise if the experiment was conducted far away from the lake. The purpose of the experimental set-up was to determine the nutrient uptake rates of water hyacinth and their subsequent effects to biomass change. Two stages of plant growth (young and mature) were used for setting up the experiments. In this study, young plants (juveniles) were identified as newly developing shoots from the parent plant, whilst mature plants were those having a juvenile attached to it. Individual young and mature (parent) plants were detached from the stolons and weighed to obtain wet weights. The young and mature plants that were used at the beginning of the experiment weighed 12±0.96g and 150±2.19g respectively at the beginning of the experiment. An example of a young plant developing from a stolon of a mature water hyacinth is shown in plate 2.

Plate 2: Mature water hyacinth with a young plant (juvenile) attached to a horizontally growing stolon

The plants were grown in 20 liter buckets of approximately 30 cm diameter (0.071 m^2 surface area) with water of six levels of N and P supply (0, 0.01, 0.15, 1.60, 6.40 and 25.60 mg N/L and 0, 0.012, 0.038, 0.20, 0.80 and 3.20 mg P/L respectively). The third nutrient level (0.15 mg N/ L and 0.038 mg P/ L) was that of buckets filled with lake water as the control. Except for the setup with lake water, the other five levels were made enriching distilled water using Ammonium Nitrate and Sodium phosphate. The different levels of N and P concentration was to mimic water systems with low to moderate and high nutrient levels and the subsequent effect of nutrient levels on the biomass accumulation of water hyacinth. To each of the nutrient enriched buckets, 2 mg/l of Potassium (K) and was added in form of K_2SO_4. K is a major plant nutrient that can potentially limit the growth and nutrient uptake by hyacinth. The buckets with nutrient levels above that of the lake water were enriched intermittently with the starting concentration of N and P on three occasions during the three months (33^{rd}, 47^{th} and 72^{nd} day). This was done so as to replenish the N and P that has been used up by the plants. Replenishment was not done for the buckets with lake water and with nutrient levels lower than the lake water. This was to observe how growth of water hyacinth would be affected after the growth medium was depleted of nutrients to mimic different scenarios which would occur in the lake at different times. Dead plant parts were removed regularly to prevent decay and release of nutrients back into the water. The experimental set up is shown in the Figure 3.

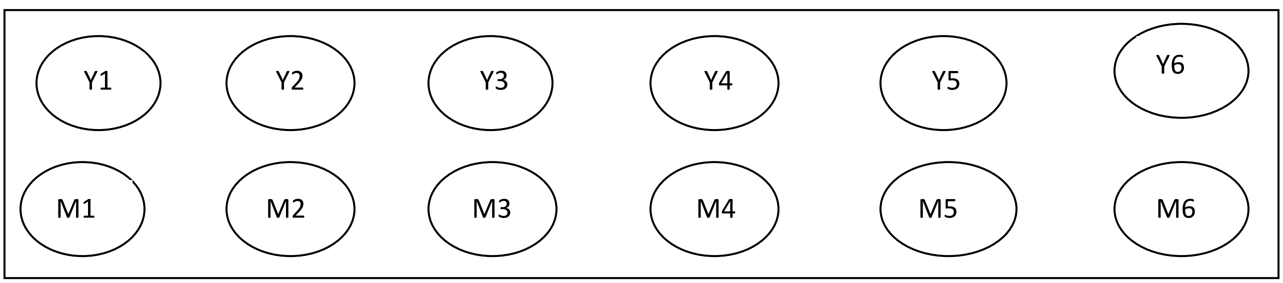

Figure 3: Experimental set up to show water hyacinth growth and nutrient uptake rate under different levels of nutrient enrichment, where the letter denotes developmental stage and number- the level of nutrient enrichment.

<u>KEY</u>

⬭	Buckets
Y	Young water hyacinth
M	Mature water hyacinth
1	Distilled water
2	Distilled water enriched with 0.01 mg N/L and 0.012 mg P/L
3	Lake water (0.15 mg N/ L and 0.038 mg P/ L)

4	Distilled water enriched with 1.60 mg N/L and 0.20 mg P/L
5	Distilled water enriched with 6.40 mg N/L and 0.80 mg P/L
6	Distilled water enriched with 25.60 mg N/L and 3.20 mg P/L

3.2.4 Laboratory samples analyses

a) TSS determination

TSS determination followed the standard procedures as given by APHA, 2005. A volume of 100 - 300 ml of water samples was filtered through pre-weighed Whatman 0.47 GFC Glass micro-fibre filters (no 32, 0.6–0.7 µm pore size, 47mm diameter circles) that had been dried at 95 ±5°C for about 6 hours until a constant weight was achieved. The filtrate was used for the determination of dissolved nutrients concentration, while the filter papers with the residue were used for determination of TSS. The suspended solids weight was calculated as follows:

$\mathrm{TSS}\ (\mathrm{mg\ l}^{-}) = (\mathrm{Wc} - \mathrm{Wf}) \times 10^{6})\mathrm{V}^{-}$)...........equation 1(APHA, 2005)

Where: TSS = Total Suspended Solids, Wf = Weight of pre-dried filter in grams and V = Volume of water sample used in ml

Wc = Weight of pre-dried filter paper + residue in grams

b) Nutrient analysis

In the laboratory nutrient analyses were undertaken using standard methods prescribed by the American Public Health Association (APHA, 2005). The soluble nutrients, including SRP, NO_3-N, NO_2-N and NH_4-N were analysed from filtered water samples, while unfiltered water samples were used for TP analysis after persulfate digestion to SRP. The SRP was analyzed using the ascorbic acid method with absorbance read at a wavelength of 885 nm. Nitrate - nitrogen (NO_3-N) was analysed using the salicylate method with the spectrophotometric absorbance read at a wavelength of 420 nm. Nitrite-nitrogen (NO_2-N) concentration was determined based on the chemical reaction between sulfanilamide and N-naphthyl-(1)-ethylendiamin-dihydrochloride to develop a pink colour. The intensity of colour formed was read at 543 nm. Ammonium-nitrogen (NH_4-N) was analyzed through the reaction between sodium salicylate and hypochloride solutions and the spectrophotometric absorbance of the green colour was read at a wavelength of 655 nm. The absorbance values read were used to work out the concentration using equations generated from the standard calibration curves made for each of the nutrient species.

c) Determination of water hyacinth dry biomass

The average dry weights for live and senesced plants within the quadrats were obtained and computed as dry weights per square meter. This was done by chopping the plants which were packed in paper bags and dried at 80^{o}C until a constant weight was achieved after a period of five days. The average dry weight and moisture content was calculated as a percentage of the fresh weight as follows:

$$\text{Dry weight (\%)} = \frac{\text{Dry weight}}{\text{fresh weight}} \times 100 \text{.......equation 2}$$

3.2.5 Determination of nutrient uptake and growth of *E. crassipes* in the experimental setup

a) Determination of nutrient uptake

From each of the buckets enriched with N and P, water samples were taken on five different occasions on time duration indicated below within a period of 86 days and analysed for NH_4-N, NO_3-N and SRP. The concentrations of these nutrients per liter were multiplied by the volume of the water in the buckets to determine amount nutrients within the buckets. Sampling was done on the 19th, 33rd, 47th, 72nd and 86th day. Nutrient uptake rate of the water hyacinth was determined by measuring the residual N and P in the growth medium after a specific growth period on a known amount of nutrients. The remaining nutrients concentration in the medium was subtracted from the initial amount to get the amount of N and P that had been taken up by the plants. This was then divided by the number of days between the enrichment date and the sampling date in order to obtain the rate of uptake per day. Nutrient uptake rate was calculated using the equation 3 below:

Nutrient uptake rate (mg /day) = $\frac{\text{iC} - \text{rC}}{\text{Time in days}}$ ....equation 3 (Rommens *et al*., 2003)

Where: iC = Initial amount of nutrients at the start of a growth period (mg), rC = residual nutrient at the end of a growth period (mg).

The equation is based upon the assumption that nutrient uptake by the plant biomass is the sole removal mechanism. The uptake rates in an area of 0.071 m^2 was computed to uptake rate per square meter.

b) Determination of the biomass change and multiplication of water hyacinth

The wet weights and number of newly produced plants (juveniles) were determined on the 1st, 19th, 33rd, 47th, 72nd and 86th day. The plants were removed from the water, shaken gently and allowed the water to drain for about three minutes, before being weighed on a balance to determine the cumulated biomass at different times during the growth period. The weighed plants were returned into the buckets. The rate of biomass change per day was computed by dividing differences in cumulative biomass within a known period by the number of days. The cumulative biomass and rates of biomass change per square meter were computed.

c) Calculation of half saturation constants

The relationship between specific rates of change in biomass and nutrient concentrations of N and P was described using the curve in Figure 4, based on Monod's kinetics (Monod, 1942).

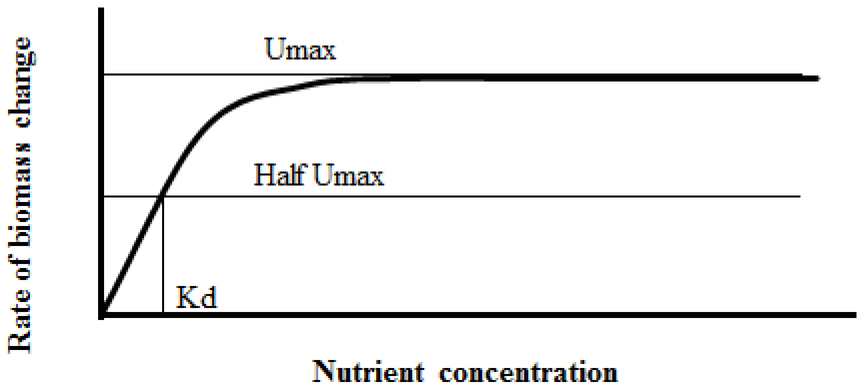

Figure 4: Rate of biomass change as a function of nutrient concentration

The equation describing the curve above is;

$$U = Umax \frac{Cn}{Cn + Kd} \text{..................equation 4}$$

In which U is the rate of biomass change, Umax is the maximum specific rate of change in biomass, C*n* is the concentration of nutrients and K*d* is half saturation constant (the concentration of nutrients, when growth rate is ½ specific maximum growth rate). It is known that the value of k*d* has an effect on the change in U at different values for C*n*.

3.3 Data analysis

Statistical tests and data analysis were done using SigmaStat version 3.5 graphics Software. In all the analyses, 95% level of significance was used as the critical point (P= <0.05). Physical and chemical data were summarized into tables, and presented using bar graphs and line graphs. The data sets were tested for normality prior to use of parametric statistical tests. The data from the experiment had non-normal distribution and thus transformed then analysed using non parametric statistics. Nutrient uptake rates between the young and mature plants were analysed using Man-whitney U test. Biomass accumulation by the young and mature water hyacinth grown in different levels of nutrient enrichment was analyzed using Kruskal-wallis one way ANOVA on Ranks test. Data on physico-chemical parameters (EC, DO, Temperature, NO_3^-, NO_2^-, NH_4^+, SRP, TP, TSS and Secchi depth) were computed for all the stations to find their mean values. pH values were reported as ranges. The data had normal distribution and one-way ANOVA was used to compare means recorded on different sampling dates and sites for the various variables. Means were separated using Least Significance Difference (LSD) of the Post Hoc test. Pearson's correlation was used to compare the relationship between the following; water hyacinth biomass and density and the subsequent impacts on the physico-chemical characteristics of water such as, DO, TSS, electrical conductivity, temperature and nutrient concentration.

CHAPTER FOUR

RESULTS

4.1 Variation of physico-chemical parameters between the sampling sites

The results for the means, standard deviations and range values for physico- chemical parameters from the three sampling sites are presented in Tables 2. Malewa and Sewage sites recorded means of 73.86±36.96 and 51.13±14.73 mg/l respectively for TSS. The mean value for the concentration of TSS was 26.78±15.9 mg/l in the open water site. Secchi depth was highest in the open water with a mean value of 58.5±25.86 cm, while Malewa and Sewage sites had mean values of 26.90±8.16 and 25.20±6.53 cm respectively. Dissolved oxygen mean values at the Sewage and Malewa stations were 2.19±1.07 mg/l and 2.79±1.91 mg/l respectively. This was very low compared to the open water site where dissolved oxygen concentration was 6.17±1.11 mg/l. pH ranges of 6.85-9.18, 6.16-8.1 and 5.5-8.25 were recorded for open water, Sewage and Malewa sites respectively.

The secchi depth values for the open water were significantly higher than for Malewa and Sewage sampling sites, while TSS was lower in open water using One-way, ANOVA, F= 9.06 and 13.57 respectively, df= 3, 29 and P< 0.05. The average water temperature was higher in the open water than in Malewa, using One-way, ANOVA, F= 3.790 and 2.650 respectively, df= 3, 29 and P< 0.05. The electrical conductivity for the Sewage station (320.25±69.33 µS/ cm) was significantly higher than in the open water (243.20±29.34 µS/ cm) and Malewa (200.56±39.04 µS/ cm) sampling sites, using One-way, ANOVA, F=, 15.352, df= 3, 29 and P< 0.05, whereas dissolved oxygen concentration was significantly higher in the open water as compared to Sewage and Malewa using, One-way, ANOVA, F= 23.03, df= 3, 29 and P< 0.05. In the three sampling stations, the mean values for SRP, NO_3^-, NO_2^- and NH_4^+ showed no significant difference, using One-way ANOVA, F= 0.096, 0.207, 1.315 and 0.705 respectively, df= 3, 29 and P> 0.05, but total phosphorus concentration in Malewa (0.149 mg/l) was significantly higher than in the open water (0.075 mg/l) using One-way, ANOVA, F= 3.790 and 2.650 respectively, df= 3, 29 and P< 0.05.

Table 2: TSS, secchi depth, DO, EC, pH, temperature, Nitrogen and Phosphorus for the sampling sites (values are means ± standard deviations except for pH which is given as ranges)

Parameter	Sewage	Malewa	Open water
TSS (mg/ L)	51.13± 14.73	73.87±36.96*	26.78±15.90
Secchi depth (cm)	25.20 ± 6..53	26.90±8.16	58.50±25.86*
DO (mg/L)	2.19 ± 1.07	2.79±1.91	6.17±1.11*
EC (µs/ cm)	320.25± 69.33*	200.56±39.04	243.12±29.34
pH	7.24±0.57	7.19±0.71	8.23±0.62*
Temperature (°C)	20.94± 0.41	20.51±0.85	21.29±0.55*
NO_3-N (mg/l)	0.086± 0.051	0.111±0.108*	0.097±0.087
NO_2-N (mg/l)	0.003± 0.002	0.009±0.009*	0.006±0.009
NH_4-N (mg/l)	0.016±0.057	0.048±0.029	0.080±0.094*
SRP (mg/l)	0.022±0.038	0.019±0.012	0.025±0.035*
TP (mg/l)	0.136±0.090	0.149±0.094*	0.075±0.033

Asterisks indicate the highest mean values.

4.2 Temporal variation of physico-chemical parameters in the lake

The values for physico-chemical parameters in the study sites showed significant variation during the five months of study (Table 3). Water transparency varied over time with a gradual increase in turbidity from the dry period (September-October, 2011) to the rainy season (November-December, 2011). The secchi depth readings in January 2012 were significantly higher than in September, October and November in the Malewa site and significantly lower in December than in October at the Sewage, using One-way, ANOVA, F= 25.377, df= 14, 44 and P< 0.05. In the open water, secchi depth readings were significantly higher in December and January as compared to September, October and November. The TSS concentrations did not show significant temporal variation in the open water and Sewage sites but was significantly higher in December than November in Malewa, using One-way, ANOVA, F= 4.215, df= 14, 44 and P< 0.05. However, in October and December, TSS concentration was significantly higher in Malewa than Sewage. Water temperature in the open water was lowest in January while in Malewa and Sewage sites, temperature was significantly lower in November than in October and September, using One-way, ANOVA, F= 3.584, df= 14, 44 and P< 0.05. The values for electrical conductivity reduced from September to December in the three study sites. The highest EC mean value (420.42 µS/cm) was recorded in September at Sewage and the lowest (153.59 µS/cm) in December at Malewa with November and December having significantly lower electrical conductivity values than September, October and January at the Sewage and Malewa sites. In the open water site, the electrical conductivity value for December was significantly lower than for September, October, November and December, by One-way, ANOVA, $F= 46.990$, $df= 14, 44$ and $P< 0.05$.

Dissolved oxygen concentration and pH ranges in the lake also showed variation during the study. The lowest pH ranges were recorded in November and December. In the Sewage sampling site, dissolved oxygen concentration was significantly higher in January than in November and December by One-way, ANOVA, $F= 13.225$, $df= 14, 44$ and $P< 0.05$. In the Malewa site, dissolved oxygen concentration was significantly lower in October than in September and December whereas the open water site had significantly lower values in December than October, September and November, using One-way, ANOVA, $F= 13.225$, $df= 14, 44$ and $P< 0.05$.

Table 3: Temporal variation of TSS, secchi depth, temperature, EC, DO and ranges for pH in sampling sites (data presented as means ± standard deviations).

Parameter	Site	September	October	November	December	January
TSS (mg/l)	Sewage	47.28±14.42	36.06±7.08	64.89±11.17*	49.33±3.84	56.22±10.54
	Malewa	66.06±32.36	76.73±1.51	51.89±13.50	94.22±51.67*	78.83±35.75
	Open water	38.67±5.18	41.17±7.25*	31.72±8.84	12.28±10.69	9.61±1.67
Secchi depth (cm)	Sewage	29.50±5.5	31.00±6.00*	24.00±1.00	17.00±1.00	24.50±1.50
	Malewa	23.50±6.50	19.33±16.56	21.50±5.50	24.00±3.00	37.50±2.50*
	Open water	37.50±7.50	40.00±1.20	47.50±7.50	69.50±14.50	99.67±14.41*
Temperature (° C)	Sewage	21.38±0.39*	20.74±0.19	20.54±0.19	21.27±0.10	20.79±0.06
	Malewa	20.58±0.14	21.20±1.40*	19.99±0.66	20.54±0.19	20.23±0.03
	Open water	21.82±0.18*	20.72±0.44	21.55±0.09	21.41±0.54	20.60±0.45
EC (µs/cm)	Sewage	420.42±43.38*	342.92±14.88	313.50±10.75	234.99±8.81	289.17±2.75
	Malewa	212.87±15.54	219.84±25.73	173.01±22.12	153.59±1.57	245.06±6.58*
	Open water	267.94±12.92*	258.20±0.82	254.94±6.64	191.48±0.83	243.10±1.49
Oxygen (mg/l)	Sewage	2.52±0.42	2.14±0.69	0.98±0.58	1.61±0.31	3.64±0.23*
	Malewa	4.03±1.93*	1.31±0.91	2.56±2.28	3.41±1.07	2.58±1.15
	Open water	6.34±0.23	7.57±0.16*	6.22±0.63	4.59±0.32	6.06±0.63
pH	Sewage	7.47-7.64	6.8-7.95	6.40-7.45	6.40-6.80	7.20-8.10*
	Malewa	7.48-7.87	7.00-7.58	5.50-6.58	6.15-6.69	7.50-8.25*
	Open water	8.61-9.18*	8.50-9.14	6.96-8.72	6.85-8.80	7.60-8.66

Asterisks indicate the highest mean values and range values for each site.

Phosphorus concentrations showed significant variation in the lake during the five months of study as shown in Figure 5 and Appendix table 1. The concentrations of TP in December were significantly higher than in the other four months in the Malewa site (One-way, ANOVA, F= 5.693, df= 14, 44 and P< 0.05). At the Sewage site, TP concentrations in November, December and January were significantly higher than in September and October (One-way, ANOVA, F= 5.693, df= 14, 44 and P< 0.05). In the month of December, the TP concentration was significantly higher at Malewa compared to Sewage and open water sites (One-way, ANOVA, F= 5.693, df= 14, 44 and P< 0.05). The concentration of SRP in December was significantly higher than in the other four months at the Sewage site (One-way, ANOVA, F= 2.096, df= 14, 44 and P< 0.05). Malewa showed no temporal variation with regard to SRP concentration while in the open water; SRP concentration was higher in November than in December and January. However in December, SRP concentration in the sewage site was higher than in Malewa and open water (One-way, ANOVA, F= 2.096, df= 14, 44 and P< 0.05).

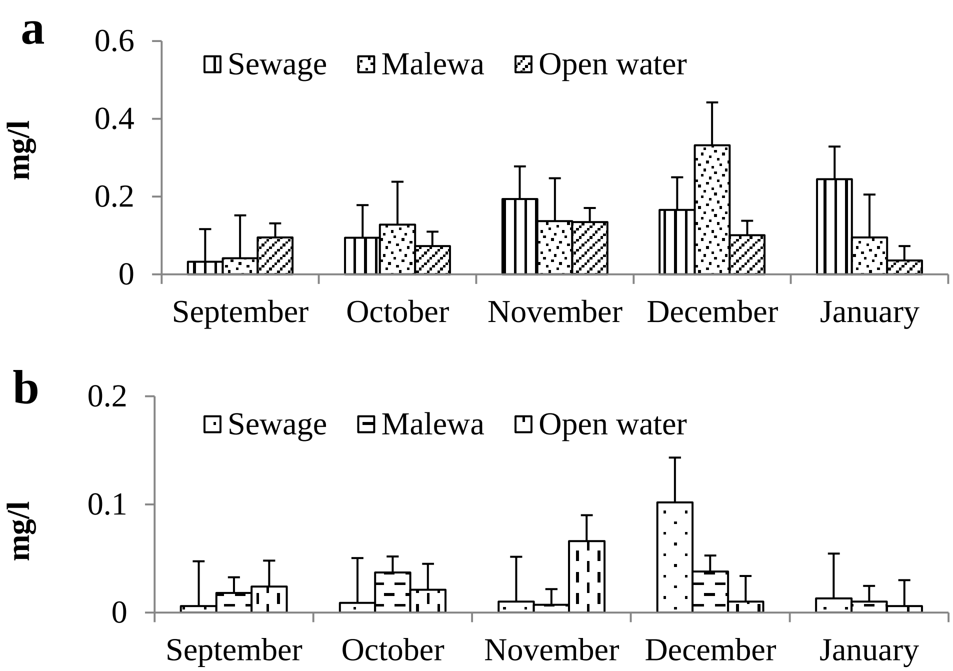

Figure 5: Temporal variations of (a) TP and (b) SRP concentrations in the study sites (values are means±SD, n=30).

The concentrations of NO_3-N, NO_2-N and NH_4-N varied significantly over time (Figure 6 and Appendix table 1). At the Malewa site, significantly higher concentrations of NO_3^- and NO_2^- were recorded in November and December as compared to September, October and January (One-way, ANOVA, F= 3.441 and 3.259, df= 14, 44 and P< 0.05). The concentration of NO_3^- at the Sewage site was significantly higher in December than January while at the open water site, September and October recorded higher values than January (One-way, ANOVA, F= 3.441, df= 14, 44 and P< 0.05). The open water site had a significantly higher concentration of NO_2^- in December and January as compared to September, October and November (One-way, ANOVA, F= 3.259, df= 14, 44 and P< 0.05). Malewa site recorded a significantly higher concentration of NO_2^- than Sewage and open water sites in December (One-way, ANOVA, F= 3.259, df= 14, 44 and P< 0.05). The concentration of NH_4^+ did not show significant variation in the Malewa site but was higher in December than in October, November and January at the Sewage and open water sites (One-way, ANOVA, F= 5.196, df= 14, 44 and P< 0.05). During December and January, the concentrations of NH_4^+ at the open water site was higher than in Malewa and Sewage sites (One-way, ANOVA, F= 5.196, df= 14, 44 and P< 0.05).

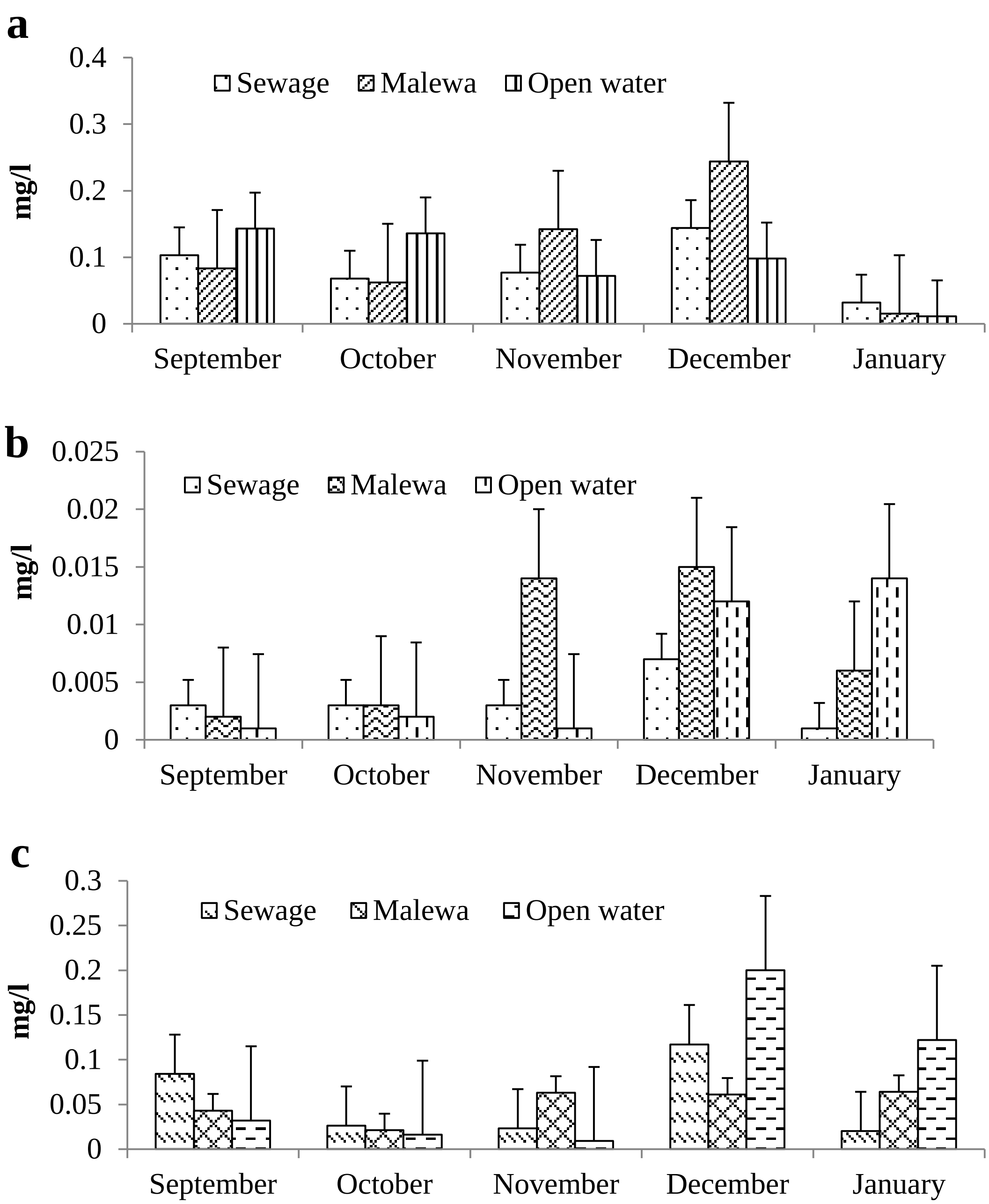

Figure 6: Variation of (a) NO_3-N, (b) NO_2-N and (c) NH_4-N concentrations in the study sites over time (values are means±SD, n=30).

4.3. Water hyacinth biomass and density in the Sewage and Malewa sampling sites

The dry weight biomass values for water hyacinth were similar in both sites. The means for biomass were 18.9 and 18.2 tons/ha in Sewage and Malewa sampling sites respectively (Table 4). The proportion of senesced biomass to live biomass was 21.01 and 19.04% in Malewa and Sewage respectively. There was no significant variation in the values of water hyacinth population density and number of plant juveniles in Malewa and Sewage, using Mann-Whitney U Test, U= 47.500 and 62.500 respectively, n= 20 and P> 0.05). The proportion of juveniles to mature plants was 65.53 and 32.30% in Malewa and Sewage respectively. The mean values of water hyacinth live biomass and senesced biomass were not significantly different using Student T-test, t= 0.190 and -0.661 respectively, df= 18 and P> 0.05.

Table 4: Water hyacinth live and senesced biomass, population density and number of juveniles for the sampling sites (data presented as means ± standard deviations).

Parameters	Sewage	Malewa
Live biomass (tons/ha)	18.9±8.5*	18.2±7.1
Senesced biomass (tons/ha)	2.98±1.3	3.4±2.1*
Population density (plants/ m²)	63.0±21.6	63.0±19.6
Juveniles (plants/ m²)	14.0±18.7	21.0±25.1*

Asterisks indicate the highest mean values.

4.4 Temporal variation of water hyacinth biomass and density in Sewage and Malewa

Significant temporal variations in the population densities, number of juveniles and biomass of water hyacinth was recorded showed highest population density in Sewage of 94 plants per m^2, recorded in December. Malewa site recorded a slightly higher density of 98 plants per m^2 in January. The proportion of juveniles in the population increased from 8 and 6 % in September to 84 and 68 % in January at the Sewage and Malewa sites respectively. The results of temporal variations of water hyacinth population density and number of juveniles in Sewage and Malewa are shown in figures 7 and 8 and Appendix table 2. The population densities for both sites were significantly high in December and January. In the Malewa site, the number of juveniles was higher in December and January than in September, October and November with the highest population density being in January, using One-way, ANOVA, F= 82.498, df= 4, 19 and P<

0.05. At the Sewage site, the number of juveniles and the population density recorded in September and October were significantly lower than the subsequent three months, by One-way, ANOVA, F= 82.498, 13.808; df= 4, 19 and P< 0.05. During October and January, the population density of water hyacinth was significantly higher in Malewa than in Sewage while in December it was higher in Sewage than in Malewa, using One-way, ANOVA, F= 13.808; df= 4, 19 and P< 0.05.

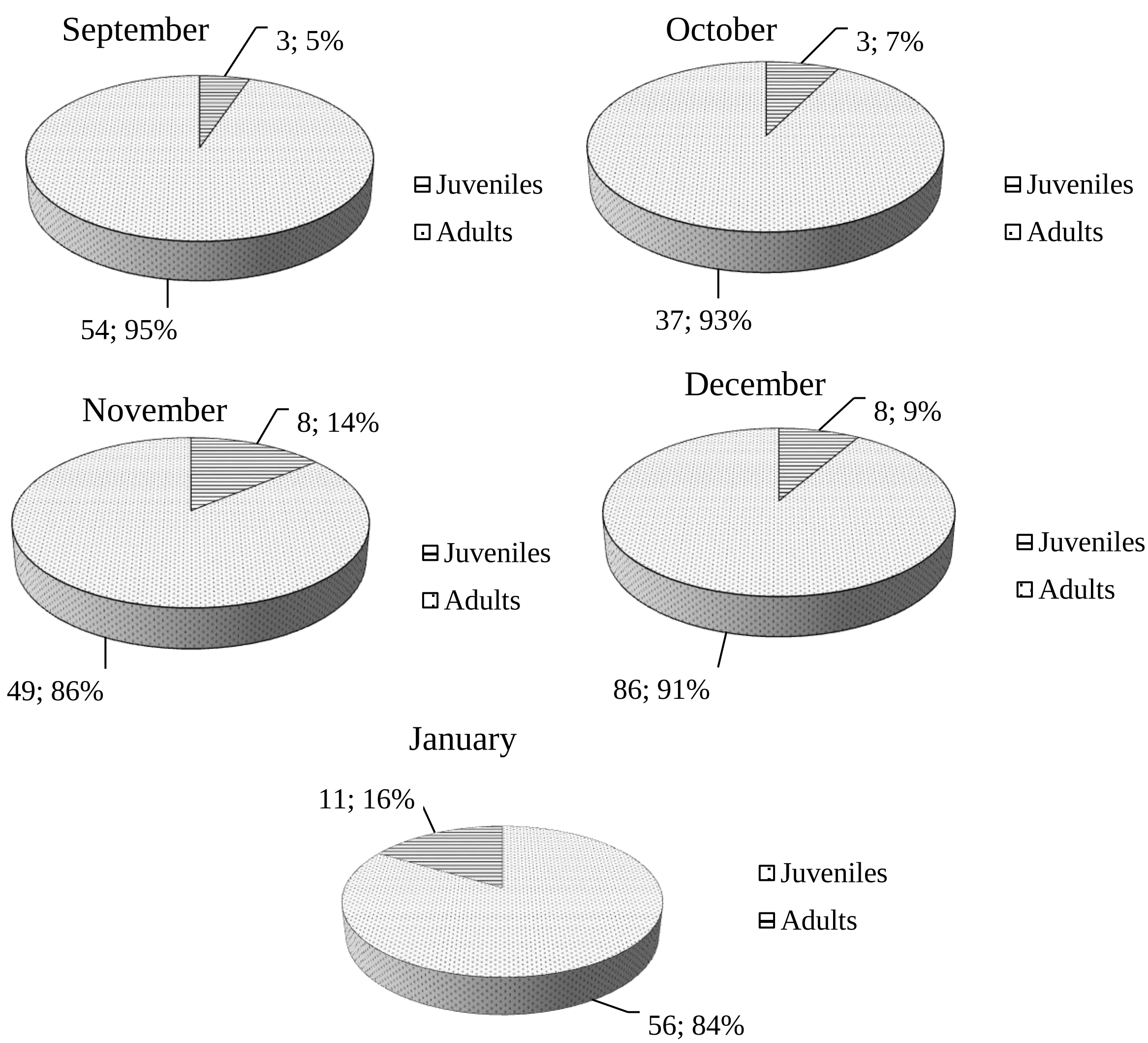

Figure 7: The numbers and percentages of juvenile and adult water hyacinth in Sewage site (September 2011 to January 2012). The first digit (s) represent the number of individuals per square meter while the second digit (s) represent the percentage of individuals in the population.

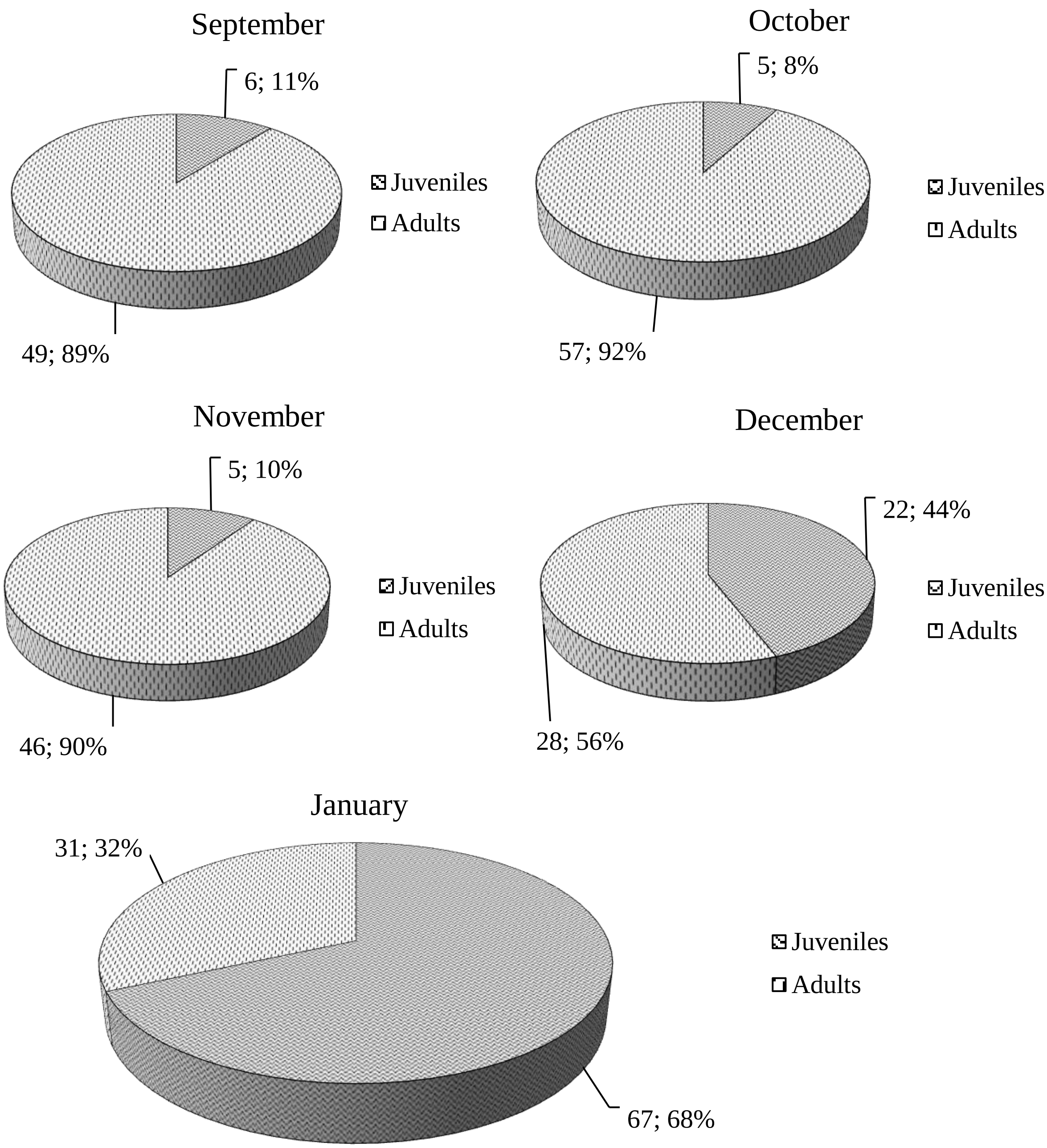

Figure 8: The number and percentages of juvenile and adult water hyacinth in Malewa site (September 2011 to January 2012). The first digit (s) represent the number of individuals per square meter while the second digit (s) represent the percentage of individuals in the population.

The live biomass of water hyacinth also showed significant temporal variation in both Malewa and Sewage sites. Figure 9 shows the variation of water hyacinth live biomass over time in Sewage and Malewa sites. The live biomass of water hyacinth was highest in January in both Malewa and Sewage sites, by One-way, ANOVA, F= 12.735; df= 4, 19 and P< 0.05. Malewa recorded a significantly higher biomass than Sewage in October, while in December, Sewage site had a higher biomass than Malewa, by One-way, ANOVA, F= 12.735; df= 4, 19 and P< 0.05.

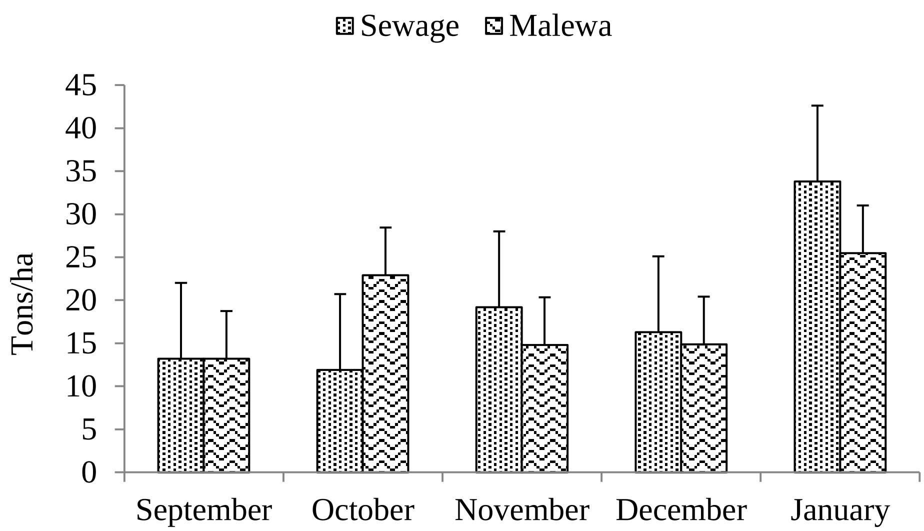

Figure 9: Temporal variation of water hyacinth live biomass in Sewage and Malewa sites (values are means±SD, n=20).

Senesced biomass also varied significantly within the two sites (Malewa and Sewage) during the study period as indicated in Figure 10. At Malewa, senesced biomass was highest in November, with September also recording a significantly higher value than December, using One-way, ANOVA F= 16.667; df= 4, 19 and P< 0.05. Senesced biomass at the Sewage site was lowest in November and December and significantly highest in September, by One-way, ANOVA F= 16.667; df= 4, 19 and P< 0.05. In November and January, Malewa recorded higher values of senesced biomass than Sewage while in October, the Sewage site had a significantly higher senesced biomass as compared to Malewa, by One-way, ANOVA F= 16.667; df= 4, 19 and P< 0.05.

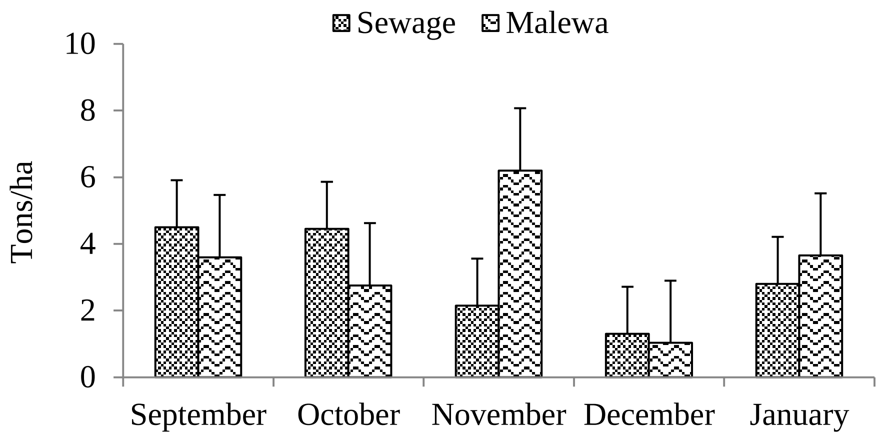

Figure 10: Temporal variation of water hyacinth senesced biomass in Sewage and Malewa sites (values are means±SD, n=20).

4.5 Correlations between water hyacinth population, biomass and physico-chemical parameters in the lake

Correlations between water hyacinth density, live biomass and senesced biomass and the various physico-chemical parameters measured in the lake are shown in Table 5. The results indicate that water hyacinth population density had significant positive correlations with the number of juveniles and concentration of TP but negatively correlated with secchi depth (Pearson's correlation, $r = 0.761$, 0.760 and -0.676, $P < 0.05$). The number of juveniles was positively correlated to the concentrations of NO_2^-, NH_4^+, SRP and TP and negatively with secchi depth and electrical conductivity (Pearson's correlation, $r = 0.812$, 0.658, 0.689, 0.659, -0.726 and -0.721, $P < 0.05$). The results also indicate that DO concentration significantly decreases with an increase in water hyacinth live biomass (Pearson's correlation, $r = -0.595$, $P < 0.05$). Hyacinth senesced biomass had significant negative correlations dissolved oxygen concentration and correlated positively with electrical conductivity using Pearson's correlation, $r = -0.908$ and 0.747, $P < 0.05$ respectively. Secchi depth showed negative correlations with TSS and TP concentrations but correlated positively with electrical conductivity (Pearson's correlation, $r = -0.639$, -0.624 and 0.718, $P < 0.05$). Negative correlation between TP concentration and electrical conductivity was observed (Pearson's correlation, $r = - 0.718$, $P < 0.05$).

Table 5: Correlation matrix between water hyacinth density, live biomass and senesced biomass and the various physico- chemical parameters measured in the lake.

	Juv.	HD	SB	NO_3^-	NO_2^-	NH_4^+	SRP	TP	TSS	SD	DO	Temp.	EC
HD	0.761*	0.166	-0.180	0.197	0.458	0.430	0.325	0.760*	0.014	-0.676*	0.095	0.232	-0.495
Juv.	_	-0.055	-0.423	0.539	0.812*	0.658*	0.689*	0.659*	0.006	-0.726*	-0.245	0.359	-0.721*
LB	_	_	-0.370	-0.453	-0.357	-0.305	-0.068	0.306	0.313	-0.124	-0.595	-0.340	-0.326
SB	_	_	_	-0.003	-0.497	0.373	-0.488	-0.461	-0.367	0.361	-0.703*	0.324	0.747*
NO_3^-	_	_	_	_	0.484	0.321	0.588	-0.173	0.054	-0.441	0.333	0.326	-0.052
NO_2^-	_	_	_	_	_	0.359	0.592	0.424	0.033	-0.439	-0.546	0.550	-0.565
NH_4^+	_	_	_	_	_	_	-0.184	0.106	-0.349	-0.100	-0.078	0.423	0.112
SRP	_	_	_	_	_	_	_	0.120	-0.058	-0.330	-0.323	0.165	-0.414
TP	_	_	_	_	_	_	_	_	0.254	-0.624*	0.023	-0.034	-0.718*
TSS	_	_	_	_	_	_	_	_	_	-0.639*	-0.060	0.033	-0.332
SD	_	_	_	_	_	_	_	_	_	_	-0.032	-0.195	0.718*
DO	_	_	_	_	_	_	_	_	_	_	_	0.085	0.105
Temp.	_	_	_	_	_	_	_	_	_	_		_	-0.035
EC	_	_	_	_	_	_	_	_	_	_	_	_	

DO= dissolved oxygen; EC= electrical conductivity; LB= live hyacinth biomass; HD= hyacinth density; Juv. = number of juveniles; SB= senesced hyacinth biomass

***Correlation is significant at P< 0.05, (2 tailed, N= 20)**

4.6 Effect of varying nutrient concentration on water hyacinth growth

4.6.1 Nutrient uptake

It was evident that the uptake rates of N and P tended to increase in the growth periods that followed soon after addition of nutrients (33rd, 47th and 72nd day). It was also noted that the uptake rates for various nutrients decreased over time. There was complete uptake of phosphorus that had been added in the first five levels (0, 0.012, lake water (0.038), 0.20, 0.80 mg/L) of P enrichment within the first 19 days. Since there was no further replenishment of nutrients in the first three levels, only the trends in biomass change were recorded and not nutrient uptake rates. The highest uptake rate for phosphorus was 185.29 and 82.29 mg m^{-2} day^{-1} at day 19 for young and mature hyacinth respectively. The uptake rate per unit area per day ranged between 2.9-185.29 mg P m^{-2} day^{-1}. The daily removal capacity from the growth medium of the phosphate load ranged between 5.04-7.14 %. The results for phosphorus uptake rates are shown in Figure 11. The uptake rate for phosphorus was significantly different between the two growth stages of water hyacinth using Mann-Whitney U Test, U= 109.0, 113.5 and 113.0 respectively, n= 15 and $P < 0.05$.

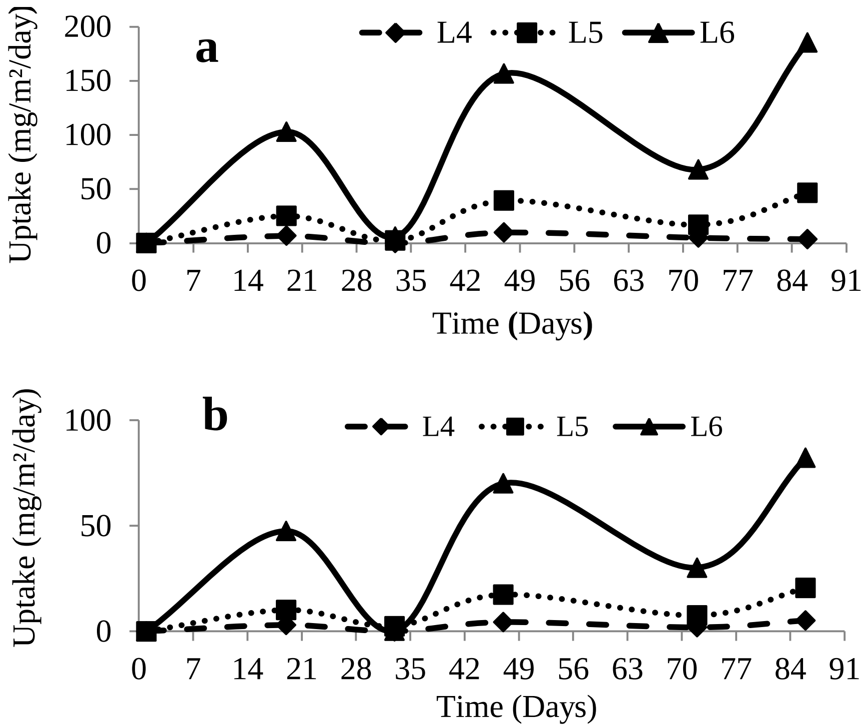

Figure 11: P uptake rates per square meter of (a) young and (b) mature water hyacinth grown in levels 4- 6 (0.20, 0.80 and 3.20 mg/L) of P supply.

Within the first 19 days, all the plants that were subjected to the first four levels of nutrient enrichment; that is, 0, 0.01, lake water (0.015), 1.60 mg N/L and 0, 0.012, lake water (0.038) and 0.20 mg P/L had taken up all the initial NO_3^-. The highest NO_3^- uptake rates recorded were 681.17 and 269.18 mg $m^{-2}day^{-}$ for the young and mature plants respectively. The results for the rates of NO_3^- uptake are indicated in Figure 12 below.

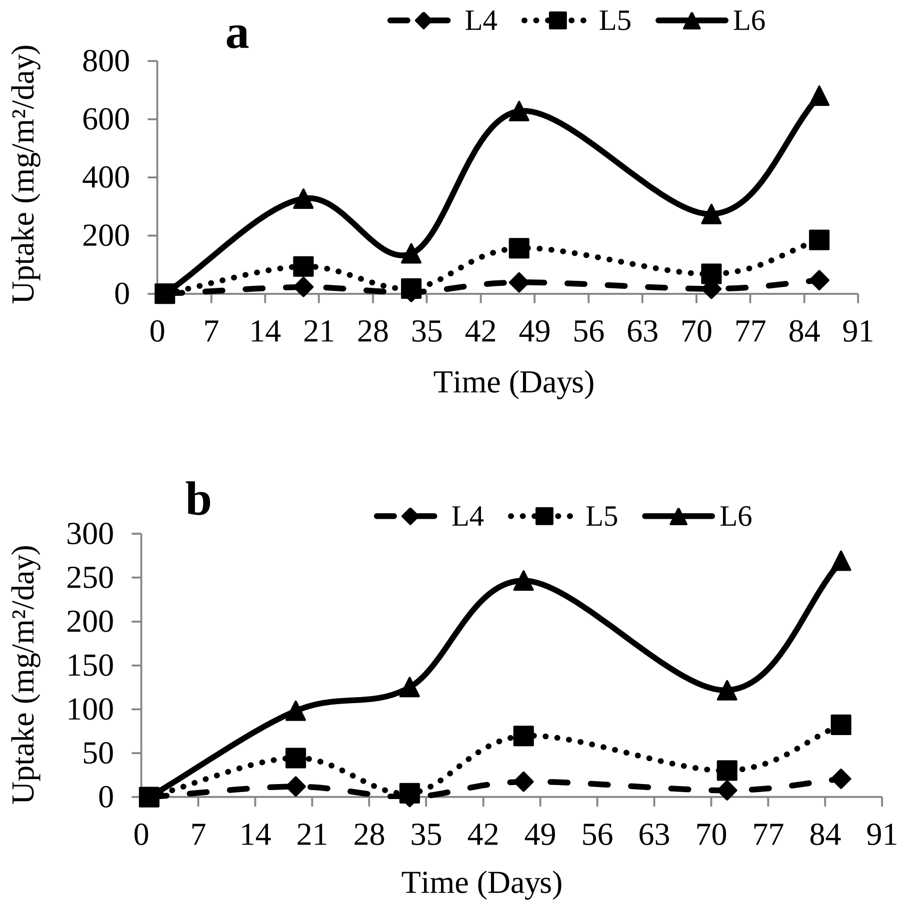

Figure 12: NO_3-N uptake rates per square meter of (a) young and (b) mature water hyacinth grown in levels 4- 6 (1.60, 6.40 and 25.60 mg N/L) during the entire growth period.

The highest NH_4^+ uptake rates recorded were 741.17 and 285.18 mg m^{-2} day^{-} for the young and mature hyacinth respectively as shown in Figure 13. The highest uptake of total dissolved nitrogen by young and mature hyacinth was therefore, 1422.34 and 554.36 mg m^{-2} day^{-} respectively.

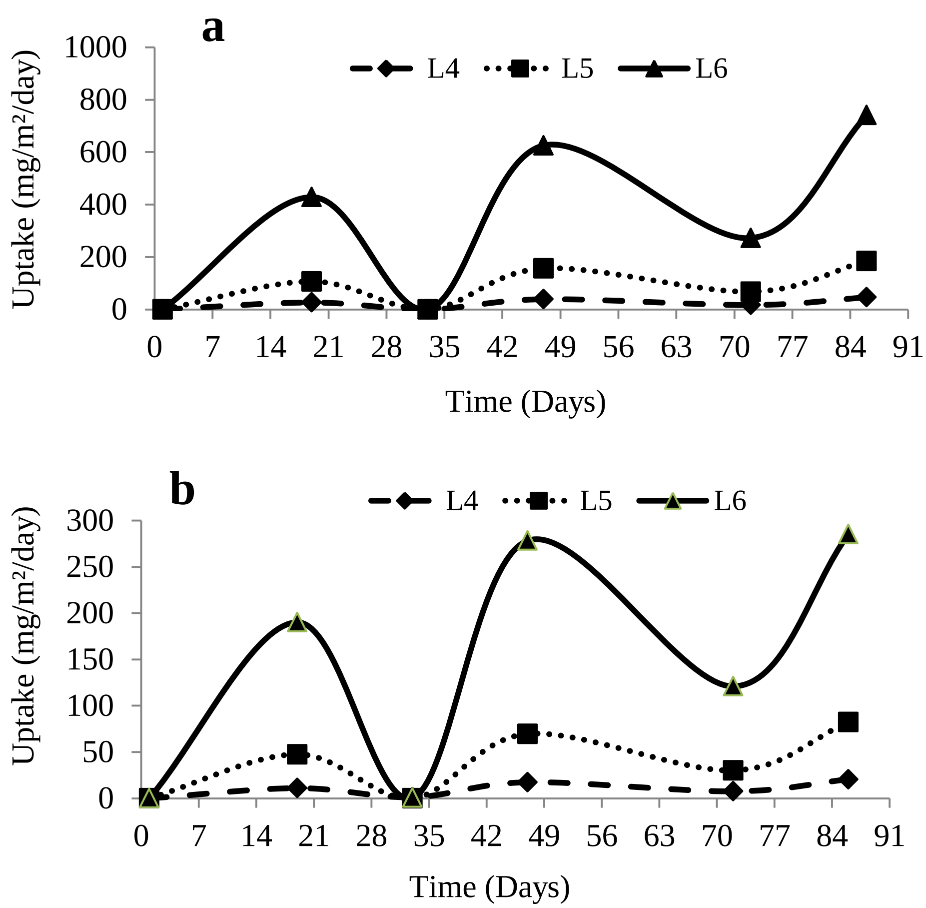

Figure 13: NH_4-N uptake rates per square meter of (a) young and mature (b) water hyacinth grown in levels 4- 6 (1.60, 6.40 and 25.60 mg N/L).

Range values of 2.7-7.14% and 5.25-7.14% were taken up daily by water hyacinth from the total nitrate and ammonium stocks, respectively. The young water hyacinth exhibited a significant higher NO_3^- and NH_4^+ uptake rates than their mature counterparts by one-way, ANOVA, F= 3.98, df= 3, 59 (P< 0.05).

4.6.2 Water hyacinth biomass under varying nutrient concentration

a) Cumulative biomass

The results for the build-up of water hyacinth biomass in response to nutrient enrichment are shown in Figure 14 and plate 3. The plants that had a continuous nutrients supply gradually increased in biomass up to the 70th day after which biomass accumulation slowed. The plants that were deprived of continuous nutrient enrichment increased their biomass during the first month, after which, biomass declined. The young plants that were deprived of nutrient supply died after the 46th day as shown in Plates 4 and 5 below. The highest biomass that was attained after 86 days was 2.48 kg (fresh biomass) in an area measuring 0.071 m^2 by the water hyacinth grown in the sixth level of nutrient enrichment (3.20 mg P/L and 25.60 mg N/L). This was equivalent to a dry matter production rate of 126.36 tons/ ha/ year, considering an average dry matter content of 8.5 % of the fresh weight.

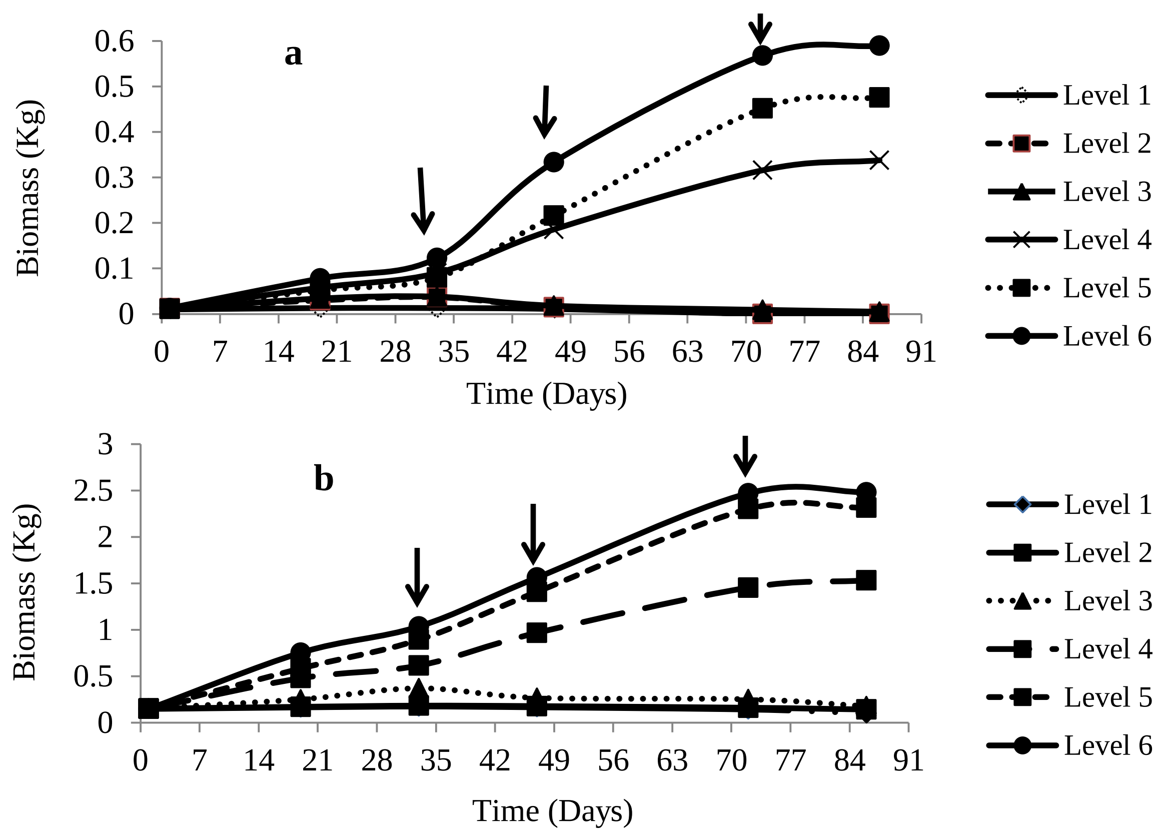

Figure 14: Cumulative biomass for (a) young and (b) mature water hyacinth grown in levels 1-6 (0, 0.01, 0.15, 1.60, 6.40 and 25.60 mg N/L and 0, 0.012, 0.038, 0.20, 0.80 and 3.20 mg P/L respectively) of nutrient supply. Arrows indicate additional enrichment points for Levels 4-6.

Plate 3: Pictures showing the robust growth of water hyacinth in response to nutrient enrichment (two months after the beginning of the experiment).

Plate 4: Pictures showing the senesence of young water hyacinth in response to nutrient deficiency; that is, levels 1-3 (one and a half months from the beging of the experiment).

Plate 5: Pictures showing mature water hyacinth having reduced in size in response to nutrient deficiency (two months after the beginning of the experiment).

b) Rates of biomass change

The plants that were continuously supplied with nutrients showed gradual increase in the rates of biomass change up to the end of the second month and then slightly reduced in the third month. The highest rates of change in biomass recorded were 1.48 and 3.69 Kg/ m^2/week (wet weight) for the young and mature hyacinth respectively grown in 3.20 mg P/L and 25.60 mg N/L of nutrient enrichment. This was achieved between the 33^{rd} and 47^{th} day. However, the rates of biomass change reduced to 0.15 and 0.084 Kg/ m^2/ week (wet weight) for the young and mature plants respectively between the 72^{nd} and 86^{th} day (Figure 15). The rate of change in biomass of young and mature water hyacinth grown in 25.60 mg N/L and 3.20 mg P/L was significantly higher than those grown in 1.60 mg N/L and 0.20 mg P/L, using Kruskal-Wallis, one-way, ANOVA on ranks, H= 18.742; df= 5, 29 and $P < 0.05$.

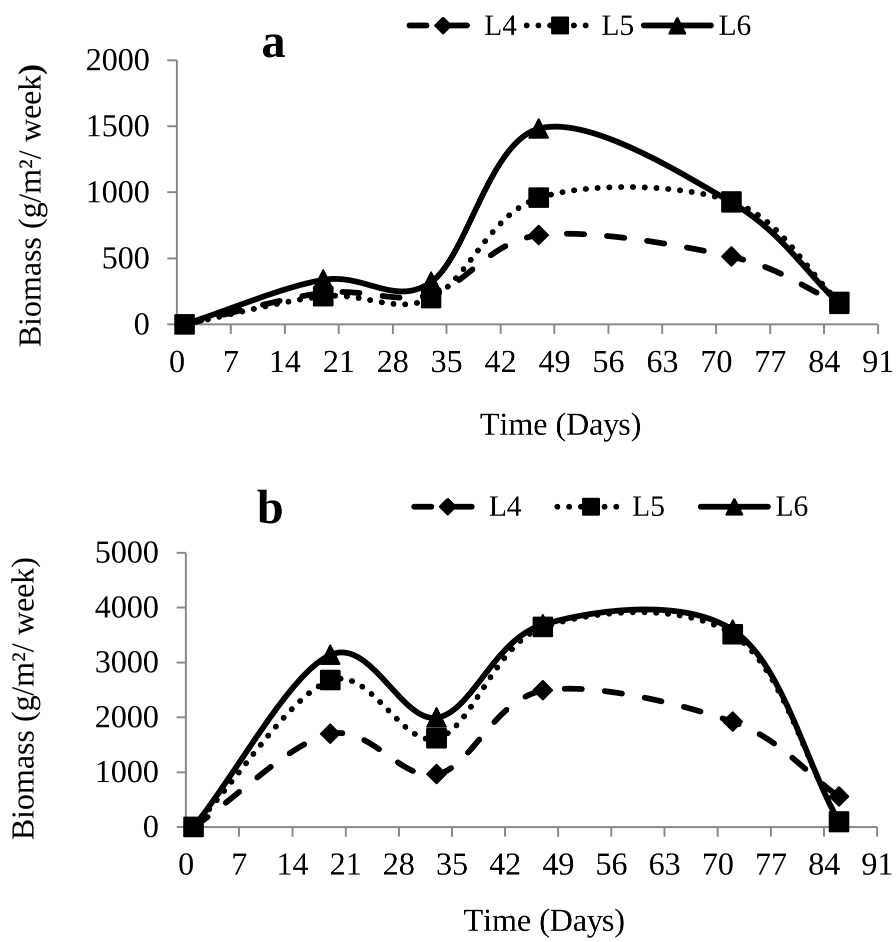

Figure 15: Rates of water hyacinth biomass change per week for (a) young and (b) mature water hyacinth grown in levels 4-6 (1.60, 6.40 and 25.60 mg N/L and 0.20, 0.80 and 3.20 mg P/L) of nutrient supply.

The plants that were deprived of continuous nutrient enrichment increased their biomass during the first month, after which, the rate of increase in biomass showed a decline. The second and third months were marked with decline in biomass and subsequent deaths of the young plants as shown in Plates 5 and 6 above. Negative rates of change in biomass were recorded for the mature plants. The highest rates of change in biomass recorded were 0.12 and 0.84 Kg/ m^2/ week (wet weight) for the young and mature hyacinth respectively grown in 0.038 mg P/L and 0.15 mg N/L of nutrient enrichment. This was achieved between the 1st and 19th day. However, the rates of biomass change reduced to -140.85 and -725.35 g/ m^2/ week for the young and mature plants respectively between the 33rd and 47th day.

c) Half saturation constants of N and P for water hyacinth

The relationship between specific rates of change in biomass and nutrient concentrations of N and P is shown in Figures 16 and 17. The curves are based on Monod's equation as had been described earlier in equation 4.

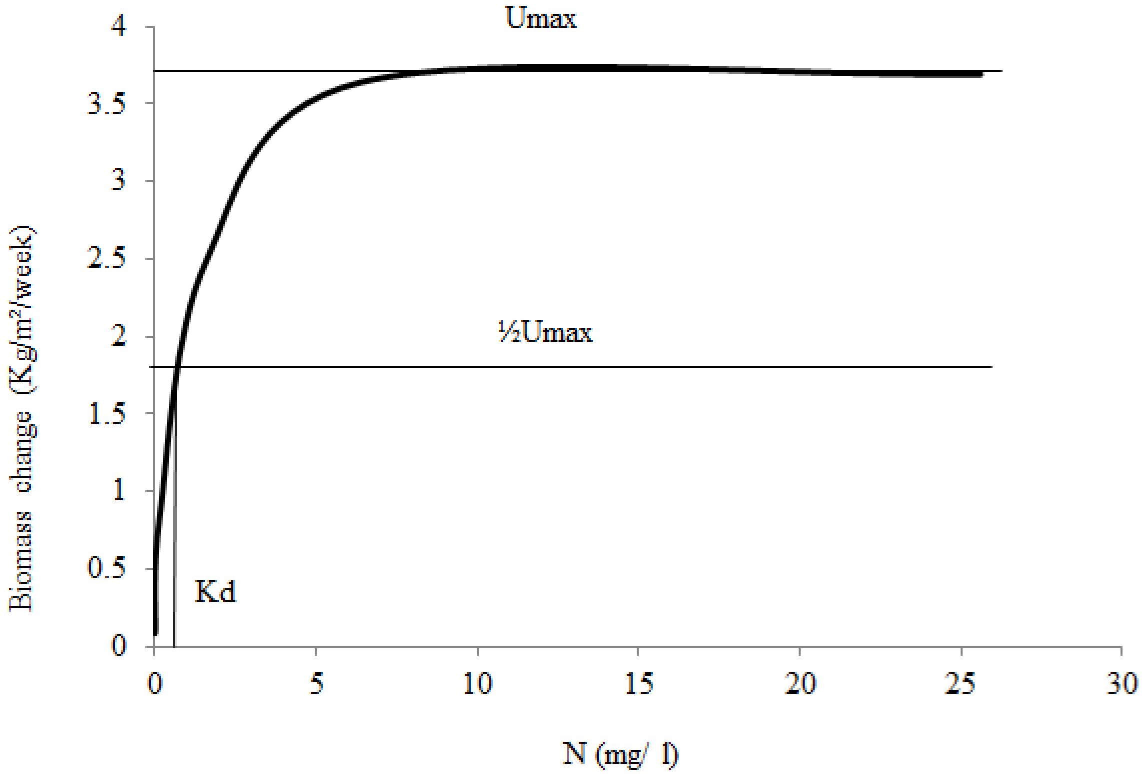

Figure 16: Biomass change as a function of bioavailable N concentration (Kd = 0.6, Umax = 3.69 Kg wet weight m^{-2} $week^{-1}$ and ½Umax = 1.85 Kg wet weight m^{-2} $week^{-1}$).

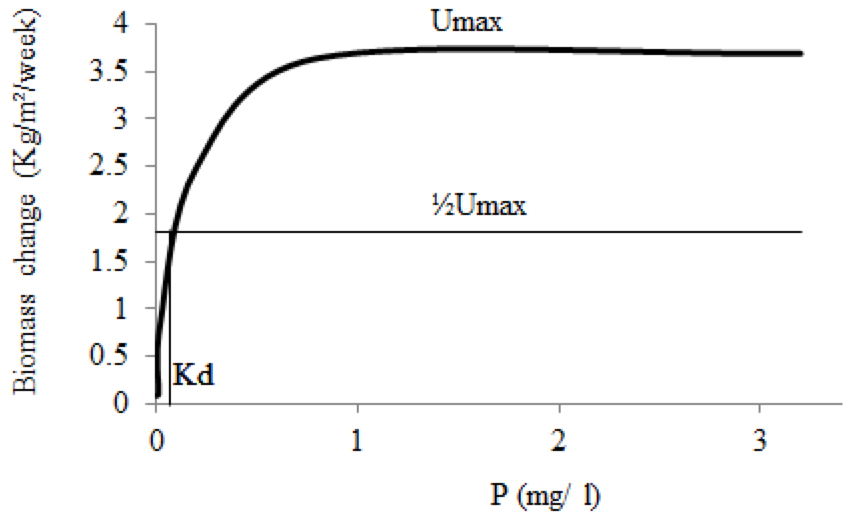

Figure 17: Biomass change as a function P concentration (Kd = 0.05, Umax = 3.69 Kg wet weight m^{-2} $week^{-1}$ and ½Umax = 1.85 g wet weight m^{-2} $week^{-1}$).

Based on the Umax and Kd above, the rates of biomass change of water hyacinth at given concentrations of N and P can be calculated as;

For N: $U = 3.69 Kg\ m^{-2} week^{-} \frac{Cn}{Cn + 0.6}$

For P: $U = 3.69 Kg\ m^{-2} week^{-} \frac{Cn}{Cn + 0.05}$

d) Reproduction of juvenile plants

The results for the reproduction of new individual plants by water hyacinth under different levels of nutrient enrichment are shown in Figure 18. The experiment began with individual plants that had not produced any new juveniles; hence, the density of juveniles on the first day was zero. The young water hyacinths that had a steady supply of nutrients produced the first juveniles after one and a half months while those that lacked continuous nutrient input did not produce new plants. All the mature plants produced new individuals within the first 19 days. The plants in level 1 (distilled water) and level 2 (0.01 mg N/L and 0.012 mg P/L) produced one juvenile each, while those grown in level 3 (lake water) produced 2 new young plants after 19 days. In all the buckets without nutrient replenishment, further multiplication of the plants was not observed after the 19^{th} day. The plants that were grown in water with steady nutrient supply continued to reproduce new individuals during the study period. The fastest multiplication rate recorded was the development of a new plant in 9 days by the mature plants grown in 3.20 mg P/L and 25.60 mg N/L of nutrient enrichment.

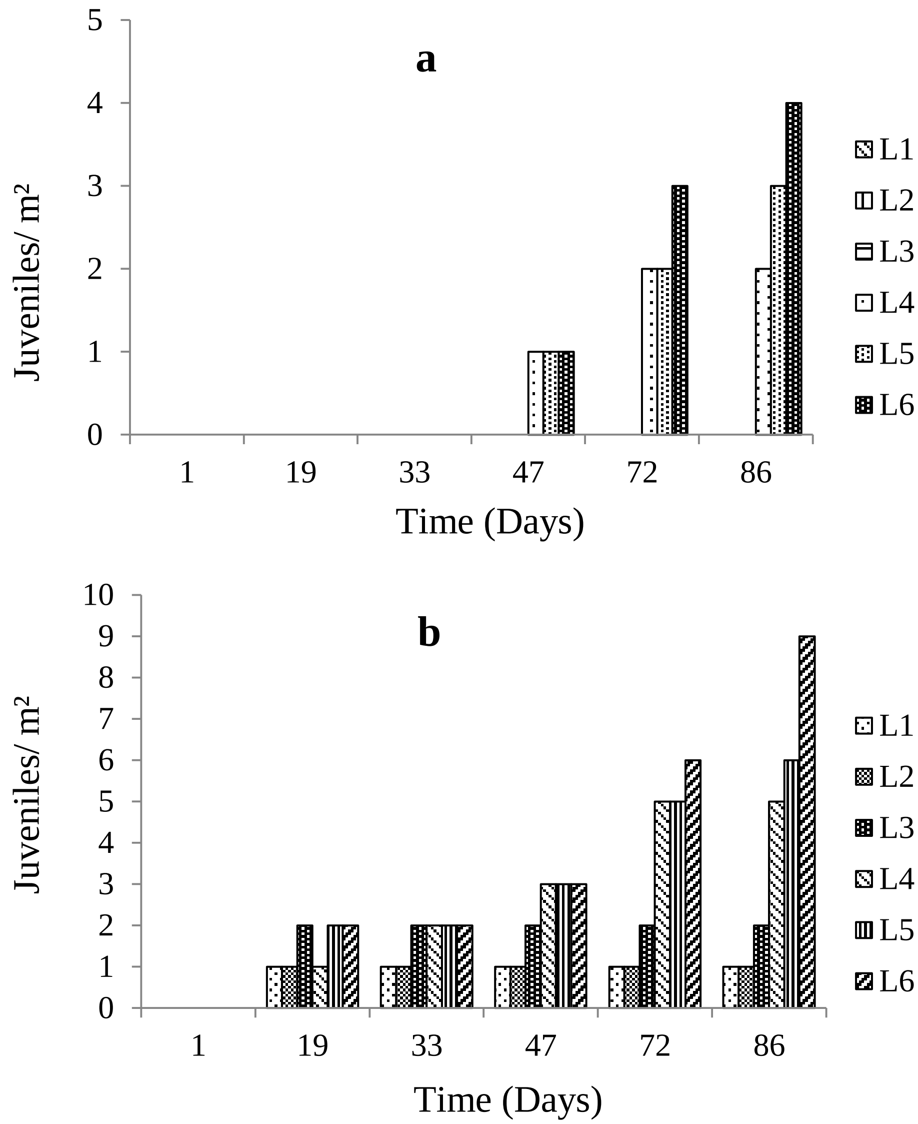

Figure 18: Number of juveniles produced over time by (a) young and (b) mature water hyacinth grown in different levels of nutrient supply.

CHAPTER FIVE

DISCUSSION

5.1 Spatial variation of physico-chemical parameters in the study sites

Most of the physico-chemical parameters in the sites with water hyacinth showed significant variation from the open water site. The results on spatio-temporal variation of physico-chemical parameters concur to a large extent with what has been documented from other studies. The high TSS concentration in Malewa is due to the fact that Malewa River transports suspended sediments into the Lake from upstream erosion during rainfall events. Kitaka *et al*. (2002) and Bercht *et al.* (2006) noted that the inflow of rivers (Malewa and Gilgil) at the northern end of the lake may contain a large amount of sediment. The significantly high level of total suspended solids and low secchi depth in Malewa and Sewage sites as compared to open water may also be due to continuous input of fragments of decaying water hyacinth detritus into the water column. It was observed that roots and leaves were constantly decaying as the plants senesced and replaced by new daughter plants. Natural growth of water hyacinth added debris to water and allowed water colouring chemicals to leach into the water there by increasing turbidity and limiting visibility. Suspended solids also get attached to the dangling roots of hyacinth hence get released when the roots are disturbed. Mironga *et al.* (2012) found out that the TSS concentrations in sites with hyacinth (92.48±4.00 mg/l) were significantly higher than in the open water (54.00±5.85 mg/l) in Lake Naivasha.

The values for temperature and EC differed considerably between the sampling sites. Water temperature was considerably lower is the sites with water hyacinth mats than in open water. Water hyacinth shaded the water from direct radiation by sunlight, hence reduced its penetration into the water column and subsequent warming up. Electrical conductivity was significantly higher in Sewage site than in the other two sites even though the levels of dissolved nutrients showed no significant differences between the sites. It is possible that the high electrical conductivity at the Sewage station may have been due to other ions which were not determined during this study and have electrical conductivity potential and are not taken up actively by plants and remain within the water column.

Low values of dissolved oxygen and lower pH ranges in water hyacinth infested sites was due to a variety of factors. According to Bianchini *et al*. (2008), the decomposition of plant detritus may raise the oxygen demands. The current study showed that water hyacinth detritus had mean biomass (dry weight) of 0.288 and 0.343 Kg/ m^2 for the Sewage and Malewa sites respectively. This showed that there was organic matter raindown from senescing plants, leading to oxygen consumption by bacterial respiration. Algal photosynthesis is limited beneath water hyacinth mats, and hyacinth by being a free-floating macrophyte does not release oxygen into the water as do phytoplankton and submerged vegetation, resulting to decrease in dissolved oxygen concentration (Meerhoff *et al.*, 2003). Gherardi *et al*., (2011) also noted that the dense mats formed by these invasive floating plants lower oxygen concentration by blocking the air-water interface. The dense mats reduce atmosphere-water column interaction and mixing there by limiting water aeration and distribution of oxygen. Low pH values within water hyacinth sites was due to presence of free CO_2 within the water column which results from aerobic breakdown of organic matter. Mironga *et al*. (2012) reported that free carbon dioxide was significantly higher in water hyacinth infested areas (26.45±1.02 mgL^{-1}) than in clear open water (12.86±1.92 mgL^{-1}). These values are way more than the < 8 mg/l of free CO_2 documented by ICAR, (2006) for ideal freshwater systems. The presence of water hyacinth mats in lentic water bodies have been found to lower temperatures, pH, bicarbonate alkalinity and dissolved oxygen content and at the same time increase the free carbon dioxide content (Gopal, 1987). Other studies have also shown that dissolved oxygen concentration and pH ranges tend to decline in the water column under water hyacinth mats. Mironga *et al*. (2012) study which was carried out in Lake Naivasha between October, 2003- November, 2004 showed that dissolved oxygen was significantly lower in the water hyacinth infested areas (1.96±0.71 mgL^{-1}) when compared with open water (5.98±0.85 mgL^{-1}). Rommens *et al*. (2003) recorded low oxygen concentration and low pH in sites with water hyacinth than in limnetic sites or littoral sites without water hyacinth in Lake Chivero, Zimbabwe. Similarly, Toft *et al.* (2003) reported that water below water hyacinth mats in Sacramento-San Joaquin River, California had lower dissolved oxygen concentrations less than 5 mg L^{-1}.

High concentration of total phosphorus in the sites with water hyacinth was probably due to continuous input of mineralized phosphates from water hyacinth detritus as well as leachates from the senescing plants. However, the level of bio-available nutrients was not significantly different between the three sites despite the northern shores receiving more nutrients through rivers inflow. This can be explained by the fact that most of the N and P inputs into the lake are in particulate form. Similarly, Kitaka *et al*. (2001) obtained a very strong significant correlation between TSS and PP (R^2= 0.97), inferring that most phosphorus was transported bound in suspended soil particles. Kitaka *et al.* (2002) also indicated that phosphorus for instance, enters the lake bound to the sediment particles after which it is reduced by sedimentation but also transformed as SRP and turned into biologically available form for phytoplankton and macrophytes.

5.2 Temporal variation of physico-chemical parameters in the study sites

The results on temporal variations indicate that physico-chemical characteristics and nutrients concentrations showed significant variation during the five months of the study. The months of September and October were relatively dry but rains began towards the end of October, increased in November to December leading to high lake level (Appendix table 3). In January there was no rain but the lake level remained high. Water in Malewa was more turbid in October and December than in the other study sites; hence, indicating the high contribution of River Malewa in the input of total suspended solids into the lake during the rainy season. The electrical conductivity of water in the three sampling sites was low during the rainy season due to dilution of the lake by rain water. Dissolved oxygen concentration and pH ranges were also significantly lower in December in the three sites. In addition to the decomposition of senescing water hyacinth, the heavy rains may have brought into the lake large amounts of organic matter through the river inputs and surface runoff. These raised oxygen demand there by lowering the concentration of dissolved oxygen and increased the concentration of CO_2 leading to low pH in November and December.

It's important to note that in December, Malewa site had significantly high concentrations of total phosphorus, $NO_3^-$and NO_2^- than Sewage and open water sites. The input through runoff from the catchment and inflowing rivers during the rainy season may have contained organic non ionized particles, and nutrients; hence, the high values of total phosphorus NO_3^- and NO_2^- concentrations. Even though the Sewage site also recorded significantly high amounts of total phosphorus and NO_3^- in December than in the other months, Malewa River inlet proved to be a major contributor of TSS, NO_3^- and TP into the lake than the Municipal wastewater treatment plant. These results confirm earlier findings by Kitaka *et al*. (2002) who noted that evidence from the Malewa River input was adequate to explain the increased trophic state of the lake without citing any additional nutrient inputs from urban or horticultural sources. They found out that the Malewa River contribution of phosphorus led to total phosphorus loading of 1.4 g m^{-2} lake surface in the very wet period compared to 0.2 in the 'normal' and a mean phosphorus export coefficient of 1.54 Kg ha^{-1} yr^{-1} (Kitaka *et al.* 2001). In the current study, the concentrations of nutrients in Malewa generally increased during the rainy season, even though the rise in SRP and NH_4^+ concentrations was not statistically significant. The TP concentrations were much higher than the findings by Kitaka *et al.* (2002). They recorded means of 83.9±33.2 and 54.2±18.0 µg/l in Malewa and open water respectively, comparative to 332±127 and 101±88 µg/l in the current study. This further confirms the catchment's contribution to the trophic status of the lake and that it has probably worsened over the years. The Sewage site had significantly high concentrations of NH_4^+ and SRP in December than Malewa and open water. Sub-surface flow of wastewater from the oxidation ponds of the Naivasha Municipal wastewater treatment plant during the rains may have contributed to the input of mineralized nitrogen and phosphorus into the lake. This coupled with very low dissolved oxygen concentrations (below 2 mg/l) at that time favored these reduced forms of nitrogen and phosphorus. The decline in the concentrations of SRP, NO_3^- and NH_4^+ after December in Malewa and Sewage sites may have been due to active uptake by the newly produced water hyacinth. It was noted that the total density, population of juveniles and biomass of water hyacinth were highest during January, showing that the population was actively growing, in response to increased nutrient levels in the lake. This view is supported by Pinto-Coelho and Greco (1999) who noted that water hyacinth has the potential to significantly reduce nutrient concentrations in a water body, although this is highly dependent of the extent of its cover and density. In the open water, the concentrations of NH_4^+, NO_2^- and SRP increased in November and December. The levels of NO_2^- and NH_4^+ remained high in January after the rains. This can be attributed to lack of robust nutrient absorbers such as water hyacinth in the open water site. It is notable that the levels of nitrogen and phosphorus in the lake rose during the rainy season. This view is supported by Njuguna (1982) who noted that peaks in nutrient concentrations in Lake Naivasha occurred during or immediately after the two rainy seasons of March-May and October-December.

5.3 Water hyacinth density and biomass in the lake

During the present study, water hyacinth biomass and density in sheltered areas of the lake was generally high. No significant variation occurred in the mean values of water hyacinth population density, number of juveniles and biomass between Malewa and Sewage sampling sites. This was due to relatively similar physico-chemical characteristics (more so nutrients) within the two sites. However, significant temporal variations of water hyacinth density and biomass were observed in Malewa and Sewage. It is worth noting that the number of hyacinth juveniles at the Sewage site was higher than that of Malewa in December (wet period). During that time, the concentrations of NH_4^+ and SRP were also higher than in Malewa. However, in January the number of water hyacinth juveniles was higher in Malewa than Sewage, corresponding to high levels of NH_4^+ at Malewa. This infers that NH_4-N played a significant role in water hyacinth growth and especially production of juveniles. In January, the many juveniles that had been produced in December at the Sewage site had grown in size, hence resulting to increase in biomass. This explains why water hyacinth live biomass in January was higher in the Sewage site than Malewa. The increase in the density of the water hyacinth population in response to increased levels of nutrients in the lake became evident within the second month of the rains (December). This trend was also observed in the experimental set-up where young plants took one and a half months to grow to maturity and reproduce new daughter plants.

The results obtained for water hyacinth live biomass in Malewa and Sewage showed that January had significantly higher values than the preceding four months. A similar trend was reported by Kariuki (1993) during his study in 1992, suggesting that the growth period in Lake Naivasha corresponds to a time when nutrient levels in the water are high especially a few weeks after the rains. However, the senesced biomass was significantly higher in September than in December and January in both sites. This is due to the fact that there was high biomass of detritus in September corresponding to the dry season associated with low lake water level coupled with low nutrient influx into the lake. During that time, much of the standing biomass was made up of mature plants where most of were senescing with few juveniles observed.

The results on water hyacinth biomass and density obtained in this study showed disparity with the outcome of other studies. Kariuki (1993) carried out a study in 1992 and reported lower densities of 34.3±5.35 and 33.0±6.32 plants per square meter during the rainy and dry seasons respectively in Lake Naivasha. The densities recorded in the current study were 50 plants/ m^2 during the dry period and a high value of 98 plants/ m^2 a month after the rains. A minimum seasonal biomass of 0.18±0.039 kg m^{-2} was recorded by Kariuki (1993) at the end of the dry period comparatively to 1.32±0.27 kg m^{-2} during this study. It is important to note that during that time (1992), the coverage of water hyacinth in the lake was 5 km^2, lower than it was during this study where water hyacinth had covered approximately 28km^2 since 2010 (Harper *et al*., 2011). The higher density and biomass recorded in the current study indicate that the weed has established itself and continues proliferate. It is also a sign that the eutrophic state of the lake has probably increased since 1992. During the current study in 2011, especially in November, December and January, several beaches and landing sites were covered with extensive mats, however, the area covered was not determined. Almost the entire Northern shores, Crescent Island, Kamere beach and several parts of the open water in the Lake were covered by water hyacinth mats. In January 2012, the problem intensified, rendering navigation almost impossible. Extensive migratory mats were observed in the pelagic zone rendering navigation and fishing very difficult. This clearly indicates that water hyacinth growth and multiplication had increased during the rainy season. The role of wind in breaking off and spreading huge mats of water hyacinth into the open water cannot be ruled out. Floating plant masses along with water hyacinth were also noted. Associations of water hyacinth and other obligate surface floating plants such as small patches of *Salvinia molesta* and *Azolla pinnata* were observed within water hyacinth mats. Littoral vegetation such as *Cyperus papyrus* and associated plants such as *Ludwigia stolonifera*, *Sphaeranthus* sp., *Crassula schimperi, Polygonum sp.* and *Hydrocotyle* sp. that grow at the outer (lakeward) edge of the swamp would detach from the substrate as water levels rose to form floating islands in association with water hyacinth mats which were carried by wind and water currents to the open water.

It appears that nutrients play an important role in seasonal variation of water hyacinth biomass in Lake Naivasha as growth and reproduction increased with increased nitrogen and phosphorous levels. Interestingly, even with comparable nutrient levels to other systems, water hyacinth biomass in Lake Naivasha is still lower than what has been recorded in other studies. For example, higher biomass of 2.4-4.9 Kg m^{-2} was reported by Amoding *et al*. (1999) in Lake

Victoria. These results had been obtained at a time when control efforts were going on in the lake. IUCN (2003) also reported that the rate of water hyacinth growth in Lake Naivasha was small compared with its invasion and persistence in Lake Victoria, the Sudd and elsewhere throughout the tropics and sub-tropics. Lower production rates by water hyacinth in Lake Naivasha can be attributed to low temperature in the lake. Imaoka and Teranishi (1988) suggested that the intrinsic growth rate, r, increases exponentially with ambient temperatures in the range of 14-29 ºC. The mean monthly temperature in Lake Naivasha ranged between 20-21.8 ^{o}C in the lake and has been reported to go as low as 6 ºC at night. On the contrary, surface water temperatures range between 23.5° C and 29.0°C in Lake Victoria (Osumo, 2001). Whilst it has been shown that temperature affects the growth of water hyacinth, it is not clear how climate change may influence the dynamics of weed proliferation especially in Lake Naivasha.

5.4 Effect of varying nutrient concentration on water hyacinth growth

5.4.1 Nutrient uptake

Water hyacinth responded with a steady rise in the rates of nutrients uptake in the periods that followed the enrichment of the growth media with nutrients. Water hyacinth has been reported to exhibit luxury uptake of nutrients when nutrient supply is increased (Petrucio and Esteves, 1999). The young water hyacinth exhibited up to two and a half times higher N and P uptake rates than their mature counterparts. However, even as the young water hyacinth plants continued to grow, the rates of nutrient uptake reduced. This showed that young plants needed more nutrients than older plants. Young plants require nutrients for growth and development. The uptake rates were higher whenever most of the plants were newly produced due to increased nutrients demand by both the mother and daughter plants (juveniles).

The highest NO_3^- uptake rates recorded were 681.17 and 269.18 mg m^{-2} day^{-} for the young and mature plants respectively, while NH_4^+ uptake rates recorded were 741.17 and 285.18 mg m^{-2} day^{-1} for the young and mature hyacinth respectively. This acts as evidence of requirement of NH_4^+ in hyacinth growth since the field studies showed that the highest number of juveniles in the lake corresponded to high levels of NH_4-N. The uptake rate for phosphorus was 185.29 and 82.29 mg m^{-2} day^{-} for young and mature hyacinth respectively. The highest N and P uptake rates per square meter obtained in the current study were 1422.34 and 185.29 mg m^{-2} day^{-}

respectively. Reddy and Tucker (1983) reported higher nutrient uptake values. Nitrogen uptake rates were in the range of 533-2,161 mg N m^{-2} day^{-1} for the systems receiving NH_4^+, NO_3^- and urea. Phosphorus uptake rates were found to be in the range of 59-542 mg P m^{-2} day^{-1}. Low temperature below optimal (29 °C) in Naivasha must have reduced growth hence slowing nutrient uptake rates. The results from this study indicated that one hectare of water hyacinth would absorb 5191.54 kg of nitrogen and 676.31 kg of phosphorus per year.

5.4.2 Water hyacinth biomass response to variation in nutrient concentrations

The young and mature plants that were deprived of continuous nutrient supply responded differently to treatment. Older plants took longer time to die and were able to reproduce despite lack of nutrient replenishment. This means that they had nutrients stored in their systems and was used to nourish daughter plants. However, the number of daughter plants produced in the first 19 days did not increase and the plants lost weight with time. This is attributed to the eventual depletion of the plants nutrient reserves and hence, degeneration of the plants. The young plants grown in 0, 0.01, lake water (0.15) mg N/L and 0, 0.012, lake water (0.038) mg P/L exhibited stunted growth. They did not reproduce any daughter plants and died out of starvation within one and a half months. This showed that they lacked nutrient reserves that could enhance nourishment in the absence of external supply of nutrients. As such, depriving water hyacinth of nutrient supply could contribute to the control of the establishment and proliferation of water hyacinth.

The plants that were continuously supplied with nutrients showed gradual increase in the rates of biomass change until the end of the second month, then biomass declined in the third month. The increase in the rates of biomass change was due to uptake of nutrients and production of new individual plants that enhanced the build-up of biomass. In the third month, the initial parent plants were observed to reduce in size and most of their leaves were senescing. This coupled with overcrowding and the aging of other plants within the population led to lower rates of biomass increment. The rate of change in biomass of young and mature water hyacinth grown in level 6 (25.60 mg N/L and 3.20 mg P/L) was significantly higher than those grown 1.60 mg N/L and 0.20 mg P/L. That clearly indicated that plants respond to eutrophication by increase in biomass and multiplication. High nutrient concentration enhanced uptake of nutrients which were used to build up the plant biomass. The rates of biomass change recorded (1.02-44.81 g dry wt m^{-2} day^{-1}) were lower than the results of other studies. Reddy and Tucker (1983) found that when the average ambient temperature was 26-28°C, biomass yields were in the range of 19-53 g dry wt m^{-2} day^{-1}. The production (164 tons/ ha/ year) in the present study was also lower than the levels of production that have been reported in other studies. Edwards (1980) showed that annual production of 200 tons/ ha/ year might be attainable in eutrophic waters in the tropics. Coche (1983) reported an even higher yield of 750 tons/ ha/ year in irrigation canals in China. This further provides information which infers that low temperatures in Naivasha led to low nutrient uptake rates and limited the plants metabolic activities hence low biomass.

Despite the low biomass obtained for Naivasha, the results for multiplication rate that were obtained in this study were within the range reported elsewhere. It took one and half months (45 days) for the young water hyacinth plants with continuous replenishment of nutrients to produce new individuals whilst those that were batch loaded without any further additional nutrients failed to produce new plants. The fastest doubling time recorded in the present study was 9 days under the highest level of nutrient enrichment. According to Lindsey and Hirt (1999) and KARI (2001), water hyacinth may double its mass in as few as 6-15 days. Faster multiplication rates can be achieved; for instance, Amoding *et al.* (1999) reported doubling time of 4-7 days in Lake Victoria, Uganda. Very high multiplication rates were reported in River Zaire where up to 1200 daughter plants developed from 2 plants within only four months (Ivens, 1993).

The results for the half saturation coefficients of 0.05 and 0.6 for N and P were within the ranges reported in other studies. The half-saturation co-efficients for water hyacinths grown under constant conditions have been found to range from 0.05-1 mg/l for total nitrogen and 0.02-0.1 mg/l for phosphates, (Wilson *et al.*, 2005). Below the lower limits (0.05mg/l N and 0.02mg/l P), growth is likely to reduce drastically. From the nutrient response experiment, it was observed that nutrient levels below 0.01 mg N/L and 0.012 mg P/L can limit the establishment and proliferation of water hyacinth. If the nutrient inputs into the lake were to reduce, then the plant biomass accumulation will decline and subsequently the problems associated with excessive plant biomass will reduce. This was evident in the set up where water hyacinth was grown in lake water without further input of nutrients.

CHAPTER SIX
CONCLUSION AND RECOMMENDATION

6.1 Hypotheses review and conclusions

6.1.1 Hypotheses

1. Due to significant correlations between water hyacinth density and biomass and the physico-chemical parameters, the hypothesis that there is no difference in the effects of water hyacinth biomass dynamics on the physico-chemical parameters of underlying water in the lake is rejected.

2. With regard to the results, the hypothesis that there is no significant difference in the change in biomass of water hyacinth grown under different concentrations of nitrogen and phosphorous enrichment is rejected.

3. Based on the results for N and P uptake rates, the hypothesis that there is no significant difference in the uptake rates of nitrogen and phosphorous by different growth stages of water hyacinth is rejected.

6.1.2 Conclusion

1. Water hyacinth growth has significant influence on water quality in the lake. The water column below water hyacinth mats had three times lower dissolved oxygen concentration as compared to the open water, with values below 1mg/l recorded in some cases. In sites with water hyacinth, water transparency was two times lower, with twice as high total phosphorous concentration compared to the open water. High water hyacinth biomass slightly lowers pH ranges and temperature. Water hyacinth density, live and senesced biomass show no variation between the Sewage and Malewa study sites. However, increase in lake level during the rainy season coupled with increase in the concentrations of nitrogen and phosphorus lead to an increase in the density and live biomass of water hyacinth. The number of daughter plants increased significantly during the rainy season indicating high multiplication rates.

2. The results from the experimental set up indicate that the young water hyacinth plants are capable of taking up to 2.5 times more N and P per unit area than old plants.

3. The accumulation of biomass and reproduction rate of water hyacinth is dependent on the availability and amount of nitrogen and phosphorus. The rates of biomass change increases by at least 1.4 times when the N and P enrichment is doubled. Depriving plants of continuous N and P enrichment leads to a decline in biomass and eventual death.

6.2 Recommendations

The following recommendations should be considered to control the growth of water hyacinth and improve the quality of water in Lake Naivasha.

- Reducing nutrient inputs into the lake (from point and diffuse sources) has the potential of limiting the establishment and proliferation of water hyacinth. This can be achieved through regular water monitoring programs for all the water input sources into the lake. Management and rehabilitation measures must be taken in the hot spots, more so in the Malewa River and its catchment, the Naivasha Municipal wastewater treatment facilities and the other rivers that drain into Lake Naivasha.

- Comprehensive studies to determine the influence of seasonality on the loading of nutrients and how this affects water hyacinth phenological cycles in the lake should be done. More studies should be done on the lake to find out how much nutrients is locked up in the water hyacinth biomass in the lake and subsequent release of those nutrients into the water column and sediments upon senescence.

- It would be important to investigate the magnitude with which climate change and rise in temperature would influence water hyacinth growth in Lake Naivasha. It would also be interesting to find out the effect of water hyacinth in the control of greenhouse gases for Naivasha basin since it is evident that sites with water hyacinth have higher concentration of free CO_2.

- Spatial spread of water hyacinth alongside the temporal aspect is a knowledge gap that needs to be studied into details since it cannot be explained in this study.

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APPENDICES

Appendix Table 1. Temporal variation of nutrients in the sampling sites (data presented as mean±SD)

Parameter	Site	September	October	November	December	January
NO3-N (mg/l)	Sewage	0.103±0.006	0.068±0.054	0.077±0.024	0.144±0.037	0.032±0.009
	Malewa	0.083±0.003	0.062±0.021	0.142±0.040	0.244±0.139	0.015±0.010
	Open water	0.143±0.005	0.136±0.142	0.072±0.020	0.0980.029±	0.011±0.007
NO2-N (mg/l)	Sewage	0.0030±0.0005	0.0030±0.0014	0.0030±0.0009	0.0070±0.0001	0.0010±0.0009
	Malewa	0.0020±0.0004	0.0030±0.0028	0.0140±0.0100	0.0150±0.0102	0.0060±0.0031
	Open water	0.0010±0.0008	0.0020±0.0011	0.0010±0.0002	0.0120±0.0089	0.0140±0.0097
NH4-N (mg/l)	Sewage	0.084±0.048	0.026±0.008	0.023±0.010	0.117±0.081	0.020±0.007
	Malewa	0.043±0.005	0.021±0.015	0.063±0.031	0.061±0.028	0.064±0.030
	Open water	0.032±0.002	0.016±0.017	0.009±0.005	0.200±0.083	0.122±0.068
TP (mg/l)	Sewage	0.032±0.014	0.094±0.025	0.194±0.054	0.166±0.038	0.245±0.207
	Malewa	0.041±0.001	0.128±0.037	0.137±0.024	0.332±0.127	0.095±0.025
	Open water	0.095±0.073	0.073±0.005	0.134±0.034	0.101±0.088	0.036±0.005
SRP (mg/l)	Sewage	0.006±0.004	0.009±0.004	0.010±0.014	0.102±0.084	0.013±0.003
	Malewa	0.018±0.004	0.037±0.016	0.007±0.001	0.038±0.005	0.010±0.008
	Open water	0.024±0.014	0.021±0.012	0.066±0.103	0.010±0.009	0.006±0.004

Appendix Table 2: Temporal variation of *E. crassipes* density and biomass in the sampling sites (values are mean±SD)

Parameters	Site	September	October	November	December	January
Population Density/ m²	Sewage	57.33±2.52	40.33±1.53	57.33±22.50	94.00±9.85	67.00±7.00
	Malewa	55.33±0.58	61.67±4.51	50.67±1.53	49.67±8.51	98.00±3.00
Juveniles/ m²	Sewage	3.00±1.00	2.67±0.58	8.33±0.58	8.00±3.00	55.67±12.22
	Malewa	6.00±1.00	5.33±0.58	5.00±2.00	21.67±1.53	66.67±5.51
Live biomass (kg dw/m²)	Sewage	1.32±0.24	1.19±0.08	1.92±0.02	1.63±0.17	3.38±0.27
	Malewa	1.32±0.07	2.29±0.18	1.48±0.17	1.487±0.82	2.55±0.49
Senesced biomass (kg dw/m²)	Sewage	0.45±0.01	0.45±0.04	0.22±0.03	0.13±0.01	0.28±0.01
	Malewa	0.36±0.01	0.28±0.04	0.62±0.19	0.10±0.07	0.37±0.02

Appendix Table 3: Variation of water depth (m) in the sampling sites on different sampling dates

Sites	16/09/11	29/09/11	13/10/11	27/10/11	10/11/2011	24/11/11	8/12/2011	21/12/11	20/01/12	31/01/12
Sewage	1.5	1.4	1.6	2	2.3	3	3.6	3.8	3.2	2.5
Malewa	1.2	1.3	1.5	2	2.5	3	3.5	3.5	3	2.7
Open water	5	5.5	5.5	5.7	6.2	7.8	>9	>9	>9	>9

Appendix 1: Calculation of biomass changes under different nutrient concentrations using the obtained kd

Considering the average concentrations of N and P in Lake Naivasha as 0.164 and 0.022 respectively, the rates of biomass change of water hyacinth as a function of N and P concentrations in the lake can be determined as follows;

For Nitrogen: $\mathrm{U} = 3.69\ \mathrm{Kg/\ m^2/\ week}\ \ \frac{0.164\ \mathrm{mg/\ L}}{0.6+\ 0.164\ \mathrm{mg/\ L}} = 0.79\ \mathrm{Kg/\ m^2/\ week}$

For phosphorus: $\mathrm{U} = 3.69\ \mathrm{Kg/\ m^2/\ week}\ \ \frac{0.022\ \mathrm{mg/L}}{0.05+0.022\ \mathrm{mg/L}} = 1.13\ \mathrm{Kg/\ m^2/\ week}$

The value of the half saturation constant has an effect on the rate of change in biomass at different concentrations of nutrients. As such, if the concentrations of nitrogen and phosphorous were to reduce by half (to 0.082 and 0.011 mg/ L respectively), the rates of biomass change would be;

$\mathrm{U} = 3.69\ \mathrm{Kg/\ m^2/\ week}\ \ \frac{0.082\ \mathrm{mg/\ L}}{0.6+\ 0.082\ \mathrm{mg/\ L}} = 0.44\ \mathrm{Kg/\ m^2/\ week}$

This shows a reduction in the rate of biomass change by 44.30 %.

$\mathrm{U} = 3.69\ \mathrm{Kg/\ m^2/\ week}\ \ \frac{0.011\ \mathrm{mg/L}}{0.05+0.011\ \mathrm{mg/L}} = 0.68\ \mathrm{Kg/\ m^2/\ week}$

This indicates a reduction in the rate of biomass change by 39.82 %.

Using the procedure above, if the concentration of nitrogen in Lake Naivasha is reduced to 0.04 mg/l which is below 0.05mg/l - the lower limit of the hyacinth N kd range given by Wilson *et al*., (2005), the growth would reduce by 70.89 %.