# THE OCCURRENCE AND EXTENT OF WATER HYACINTH IN RWANDA AND THE SELECTION OF APPROPRIATE BIOLOGICAL CONTROL

A thesis submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy

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**DECLARATION**

I declare that this thesis is my own, unaided work, unless otherwise noted within the text. It is being submitted for the Degree of Doctor of Philosophy at University of the Witwatersrand, Johannesburg, South Africa. It has not been submitted before for any degree or examination at any other University.

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20th day of April 2020 at Johannesburg, South Africa

## ABSTRACT

The notorious weed water hyacinth is an invasive aquatic plant that has been associated with major negative economic and ecological impacts in water systems worldwide including Rwanda, since the weed's establishment in the country in the 1960s. Despite efforts to control the invasion, water hyacinth continues to overwhelm Rwandan fresh water systems. Therefore, it is crucial to understand the distribution and dynamics of water hyacinth in order to quantify its abundance, to identify factors constraining biological control of the weed, and to select appropriate biocontrol agents. Specifically, the study sought to (1) determine the occurrence of water hyacinth and its distribution in the major water bodies of Rwanda using Landsat 8 imageries, (2) investigate spatial and temporal distribution of water hyacinth using Landsat TM and Landsat 8, (3) Assess water quality indicators in Rwandan water system using Landsat 8 imagaries, (4) investigate the effect of water turbidity on the pupation of water hyacinth biocontrol agent *Neochetina* weevils and (5) to assess the physiological suitability of two additional biocontrol agents (*Cornops aquaticum* and *Megamelus scutellaris*) for control of water hyacinth infestations in Rwanda. Remotely sensed data with Random Forest and Support Vector Machine, advanve machine learning algorithms were used to map water hyacinths and its surrounding landcover types. Remotely sensed imageries were also used to map water quality indicators in Rwandan water systems. Furthermore, filed survey, and laboratory trials were conducted to investigate the feasibility of biological control program in Rwanda. Remotely sensed data revealed that most Rwandan fresh water bodies are invaded by water hyacinth. Four main rivers such as the Mukungwa River, the Akanyaru River, the Nyabarongo River and the Akagera River are confirmed to be the source and distributors of water hyacinth into the wetlands, dams and lakes through which they pass. Coverage of the weed ranges from 3 to 40%, with an average of 17%; this will increase in the absence of sustainable control measures. Biological control, using the natural enemies of the weed, is safe and sustainable. However, it can be limited by water parameters such as temperature, nutrients and turbidity levels. The results showed that warm temperatures and lower eutrophication should not constrain the efficiency of biocontrol of water hyacinth. However, the high turbidity observed in Rwanda water bodies, especially during the rainy season, was found to negatively affect the development, establishment and performance of *Neochetina* weevils used for biocontrol. Climate matching analysis revealed that among the biocontrol agents tested *Cornops aquaticum* and *Megamelus*

*scutellaris* should be able to establish and perform well under climatic conditions. In addition, these two species will not be affected by high turbidity because all stages of their life cycle occur on the emergent parts of the plant (petioles and leaves). Therefore, these two insects are recommended for biocontrol of water hyacinth in Rwanda. The study concludes that remote sensing is a useful tool for mapping and monitoring the spread of water hyacinth. It should be used to evaluate pre- and post-management interventions to control water hyacinth.

## DEDICATION

***In loving memory of my beloved father Ndegejeho Christoph Cosman, who passed away in 1987.***

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**GLOSSARY AND ABBREVIATIONS**

ASTER: Thermal Emission and Reflection Radiometer

AVHRR: Advanced Very High Resolution Radiometer

CLIMEX: climate modelling software that allows the user to predict/model the potential geographic distribution of organisms based on global/local meteorological data.

CTmin and CT max: Temperature at which insects lose locomotory function

FLAASH: Fast Line of sight Atmospheric Analysis of Hypercubes

IWRM: Integrated Water Resources Management

Landsat ETM: Landasat Enhance Thematic Mapper

Landsat TM: Landsat Thematic Mapper

LT: Lethal Temperature/Turbidity: a controlled exposure to conditions inwhich 50% of the test population survive and 50% die.

MERIS: Medium Resolution Imaging Spectrometer

MINIRENA: Ministry of Natural Resource Rwanda

MINITERE: Ministere des Terres, de l'Environment, de l'Eau, des Forets et des Mines (Ministry of Land, Environment, Forestry, Water and Mines)

MODIS: Medium Resolution Imaging Spectrometer

NDVI: Normalized Difference Vegetation Indice

NTU: Nephlometic Turbidity Unit

OECD: Organization for Economic Co-operation and Development

OLI: Operational Land Manager

RF: Random Forest

REMA: Rwanda Environmental Management Authority

RS: Remote Sensing

RNRA: Rwanda Natural Resource Authority

SPOT: Satellite Pour l'Observation de la Terre

SVM: Support Vector Machine

UTM: Universal Transverse Mercator

**PROBLEM STATEMENT**

Water hyacinth (*Eichhornia crassipes)* (C. Mart.) Solms (Liliales: Pontederiaceae) is one of many aquatic invasive alien species worldwide (Kriticos and Brunel, 2016). It causes losses in biodiversity, changes in ecosystems, and socio-economic issues by affecting activities such as recreation activities, power production, agriculture, and fisheries (Hill, 2003; Degaga, 2018). Originally from the Amazon Basin of South America, the infamous water hyacinth weed has spread across the world outside its place of origin since the 1800s, largely facilitated by its ornamental value, and has become the worst scourge of surface fresh water systems, particularly in the subtropical and tropical areas (Harley, 1990). A number of researchers have shown that water hyacinth is a vascular plant with a high capability of quick multiplication (Evans, 2008). This extremely high productive potential permits water hyacinth to overgrow and increase its competitiveness over indigenous species (Malik, 2007). In good environmental conditions, water hyacinth grows vegetatively from stolons and its ramets (daughter plants) and can double its density within 6 to18 days (Malik, 2007). Water hyacinth also reproduces sexually from seeds and a single rosette of the plant is capable of producing over 3000 seeds annually, which are capable of staying dormant for 15 to 20 years under unfavourable conditions (Center *et al.*, 2002). The management of water hyacinth consists of physical, biological and herbicidal control methods (Hill, 2003). However, only biological control is deemed doable and sustainable to control water hyacinth invasion (Hoelmer and Kirk, 2005), and when successful, it is potentially 400 times more cost effective than herbicidal control (Van Wyk and Van Wilgen, 2002). Biological control has been attempted in Rwanda using *Neochetina eichhorniae* and *Neochetina bruchi*, however the water hyacinth invasion has persisted because of the negligible effects of the weevils at the release sites. Although the threats posed by water hyacinth are recognized, appropriate measures to control the weed in Rwanda are still lacking. This is probably due to (1) lack of knowledge on the extent of water hyacinth infestation as well as the level of its impacts on rivers and lakes; (2) lack of knowledge of the contribution of abiotic factors in local water conditions on the failure of the introduced weevils in Rwandan water bodies; and (3) lack of information of the potential role played by other biocontrol agents on water hyacinth growth.

# CHAPTER 1:

## GENERAL INTRODUCTION

### 1.1 Invasive plant species

One of the significant threats to global biodiversity and functioning of ecosystems is the spread of invasive plant species, which has increased with the increase of international trade (Mooney and Cleland, 2001). Invasive alien plant species are non-indigenous plants capable of out-competing indigenous species in their introduced environment by occupying their habitats, moisture, and nutrients, thus altering the whole ecosystems structure and its functioning (Blumenthal *et al.*, 2009). They cause extinction of indigenous species as well as endemic species (re). For instance, *Lythrum salicaria (Myrtale, Lythraceae)* caused the extinction of the waterfowl, *Cistothorus palustris, Ixobrychus exilis* and other marsh birds in American wetlands (Blossey *et al.*, 2000). Furthermore, the bog turtle became an endemic species because of the aggressive invasion of *L. salicaria* in wetlands (Blossey *et al.,* 2000). The United States Endangered Species Act confirmed that this invasive species contributed to 42% of the species listed as endangered species (Gurevitch and Padilla, 2004). This Act considers invasive species as the drivers of environmental challenges across the world (Gurevitch and Padilla, 2004). The grass *Bromus tectorum (Cyperales: Poaceae*) affects American natural ecosystems by accelerating the occurrence of fire. Pimentel *et al.* (2005) reported that before its introduction, fire occurred only once every 60–110 years, but after its establishment, fire frequency increased and now occurs every 3–5 years. Invasive plant species negatively affect human well-being, contributing to a decrease in food security, deteriorating health and wealth; and thus, contributing to social and economic issues by increasing the constraints on sustainable development (Hytec and Mary, 2010).

The main drivers of invasive plant species' movement from one place to another are international trade and climate change (Mooney and Hofgaard, 1999). Climate change has impacts on the intensity and frequency of extreme climatic events that may assist invasive species to disturb ecosystems. This leads to a chance that an invasive plant species can establish, grow and take over a habitat (McNeely, 2001). Travelling by vehicles or international exchange by ships and containerized cargo, people and their belongings can aid the spread of invasive species. It is through the aforementioned means that invasive alien plant species were introduced and spread to African countries, including Rwanda (Matthews and Brand, 2004).

### 1.2 Invasive plant species in Rwanda

Rwanda has committed itself to seek means of reducing the degree of biodiversity loss to contribute to poverty alleviation and to the benefit of all life on earth (Aboniyo *et al.*, 2016). However, the problem of invasive species is becoming bigger and the number of invasive plant species is increasing year by year (REMA, 2016). There are 31 invasive plant species (29 terrestrial and 2 aquatic plant species) in Rwanda, categorized according to the level of their invasiveness and these species are basically controlled manually because it is the only official method used to control invasive alien species in Rwanda (Table 1.1) (REMA, 2016). Among these, *Lantana camara* is ranked as the worst terrestrial weed in the country (REMA, 2016; Tuyizere *et al.*, 2018). It has invaded most Rwandan parks including Akagera National Park and Gishwati National Park (REMA, 2009; 2016).

Table 1.1: List of the invasive alien plant species based on their level of invasion in Rwanda (adapted from Seburanga, 2015; REMA, 2016; Tuyizere *et al.*, 2018).

| No. | Scientific name | Impact level | Distribution potential | Categories of invasiveness | Control methods |
|---|---|---|---|---|---|
| 1 | *Lantana camara* | High | High | 1 | Manual removal |
| 2 | *Eichhornia crassipes* | High | High | 1 | Manual removal |
| 3 | *Mimosa pigra* | High | Medium | 2 | Manual removal |
| 4 | *Solanum chrysotricum* | High | Medium | 2 | No control method used |
| 5 | *Acacia mearnsii* | Medium | High | 2 | No control method used |
| 6 | *Acacia melanoxylon* | Medium | High | 2 | No control method used |
| 7 | *Caesalpinia decapetala* | Medium | High | 2 | No control method used |
| 8 | *Agave sisalana* | Medium | High | 2 | No control method used |
| 9 | *Tithonia diversifolia* | Medium | Medium | 2 | No control method used |
| 10 | *Opuntia monacantha* | Medium | Medium | 2 | Manual removal |

| | | | | | |
|---|---|---|---|---|---|
| 11 | *Datura stramonium* | Medium | Medium | 3 | No control method used |

Table 1.1 (continued)

| | | | | | |
|---|---|---|---|---|---|
| 12 | *Pinus patula* | Medium | Medium | 3 | No control method used |
| 13 | *Cupressus lusitanica* | Medium | Medium | 3 | No control method used |
| 14 | *Leonotis nepetifolia* | Low | Medium | 3 | No control method used |
| 15 | *Bambusa vulgaris* | Low | Medium | 3 | No control method used |
| 16 | *Imperata cylindrica* | Low | Medium | 3 | No control method used |
| 17 | *Cuscuta campestris* | Low | Medium | 3 | No control method used |
| 18 | *Ageratum conyzoides* | Low | Medium | 3 | No control method used |
| 19 | *Senna spectabilis* | Low | Medium | 3 | No control method used |
| 20 | *Agave americana* | Low | Medium | 3 | No control method used |
| 21 | *Eucalyptus diversicolor* | Low | Medium | 3 | No control method used |
| 22 | *Eucalyptus maidenii* | Low | Medium | 3 | No control method used |
| 23 | *Eucalyptus tereticornis* | Low | Medium | 3 | No control method used |
| 24 | *Eucalyptus saligna* | Low | Medium | 3 | No control method used |
| 25 | *Senna occidentalis* | Low | Low | 4 | No control method used |
| 26 | *Psidium guajava* | Low | Low | 4 | No control method used |
| 27 | *Leucaena leucocephala* | Low | Low | 4 | No control method used |
| 28 | *Calliandra calothyrsus* | Low | Low | 4 | No control method used |
| 29 | *Aptenia cordifolia* | Low | Low | 4 | No control method used |
| 30 | *Duranta erecta* | Low | Low | 4 | No control method used |

| | | | | | |
|---|---|---|---|---|---|
| 31 | *Crocosmia paniculata* | Low | Low | 4 | No control method used |

The only aquatic weeds reported by REMA (2009; 2016) are water lilies with yellow and purple colours, found mainly in manmade impoundments and domestic ponds, and *Eichhornia crassipes* commonly named water hyacinth, found in lakes and rivers.

### 1.3 Water hyacinth

Water hyacinth is an aquatic weed, described by the naturalist C. Von Martius in 1823 (Jones, 2009). Native to Amazonia, the weed has spread into many regions worldwide. It is the main aquatic weed of the tropics and subtropics in the regions such as India, some parts of the USA, Africa, and it is also extremely invading South Eastern regin of Asia (Kriticos and Brunel, 2016). The spread of water hyacinth outside its place of origin was facilitated by humans, because of its importance as a decorative plant in the nursery trade (Shanab *et al.,* 2010). The first African countries to publish records of water hyacinth infestations were Egypt (1888), followed by South Africa (1908), Malawi (1960), Senegal (1963), Zambia (1965) and the Central African Republic (1970) (Navarro and Phiri, 2000). However, the weed was introduced into most African countries between the years 1930 and 1990 (Julien, 2001; Navarro and Phiri, 2000; Labrada and Fornasari, 2002).

Water hyacinth is capable of expanding quickly due to its sexual and asexual vegetative reproduction; the latter is indispensable for rapid colonization and expension (Jones, 2009). During its proliferation, the weed forms mats that may comprise approximately two million plants, weighing 270 to 400 tonnes per hectare (Malik, 2007). Such mats formed in water smother other aquatic organisms by inhibiting the transfer of oxygen from air to water and by preventing light penetration into water necessary for photosynthesis (Villamagna and Murphy, 2010; Degaga, 2018). Water hyacinth blocks water currents and negatively affect irrigation, fishing activities, and recreational sports (Timmer and Weldon, 1966; Hill, 2003; Villamagna and Murphy, 2010, Degaga, 2019). The deposit of dead water hyacinth and its decay reduces water quality, making it unsuited for drinking and cooking (Patel, 2012). Water hyacinth causes a serious socio-economic challenge. For instance, there has been a decrease in fishermen’s income in Burkina-Faso amounting to US$35000–45000 annually; a decrease in fisherman’s income at Mosasapoula River in Central Africa was US $429 per fisherman per year (Wise *et al.*, 2007); and a decrease in fisherman's revenue at Nselene River in South Africa was US $158 per fisherman per year (Jones, 2009). Water hyacinth infestations have affected the livelihoods of Zimbabweans whose income has depended on fishing activity in the Lake Kariba (Chikwenhere *et al.*, 1999). In Benin, It became difficult to throw the nets (because of water mats in rivers, which led to a decrease of fishermen income (De Groote *et al.*, 2003). In Victoria, fish catch rates on the Kenyan side decreased by 45% because of water hyacinth mats clogged access to fishing grounds and increased costs of fishing (Kateregga and Sterner, 2009). In Nigeria, fishing has become almost impossible task in Nigeria due water hyacinth infestation (Ndimele *et al.*, 2011; Yigermal and Assefa, 2019). Similarly, water hyacinth invasion in Lake Naivasha, affected the income of surrounding community whose life was dependent on fishing activities (Yigermal and Assefa, 2019). The invasion of water hyacinth in the Douala River in Cameroon decreased the fish production as well as the number of fishermen by 66.7% and 67.8% respectively (Kenfack Voukeng *et al.*, 2019). Apart from aforemetionned issues, water hyacinth may provide suitable breeding sites for vectors of human and animal diseases, increasing the incidence of diseases such as encephalitis, schistosomiasis, filariasis, cholera, bilharzia, malaria and typhoid in many contries (Spira *et al.*, 1981; Viswam *et al.*, 1989; Aloo *et al.*, 2013). Water hyacinth first appeared in Rwanda in 1957 (Navarro and Phiri, 2000) but it was only recognised as problem by the Rwandan government after 1994 (MINITERE, 2005).

### 1.4 Water hyacinth in Rwanda

Over the past few years, Rwanda has faced a significant pressure on its water bodies from water hyacinth invasions. This invasive weed has caused a reduction in the water quantity and threatened the livelihood of the local communities that depend on the lakes for fishing and other socio-economic activities (Gashamura, 2009). Since its introduction into the gardens and duck ponds within residential compounds of the European expatriates at Socièté de la Transformation Industrielle de Ruhengeri (SOTIRU) close to the Mukungwa valley in the Northern Province of Rwanda in 1957 (Navarro and Phiri, 2000), water hyacinth has gradually spread into the lakes and rivers linked to the Mukungwa River, including the Nyabarongo and Akagera Rivers (Seburanga *et al.*, 2014). Because of the lack of a sustainable method for its management, the swamps and lakes have been overrun by water hyacinth (REMA, 2009). The invasion of this weed caused the loss of aquatic biodiversity, a reduction in fish production as well as a reduction of water quality in Rwandan water systems (REMA 2009; Seburanga *et al.*, 2014). It is for these reasons that the government and policy makers of the country set rules for controlling water hyacinth in the 2002s. However, these efforts have been deemed ineffective, and the weed continues to spread in the water systems of the country (REMA, 2016).

### 1.5 Factors contributing to water hyacinth growth

Water hyacinth is a floating plant that grows in extensive range of aquatic habitats (Gopal, 1987). Nevertheless, it prefers calm waters even though it can withstand seasonal changes (Batcher, 2000). Water chemical properties such salinity and pH can affect water hyacinth development and growth. It is able to grow in water bodies with oligohaline conditions (<5 ppt); however, the weed cannot tolerate high salinity (Muramoto *et al.*, 1991)). High levels of salt (>5 ppt) leads to leaf chlorosis, which in return reduces plant photosynthetic capacity (Reginato *et al.*, 2014). The weed also cannot grow in water bodies with low pH (<4) or high pH (>10) (Muramoto *et al.*, 1991). However, the main factors that contribute to water hyacinth growth are water nutrients and temperature (Shu *et al.*, 2014). High level of water nutrients (>2.5mg/l N and 0.25mg/l P) allow quick growth of water hyacinth. However, water hyacinth can grow even in water bodies with low levels of nutrients (Byrne *et al.*, 2010). Temperature is another water abiotic factor that influences the growth, distribution and abundance of any living organism through its impacts on physiological and metabolic processes (Somero, 2002); hence, the growth of water hyacinth is also influenced by temperature (Gutiérrez *et al.*, 2001) and is limited by both high and low temperatures. Water hyacinth does not grow above 40 ºC or below 8 ºC (Byrne *et al.*, 2010), and frost directly affects water hyacinth growth by causing major leaf mortality (King, 2012). The maximum air temperature in Rwanda is 28 ºC and the minimum temperature is 16 ºC (Muhire *et al.*, 2015). These temperatures may enhance proliferation of water hyacinth (Byrne *et al.*, 2010). However, there is no literature about the water temperature range in Rwandan water bodies. Therefore, this thesis also included an investigation of temperature in water bodies infested by water hyacinth.

### 1.6 Management of water hyacinth

Because of its aggressive invasion, every year enormous amounts of money and effort are expended worldwide to reduce the impact of water hyacinth using physical, chemical, or biological control methods (Byers *et al.*, 2002). Physical method, which consists of the removal and harvesting of plants by hand or machine from water bodies, has been used to combat water hyacinth invasion in many countries (Patel, 2012). However, its disadvantages include the following:

i) The seeds and plant parts left behind during the removal of water hyacinth plants can grow and re-infest the water bodies.

ii) It needs large workforce, too exhaustive, and the cost of clearing water bodies is extremely high. According to Wittenberg and Cock (2001), mechanical removal of a hectare can cost on average US$600–1200. This is around six times more costly than herbicidal control (Wittenberg and Cock, 2001).

iii) Manual removal is not always suitable in deep water areas because of the risk of workers drowning.

Compared to physical methods, the use of herbicides to control weed infestation is effective when they are properly used, and before the plants' flowering stages (Khanna *et al.*, 2011). The chemicals used to control water hyacinth are Diquat, Paraquat, Amitrole, 2, 4-D acid, metsulfron-methyl and glyphosate (Villamanga and Murphy, 2010; Borokoni, and Babalola, 2012). However, there are application issues because of environmental and health concerns, which are being challenged by stricter regulations (Sodhi and Ehrlich, 2010). Tham (2012) showed that repetitive spraying of glyphosate and 2,4-dichlorophenoxy are required on water hyacinth infested water bodies to avoid reinvasion from clonal multiplication of surviving plants and seeds which inflates the cost of using herbicides and making it economically unfeasible. Thus, of all three methods for combating water hyacinth invasion, biological control is the most viable and environmentally safe option (Charudattan *et al.*, 1996; Fowler *et al.*, 2000; Law, 2007).

## 1.7 Biological control of water hyacinth

Biological control of invasive plant species uses coevolved natural enemies such as an herbivorous insect and pathogens to control their distribution outside their natural range (Law, 2007; Dagno *et al.*, 2012). Direct herbivory by such insects on different parts (leaves, petioles, roots) of the host plant reduces growth and reproduction and eventually causes the plant's mortality. The natural enemies that target an invasive weed can also be vectors of other destructive natural enemies such as pathogens, fungus and other saprophytic organisms that kill the plant (Culliney, 2005). Moran (2004) found that the scars on the leaves and other wounds from the herbivores are responsible for a pathogenic fungal infection in water hyacinth plants. Similarly, Venter *et al.* (2013), showed that the pathogens hosted by weevils contributed to the decrease of photosynthetic capacity in leaves of water hyacinth plants, inhibiting growth and proliferation (Kirschbaum, 2011).

Biological control contributed to the reduction of water hyacinth invasion (Hill and Coetzee, 2017), and has contributed to an increased fishes production and thus improving the lives of different local communities that depend on fishing for their livelihood (De Groote *et al.*, 2003; Njoka, 2004; Hill and Coetzee, 2017). Since 1971, two weevils, *Neochetina bruchi* (Hustache) and *Neochetina eichhorniae* (Warner) (Coleoptera: Curculionidae), have been largely used for water hyacinth control in Africa, Australia, and Asia (Wittenberg and Cock, 2001). After their introduction several other subsequent introductions of water hyacinth biocontrol agents have followed, and among them are the *Eccritotarsus catarinensis* (Carvalho) (Hemiptera: Miridae), *Niphograpta albiguttalis* (Warren) (Lepidoptera: Crambidae), a pyralid moth *Xubida infusellus* (Lepidoptera: Pyralidae), *Orthogalumna terebrantis* (Wallwork) (Acarina: Sarcoptiformes: Galumnidae), and the fungal pathogen, *Cercospora piaropi* (Tharp) (Mycosphaerellales: Mycosphaerellaceae) (Julien *et al.*, 2001; Coetzee *et al.*, 2011). Laboratory trials indicated that *Taosa longula* (Remes Lenicov) (Hemiptera: Dictyopharidae) (Hernández *et al.*, 2011), *Bellura densa* (Walker) (Lepidoptera: Noctuidae) (Center and Hill 2000), and *Thrypticus smaragdinus* (Diptera: Dolichopodidae) (Cordo *et al.*, 2000) are promising biocontrol agents of water hyacinth (Coetzee *et al.*, 2011). However, they have not yet been released anywhere. In addition, bug *Megamelus scutellaris* Berg (Hemiptera: Delphacidae) and the grasshopper *Cornops aquaticum* (Orthoptera: Acrididae) have been shown to be promising in fighting the water hyacinth incursion in South African water bodies (Coetzee *et al.*, 2011). The two *Neochetina* species have controlled water hyacinth in many countries, including USA, Australia, and India, (Mc Fadyen, 1998, in West Africa (Ajounu *et al.*, 2003), in Lake Victoria, a lake shared by Uganda, Tanzania and Kenya (Wilson *et al.*, 2007), in New Year's Dam, South Africa (Hill and Coetzee, 2017), and in Papua New Guinea (Julien *et al.*, 2001). *Neochetina bruchi* and *Neochetina eichhorniae* were introduced into Rwandan water bodies in 2000; however, they have failed to establish and control the water hyacinth infestation (Moorhouse *et al*., 2001). Therefore, this thesis included an investigation on the causes of the *Neochetin*a weevils' failure to control water hyacinth in Rwandan water systems.

### 1.7.1 *Neochetina* weevils

*Neochetina bruchi* and *Neochetina eichhorniae* are the mottled water hyacinth weevils (Del Fosse, 1978). They are solely natural enemies of water hyacinth, feeding on the leaf lamina, petioles and stem bases (Spencer and Ksander, 2004). *Neochetina* females lay their eggs in the petioles (DeLoach and Cordo, 1976) where the larvae develop. As the larvae feed, they tunnel down through the petiole towards the crown of the plant (Jianqing *et al*., 2002), destroying the petiole tissue and decreasing plant buoyancy. Larvae pupate by attaching to the living rootstock of water hyacinth plants (DeLoach and Cordo 1976). Once the adults emerge, they feed on the lamina, creating feeding scars that reduce the photosynthetic rate of the plant (Soti and Volin, 2010). Thus, they can have devastating effects on water hyacinth populations, reducing them by up to 95% (Jayanth, 1988). However, they are not always successful in all circumstances due to abiotic factors such as turbidity, water temperatures and nutrients (Hill and Olkers, 2001, Center and Dray, 2010). Hence, the addition of new biocontrol agents, particularly those with capabilities for rapid population increase and resistance to adverse water abiotic factors, such as *Megamelus scutellaris* (Sutton *et al*.,2016) and *Cornops aquaticum* (Bownes *et al*., 2013), is essential.

### 1.7.2 *Megamelus scutellaris*

*Megamelus scutellaris* (Berg) (Hemiptera: Delphacidae) is an insect widely distributed in Argentina, Peru, Brazil and Uruguay. It is only found where water hyacinth plants are present (Sosa *et al*., 2004). It is a multivoltine species that exhibits wing dimorphism with both a macropterous (a long-winged dispersal form, capable of flying) and a brachypterous (a short-winged, non-flying form) form (Sosa *et al*., 2005). Female and male *M. scutellaris* usually mate at the base of water hyacinth plants (Sosa *et al.,* 2005) as well as on the upper part of the leaves (Tipping *et al.,* 2008). Sosa *et al.* (2007) revealed that *M. scutellaris* did not feed on other pontederiaceae species and they do not have any negative environmental or human health effects. When feeding on water hyacinth, *M. scutellaris* insert their stylets (needle-like mouthparts) into the plant and ingest the sap (Hernández *et al.,* 2011). Saliva secreted during penetration forms a stylet sheath that acts to hold the stylets together (Hernández *et al.,* 2011). This intracellular penetration is accompanied by the disruption of organelles, which results in chlorosis and necrosis in the plants (Spiller, 1990). These reduce translocation of water and nutrients, photosynthetic rates, and higher permeability of plasma membranes in the plant (Moran, 2005), which leads to a reduction of water hyacinth vigour by weight loss, decrease in plant size and reproductive capacity, and dying of plant growth parameters. This may enhance the death of the plant. Therefore, *M. scutellaris* can complement *Neochetina* weevils in controlling water hyacinth invasions successfully. However, it is critical to investigate the impact of Rwandan water temperature and nutrient levels on *M. scutellaris*.

### 1.7.3 *Cornops aquaticum*

*Cornops aquaticum* (Bruner) (Orthoptera: Acrididae: Leptysminae) is a grasshopper originally from the Amazon Basin (Amedegnato, 1977) and extensively distributed in Argentina, Mexico, and Uruguay where water hyacinth is present (Adis *et al*., 2007). This plant feeder lays eggs inside the petioles of Pontederiaceae, specifically water hyacinth (Center *et al*., 2002). *Cornops aquaticum* is considered as the most promising biocontrol agent of water hyacinth infestations based on reports of its damage to the weed in its native range (Perkins 1974). Both adults and nymphs of *C. aquaticum* are defoliators and they destroy water hyacinth by removing the epidermis from the petioles (Franceschini *et al*., 2010). The pre-release studies of *C. aquaticum* in South Africa showed that *C. aquaticum* has the potential to reduce populations of water hyacinth even in eutrophic conditions (Bownes *et al*., 2011). Apart from eutrophic conditions, *C. aquaticum* seems to be resistant to high temperatures up to 47.8 C, which is the temperature at which *C. aquaticum* will lose coordination and stop all activity (Venturi, unpublished data). Therefore, this thesis included an investigation on the effects of both nutrients and temperature on *C. aquaticum* to determine if *C. aquaticum* can be a complementary biocontrol agent to the *Neochetina* weevils to control water hyacinth in Rwanda based on Rwandan temperature.

## 1.8 Factors affecting the success of biological control

The effective control of invasive alien weeds requires successful establishment and spread of biological control agents. However, this depends on favourable environmental factors, including predators, eutrophication, temperature, flooding, drought, hydrology of water bodies and the extensive use of herbicides (Byrne *et al.*, 2010; May and Coetzee, 2013). Chown and Nicholson (2004), among others, have shown that temperature is one of the main abiotic factors that influence the growth and development rate of insects. Low temperatures and frost were found to cause high mortality of *Neochetina* weevils and *Eccritotarsus catarinensis*, in all their growth and developmental stages (King, 2012). Beside extreme temperatures, flood events were also found to affect the success of biological control (Hill and Olckers, 2001). During a flood event, insects are removed along with water hyacinth, while the water hyacinths' dormant seeds in the sediments can germinate after such events and give rise to new plants (Hill and Olckers, 2001). In addition, the accumulation of heavy metal pollutants in the tissues of water hyacinth as a result of mining and industrial pollution was found to reduce the weevils' fecundity and negatively impact larval development (Newete *et al.*, 2014). The most constraining water abiotic factors to biocontrol agents of water hyacinth are however eutrophication, and exteme temperatures (Byrne *et al.*, 2010). Another suspected water factor is water turbidity. Turbidity impairs the development and growth of some aquatic insects by reducing oxygen in water (Wong and Fikri, 2016); thus, it may also affect the development *Neochetina* weevils.

### 1.8.1 Climatic conditions

Climate conditions impact the success of biological control since temperature is essential for insect development and growth. Hence, exposure to low or high temperatures may slow or stop insect development (Julien, 2001). Low temperatures slow down development and population growth and cause high mortality of biological control agents (Byrne *et al.*, 2010). Temperatures between 12 ºC and 15 ºC negatively affect *N. eichhorniae* oviposition and below 12 ºC *N.eichhorniae* larvae slow or stop development (Byrne *et al.*, 2010). Cold winter temperatures impede successful biological control of water hyacinth in cold regions of South Africa, USA and China (Coetzee *et al.*, 2009). Because of extreme summer temperatures, *M. scutellaris* failed to establish in Texas and Louisiana (Grodowitz *et al.*, 2017). The Rwandan weather is temperate and moderate, with average maximum and minimum and temperatures of 22.9 ºC and 14 ºC, respectively (Muhire *et al.*, 2015). Low temperatures are recorded in high altitude regions with average annual temperatures of 15.9 ºC (Nshimiyimana *et al.*, 2010). However, temperatures in Rwanda can reach as low as 7 ºC, particularly in the northern regions of the country during the heavy rain season, specifically in April and May (Haggag *et al.*, 2016). The areas with intermediate altitude (1350–1550 m) have moderate temperatures that vary between 19 ºC and 21 ºC. In the lowlands (East-West at an altitude of 900m) average temperatures are from 21 to 22.9 ºC (Muhire *et al.*, 2015). The extreme high temperatures in these regions can reach up to 35 ºC for some days in July and August (Safari, 2012; Haggag *et al.*, 2016). However, the effects of these temperatures on water hyacinth proliferation as well as the establishment and the performance of its biocontrol agents in Rwanda are unknown. Knowing the temperature range within which an organism is able to survive and reproduce, allows predictions to be made about where an organism will thrive.

### 1.8.2 Eutrophication of water bodies

Pollution of water bodies by nitrates and phosphates from agricultural and industrial activities facilitate the rapid growth of water hyacinth (Newman *et al.*, 1998; Hill and Olckers, 2001). Consequently, with such plant growth vigour, the impact of biocontrol agents is trivial. One such example is Hammarsdale Dam in KwaZulu-Natal Province (South Africa) where *N. eichhorniae* biocontrol agents were unable to reduce the water hyacinth invasion due to the high concentrations of nitrates and phosphates in the dam (Hill and Olckers, 2001). Similarly, the mirid *E. catarinensis* was unable to reduce water hyacinth invasion in sites rich in nutrients as the growth of water hyacinth was greater than the impact of the biocontrol agent (Coetzee *et al.*, 2009). Bownes *et al.* (2013) found that at high nutrient levels, water hyacinth plants were able to compensate for the damage caused by *C. aquaticum.* Thus, an investigation of the nutrient levels in Rwandan water bodies can help to direct the appropriate weed control strategies.

Beside the eutrophication, associated turbidity in rivers and lakes is thought to affect the success of biological control of water hyacinth by inhibiting the pupation stage of *Neochetina* weevils that occurs on the plant's roots.

### 1.8.3 Effect of turbidity on aquatic living organisms

Turbidity is an optical property of a liquid that causes light to be scattered and absorbed rather than transmitted in straight lines through the water sample (Brupton, 1985). It makes water look muddy or cloudy. Water turbidity is due to the presence of dissolved and suspended matter like silt, clay, finely divided organic matter, phytoplankton, dyes and organic acids (Myre and Shaw, 2006). Hence, it is considered to be a major contributor to the decrease of aquatic organisms (Henley *et al.*, 2000). This is because:

i) High turbidity in water reduces light penetration and the oxygen necessary for the growth of aquatic organism. Reduction of light penetration negatively impacts photosynthetic organisms, thus disturbing food webs, which results in high decreases of aquatic living organisms (Lunt, and Smee, 2014).

ii) The suspended matters in water bind directly with biological membranes, especially in fishes and aquatic insects that use gills for respiration (Bond and Downes, 2003). In the case of aquatic insects, they may die because of asphyxia.

Thus, there is a concern for biological control agents that pupate on the roots of water hyacinth, such as the *Neochetina* weevils. Therefore, this was the focus of this thesis to investigate the effect of Rwandan water turbidity on the *Neochetina* weevils' development.

Although the management of water hyacinth is a challenge in many countries, the major issue is to understand the distribution of the weed in the water systems (rivers linked to each other, rivers linked to lakes, dams and wetlands) before controlling it. This problem has been associated with the lack of fine scale information concerning the weed dynamics and its extent in invaded water systems (Thamaga and Dube, 2018). In general, invasive plant species can be located through species detection techniques or species habitat suitability modelling (Bradley *et al.*, 2012). However, the latter method does not provide reliable information on invasive plant species distributions nor the extent and abundance of invasive plant species in complex ecosystems (Hirzel *et al.*, 2006). Species detection is a method that aims to locate plant species (individuals or clusters) (Hauser and McCarthy, 2009). It is a method that provides detailed and updated information on the distribution, extent and abundance of invasive plant species in the ecosystem (Hauser and McCarthy, 2009). Among the methods used to locate invasive plant species are field surveys and remote sensing techniques. However, the second option is the most promising because it can accurately detect invasive plant species even in inaccessible areas, including water weeds such as water hyacinth (Thamaga and Dube, 2018).

## 1.9 Remote sensing

Remote sensing is a technique used to acquire information about an object without being in physical contact with it by sensing and recording reflected or emitted energy, which is processed and analyzed afterwards (Sivakumarand and Hinsman, 2003; Lillesand *et al.*, 2004). It uses a wide range of aerial sensors such as airborne multispectral scanners, aerial photographs, satellite imageries of high spatial and spectral resolution. These sensors can view the spatial, spectral, and radiometric relations of materials and observable objects at a distance. Most sensing modes are based on sampling of photons of corresponding frequency in the electromagnetic spectrum (Thenkabail *et al.*, 2011).

Remote sensing techniques are used in many disciplines: In the study of atmospheric temperature, monitoring water surface temperature, and monitoring water quality parameters such as sediments, nutrients, metals, pesticides, dissolved organic matter, and aquatic vascular plants (Ritchie *et al.*, 2003). It has been used in the mapping of oceans, the identification of rock types and structures, the taking of measurements of the earth's gravity, and the monitoring of deforestation and reforestation (Ali, 2010). It is used to monitor the biomass of vegetation, crop health status, forecasting crop production and monitoring the effects of climate change (Muhire, 2015). It is also used in the prediction of disasters and mapping of ecological zones (Ali, 2010).

Remote sensing has been extensively used in the field of biological invasion during the last decades due to its capacity to offer a well-documented synoptic view of invasive plant species (Van der Meer *et al.*, 2002; Lawrence *et al.*, 2006; Huang and Asner, 2009; Müllerová *et al.*, 2013). Remote sensing facilitates the discrimination of invasive weeds from other plants (Huang *et al.*, 2009). It is able to more precisely determine the abundance and distribution of invasive alien species in the environment compared to the classical technique that is based on ground surveys (Joshi *et al.*, 2006; Huang *et al.*, 2009).

Invasive plant species can be mapped using hyperspectral or multispectral sensors. Most of hyperspectral sensors have a high spectral and a high spatial resolution (0.5–1m) (Thenkabail *et al.*, 2004). However, fewhyperspectral sensons such as Hyperion (EO-1 platform), Compact High Resolution Imaging Spectrometer (CHRIS), PRecursore IperSpettrale della Missione Applicativa (PRISMA), Environmental Mapping and Analysis Program (EnMAP) and Hyperspectral Imager SUIte (HISUI) have spatial resolution of 30-m, but they are able to present fine and continuous spectral information (Transon *et al.*, 2018).

Multispectral sensors have 4–15 bands and their pixel sizes ranges from 2m (e.g QuickBird and WorldView-2 sensors) to 250m, (e.g Medium Resolution Imaging Spectrometer (MERIS) and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors) (Underwood *et al.*, 2003). Hyperspectral sensors can collect immense amounts of detailed spectral data. However, they are very expensive compared to multispectral sensors (Thenkabail *et al.*, 2004). The cost for hyperspectral data varies between US$60000 and US$100000 for a 20×20 km area at 2–3 m spatial resolution (Lass *et al.*, 2005). Therefore, the acquisition data from a hyperspectral sensor is difficult to afford for individual or unfunded researchers. As a result, multispectral sensors such as QuickBird, WorldView, Satellite Pour l'Observation de la Terre (SPOT), Landsat 4, 5, and 8, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Radarsat, ScanSAR, MODIS, MERIS have been used to map invasive plant species (Thenkabail *et al.*, 2004).

Higher spatial resolution imagery like IKONOS, WorldView, GeoEye-1, SPOT and QuickBird provide more accurate and detailed information compared to other multispectral sensors; however, their data are not free for public use. Thus, it is not easy to get data from the aforementioned multispectral sensors for large areas or a complex of water bodies because of their high cost (He *et al.*, 2011, Taboada *et al.*, 2017; Truong *et al.*, 2017; Paz-Kagan *et al.*, 2019). On the other hand, as opposed to coarse spatial resolution, sensors namely Advanced Very High Resolution Radiometer (AVHRR), ASTER, MERIS, MODIS, and Landsat with medium-spatial resolution are mainly used in the area of invasion biology for both terrestrial and aquatic invasive plant species (Huang and Asner, 2009; Bradley, 2014).

Water hyacinth was successfully mapped by multispectral sensors such as ASTER in the Rio Grande River, and this helped decision makers to decide on the control measures for the weed (Jakubauskas *et al.*, 2002). QuickBird and Landsat 7 were also used to map water hyacinth infestations and to model the rate of water hyacinth spread in the Delta estuary, California (Shruti, 2010). Using IKONOS and Landsat 7 ETM, Albright *et al.* (2004) confirmed the value of multispectral remotely sensed data in monitoring decrease or increase of water hyacinth in Lake Victoria. This informed all the stakeholders about the threat of the weed in the lake and helped to make a decision on how to control its invasion (Albright *et al.*, 2004). Therefore, the current study used a multispectral sensor based on Landsat 8 for detecting water hyacinth and determines its extent in Rwandan water systems.

Apart from mapping invasive plant species such as water hyacinth, remote sensing can provide information on water quality indicators such as turbidity, nitrogen, phosphorus, temperature etc. (Ritchie *et al.*, 2003; Somvanshi *et al.*, 2011; Joshi *et al.*, 2017). Different remote sensing sensors have shown their potential to determine the level of water parameters worldwide and to assess their spatial distribution in different seasons. Hence, they provide information on the levels of abiotic factors that contribute to aquatic weed growth (Ritchie *et al.*, 2003; Heim *et al.*, 2005; (Shrut, 2010). This thesis used remote sensing techniques to map water hyacinth and to assess water abiotic factors that contribute to water hyacinth distribution in water systems.

### 1.10 Research aims and objectives

The main aims of this thesis were to:

1. Evaluate the status and spatial distribution of water hyacinth in Rwandan water bodies.
2. Investigate the effects of abiotic water factors on the biocontrol agents of water hyacinth in Rwanda.
3. Assess the physiological potential of additional biocontrol agents of water hyacinth for Rwandan water bodies.

The specific objectives were to:

1. Determine the abundance of water hyacinth and its distribution in the major water bodies of Rwanda using Landsat 8 imageries.
2. Investigate spatial and temporal distribution of water hyacinth using Landsat TM and Landsat 8.
3. Assess water quality indicators in Rwandan water system using Landsat 8 imageries.
4. Investigate the effect of water turbidity on the pupation of water hyacinth biocontrol agent *Neochetina* weevils.
5. Assess the physiological suitability of two additional biocontrol agents (*Cornops aquaticum* and *Megamelus scutellaris*) for control of water hyacinth infestations in Rwanda.

### 1.11 Thesis layout

This thesis has eight chapters and all chapters are written in paper format except chapter 1 and chapter 8. Chapter 2 and chapter 3 have been submitted to scientific journals. Repetitive information and terms in those chapters could not be avoided, but it has been minimized. In addition, writing style such as combining results and dicussion in those chapters was done according to author instructions from the journals.

**Chapter 1: General introduction:** This chapter provides a problem statement, the general background and context for the study.

**Chapter 2**: **Mapping the distribution of water hyacinth in Rwanda using multispectral remote sensing imagery**. This chapter highlights the importance of Landsat 8 in detecting and mapping water hyacinth in the complex water systems. The results from this chapter show that water hyacinth is distributed in four main Rwandan rivers, more than 10 lakes, and the wetlands through which the rivers pass. This chapter was published in *African Journal of Aquatic Science*.

**Chapter 3: Mapping spatial and temporal variations of water hyacinth coverage in Rwanda water bodies using multispectral imagery from 1989 to 2017 years.** This chapter highlights the important role of data from Landsat systems (landsat TM and Landsat 8) in assessing the dynamics and change of water hyacinth infestation in time series. This chapter shows that water hyacinth invasion has decreased in large water bodies but increased in small lakes. This chapter also shows reinvasion of water hyacinth in some lakes where manual removal is no longer practised.

**Chapter 4: Mapping water quality parameters of Rwandan water systems that contribute to water hyacinth growth using multispectral remotely sensed imagery of Landsat 8.** This chapter looks at the importance of remotely sensed imageries of Landsat 8 in detecting water quality parameters and assessing their spatial distribution in Rwandan water systems. Rwandan water bodies are highly turbid, have high levels of eutrophication and are warmer during wet season. However, the rivers are more affected than the lakes. This chapter also revealed that rivers with high extent of water hyacinth are those with high turbidity, high nutrients and high temperature.

**Chapter 5: The effect of water turbidity on the establishment and performance of *Neochetina eichhorniae* (Warner) (Coleoptera: Curculionidae), a biocontrol agent of water hyacinth.** This chapter shows the effect of water turbidity on biological control of water hyacinth. The implication of the results from this chapter is that high turbidity does not allow *Neochetina* weevils to establish. Therefore, biocontrol agents that do not pupate in the roots of water hyacinth are suggested to combat the weed in Rwandan water bodies with high turbidity.

**Chapter 6: The effects of local water nutrient levels on the biological control of water hyacinth.** This chapter focuses on the effects of Rwandan water nutrient levels on the biological control of water hyacinth. The results from this chapter show that nutrient levels in Rwandan water bodies can allow biocontrol agents such as *Neochetina* weevils, *Megamelus scutellaris* and *Cornops aquaticum* to develop and grow as well as cause enough damage to control water hyacinth in Rwandan water bodies.

**Chapter 7: Effect of local temperature on the potential for biocontrol agents of water hyacinth in Rwanda.** This chapter highlights potential biocontrol agents for water hyacinth in Rwanda, based on the Rwandan climate. The results from this chapter reveal that the Rwandan climate is suitable to all biocontrol agents tested in this study except for *Megamelus scutellaris*, which may not establish in the Northern region of the country due to low temperatures. However, *M. scutellaris* can establish in other regions of the country.

**Chapter 8: General discussion**. This chapter consolidates the findings and discussions of all chapters. Based on the limitations pointed out by this dissertation, this chapter provides conclusion and recommendations for future research and a framework scheme on how to get continuous data of water hyacinth extent, to measure the success of control options, and lastly, gather data on abiotic factors that contribute to the weed growth and its biocontrol agents.

# CHAPTER 2:

## MAPPING THE DISTRIBUTION OF WATER HYACINTH IN RWANDA USING MULTISPECTRAL REMOTE SENSIN IMAGERY

***This chapter has been published in the African Journal of Aquatic Science.***

## ABSTRACT

Water hyacinth (*Eichhornia crassipes* Mart. Solms) (Pontederiaceae) is an invasive aquatic macrophyte that has had major negative economic and ecological impacts in Rwanda and other East African countries since its establishment in the region in the 1960s. Reliable estimates of water hyacinth distribution are required to determine the severity of the problem and identify water bodies requiring management. Remote sensing techniques based on the Landsat 8 sensor offer promising alternatives to accurately detect, map and monitor the extent of the water hyacinth invasion in Rwandan water bodies. The aim of this study was to investigate the utility of multispectral remotely sensed imagery using Random Forest (RF) and Support Vector Machine (SVM) algorithms to detect and map water hyacinth in Rwandan water bodies. RF had a higher overall accuracy of 85% compared to SVM (65%) for mapping the weed. These algorithms confirmed different levels of water hyacinth infestations in three main Rwandan rivers. Many of the wetlands along these riparian systems and most of the lakes, particularly those in the Eastern Province of the country, were found to be invaded by water hyacinth. These findings will assist government, partners and policy makers to put in place sustainable methods such as Integrated Pest Management (IPM) with considerable focus on biological control of water hyacinth invasion in Rwanda.

**Key words:** Landsat, Random Forest, spatial distribution, Support Vector Machine, weed

## 2.1 Introduction

Water hyacinth (*Eichhornia crassipes*) (C. Mart.) Solms (Liliales: Pontederiaceae) is one of many aquatic invasive plant species worldwide that causes losses in biodiversity, changes in ecosystems, and socio-economic issues by affecting transportation of goods and people (Annang, 2012; Waithaka, 2013; Honlah *et al*., 2019), affecting irrigation, fisheries, and power generation activities (Hill, 2003; Waithaka, 2013). Water hyacinth not only threatens the aquatic biodiversity, but also its mats serve as microhabitat for disease vectors and pests that affect the humans (Kateregga and Sterner, 2009; Ndimele, *et al*., 2011; Aloo *et al*., 2013). Originally from the Amazon Basin of South America (Harley, 1990), this notorious weed has spread into many tropical and subtropical parts of the world since the 1800s, largely due to its ornamental value (Harley, 1990). In recent years, Rwanda has faced considerable pressure from a worsening water hyacinth invasion. The weed has caused a reduction of water quantity in the lakes and threatens the livelihoods of the local communities by disrupting their fishing and other socio-economic activities (Gashamura, 2009). Since its introduction into the gardens and duck ponds within the residential compounds of European expatriates at Socièté de la Transformation Industrielle de Ruhengeri (SOTIRU), close to the Mukungwa Valley in the Northern Province of Rwanda, in 1957 (Navarro and Phiri, 2000), water hyacinth has gradually spread into the lakes and rivers linked to the Mukungwa River including the Nyabarongo and Akagera Rivers (Seburanga *et al*., 2014). Because of its invasive nature and the lack of sustainable management, lakes, particularly in the eastern regions of the country, have been invaded by water hyacinth (Seburanga *et al*., 2014). For instance, Lake Gishanju, one of the smallest lakes in the Bugesera district, has ceased to be of any service to the local community that once benefitted financially from fishing activities (Gashamura, 2009).

Water hyacinth has caused a loss of aquatic biodiversity, reductions in water quality and fish production (Seburanga *et al*., 2014). The management of water hyacinth in Rwanda depends on manual removal that requires continuous intervention. Although this may work for small scale infestations, the cost of this control method makes it unsustainable on large-scale infestations (Hill and Coetzee, 2008). Thus, the spread and invasion of water hyacinth continues to persist in the country. Water hyacinth utilization was attempted in Rwanda where women from the Gashora sector in the Bugesera district were encouraged to harvest water hyacinth plants to make handbags, hats and baskets (Gashamura, 2009). However, the utilization programme did not result in the control of water hyacinth and was not successful (Gashamura 2009). Manual removal of water hyacinth is also impractical in large and deep-water bodies (Hoelmer and Kirk, 2005). Because the water hyacinth in Lake Victoria originates in Rwanda via the Akagera River (Moorhouse *et al*., 2001), the East African countries as stakeholders of the lake helped Rwanda with the implementation of a biological control programme for water hyacinth, and *Neochetina* weevils were released into the major water bodies of the country in 2000 (Moorhouse *et al*., 2001). Nevertheless, they have not controlled the weed; water hyacinth continues to dominate the Rwandan freshwater systems (REMA, 2016).

Water hyacinth cannot be easily controlled in the country, because there is no accurate information on the extent of water hyacinth invasion and its distribution in Rwandan water systems. Field-based methods such as ground surveys or point data collection using the Global Positioning System (GPS) have been used to provide information on water hyacinth distribution in the Rwandan water bodies (REMA, 2016). However, these methods cannot provide fine-scale information on the extent of the water hyacinth in the country for effective and suitable management due to their associated drawbacks. Field surveys are costly, time consuming, limited to small-scale studies and often constrained by inaccessible terrain (Hoshino *et al*., 2012). On the contrary, remote sensing techniques are suitable for small- and large-scale mapping and monitoring, with access to temporal information on land cover and land use, and they are unconstrained by any geographical terrain or political boundaries (Hoshino *et al*., 2012). They can provide repeated, timely and accurate information concerning a species' distribution (Adam *et al*., 2017).

Remote sensing has been used to map the biological invasions because of its capability to offer a well-documented synoptic view of an invasive species (Van der Meer *et al*., 2002; Lawrence *et al*., 2006). Various studies have used the multispectral Landsat 7 imageries, Medium Resolution Imaging Spectrometer (MERIS), MODIS to determine the abundance and distribution of water hyacinth in the water systems in African countries (Cheruiyot *et al*., 2014; Thamaga and Dube, 2018). Landsat 8 with a swath width of 185km per scene, 30m of spatial resolution and 13 bands (Hellweger *et al*., 2004) can provide very good spatial distribution maps of water hyacinth compared to the aforementioned multispectral sensors (Dube and Mutanga, 2015). Compared to previous Landsat sensors such as Landsat 7, Landsat 8 has better spectral (13 bands), and radiometric resolutions (El-Askary *et al*., 2014). It has an improved spectral range of bands and is able to identify vegetation spectral reflectance at the near-infrared and in the panchromatic band, which is capable of collecting visible colours separately and combining them into one channel, making a black and white image (Ridwan *et al.*, 2019). In addition, Landsat 8 has a radiometric resolution of 12 bits of quantization as opposed to the 8bits in its predecessors (Holden and Woodcock, 2016). Moreover, Landsat 8 has considerable improvements in signal to noise ratios compared to Landsat 7 (Dube and Mutanga, 2015). Although, remote sensing has been used in detecting the invasion biology of water hyacinth, this tool has not been involved in identifying and mapping water hyacinth in Rwanda. Different image classifications such maximum likelihood, discriminant analysis and vegetation indices such as Normalized Difference Vegetation Index (NDVI) have enhanced water hyacinth mapping (Thamaga and Dube, 2018). However, to our knowledge, no studies have used Random Forest (RF) and Support Vector Machine (SVM) advanced algorithms to map water hyacinth. Thus, this study aimed to (1) determine the extent of water hyacinth invasion in Rwandan aquatic ecosystems through the use of Landsat 8 satellite imageries; and (2) to determine the best algorithm that can accurately map water hyacinth in aquatic ecosystems by comparing RF and SVM advanced classifiers.

## 2.2 Methods and materials

### 2.2.1 Description of study area

The study was conducted in Rwanda, a land-locked country lying between latitudes 1°- 3°S and longitudes 28°-31°E. It is bordered by Uganda in the North and Tanzania in the East, while the Democratic Republic of Congo and Burundi are in the West and South respectively (Figure 2.1).

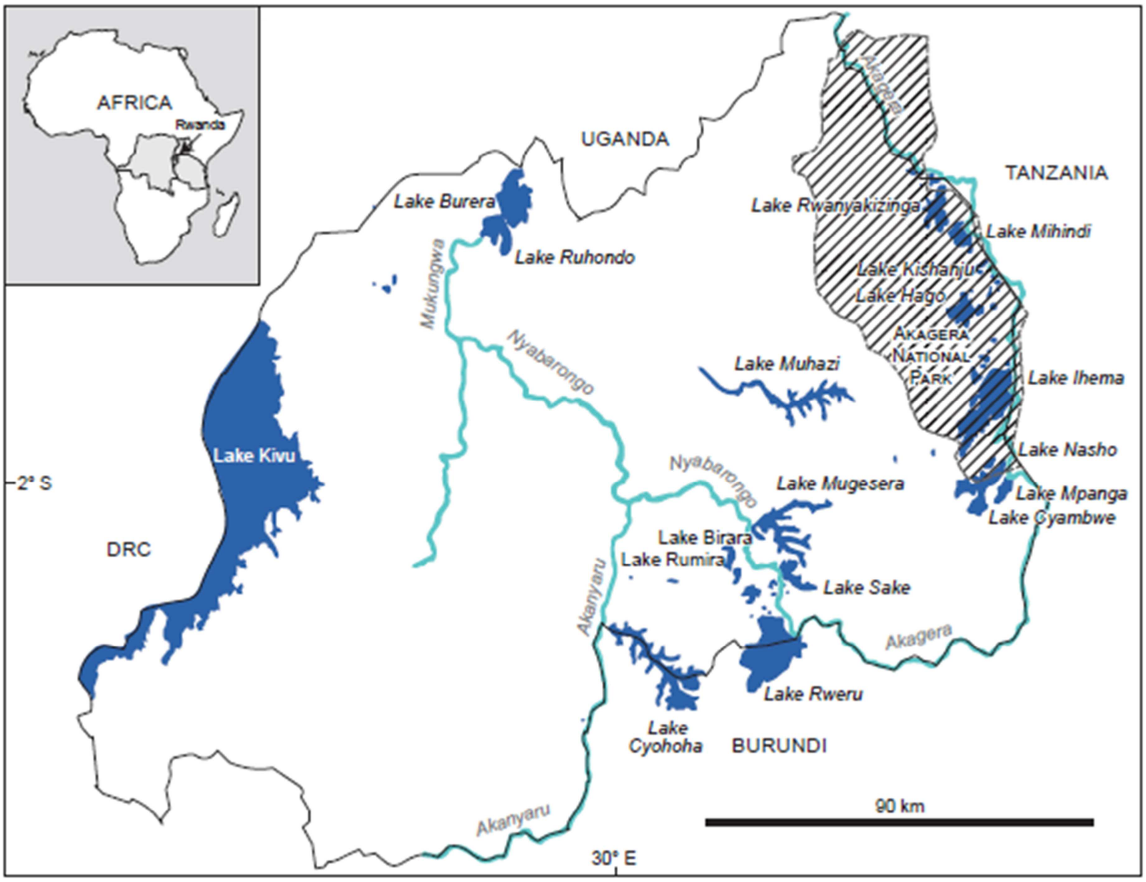


Figure 2.1: Map of Rwanda showing the major Rwandan rivers and lakes, including major lakes found in Akagera National Park.

Rwanda has two hydrographical basins separated by a line referred to as the Congo Nile (Ntwali *et al.*, 2016). To the west is the Congo River Basin that occupies 33% of the national territory, which comprises the tributaries of Lake Kivu and receives 10% of the total Rwandan waters. To the east is the Nile River Basin that covers 67% of the territory and carries 90% of the Rwandan waters (Ntwali *et al.*, 2016). This basin comprises mainly the Mukungwa, Nyabarongo, Akanyaru and Akagera Rivers.

### 2.2.2 Description of remotely sensed data

Remotely sensed imageries from the Operational Land Imager (OLI) sensor were acquired from the Landsat archive of the United States Geological Survey (USGS) to provide a synoptic view of Rwanda. The dataset is available at 30m spatial resolution, nine spectral bands and 16-day temporal resolutions. To ensure that the whole country was covered, three images apparently free of cloud cover were acquired. However, only two images used in this study because of cloud cover (Table 2.1). All acquired images were projected to 36 Universal Transverse Mercator (UTM) with the WGS-84 datum to correct geometric distortions occurred when the satellite was taking the image and to define the coordinate systems (latitude and longitude) of each pixel. This allows the correct correspondence of the image dataset and ground-truth data Global Position System (GPS points).

Table 2.1: Characteristics of the acquired Landsat 8 images from the Landsat archive of the United States Geological Survey.

| Number | Path | Row | Acquisition date | % of cloud | Sun Azimuth (degrees) | Sun Elevation (degrees) |
|---|---|---|---|---|---|---|
| **Image 1** | 172 | 61 | 28/06/2016 | 0.07 | 46.08 | 53.24 |
| **Image 2** | 172 | 62 | 30/07/2016 | 0.13 | 52 | 54 |

### 2.2.3 Image pre-processing

Weather conditions, variations in illumination, and sensor noise are responsible for remotely sensed image distortions (Hadjimitsis and Themistocleous, 2008). The aim of pre-processing is to refine the image data by suppressing unwanted distortion and enhancing features relevant for further processing analysis. All two images downloaded from the USGS were rectified for radiometric and atmospheric distortions using Environment for Visualizing Images (ENVI) 5.3 software. Radiometric calibration was applied to ensure a uniform illumination on all comparable geometrically corrected images. Fast Line-of-sight Atmospheric Analysis of Spectral Hypercube (FLAASH) was applied to correct any atmospheric errors that occurred when the satellites were taking the images. The two images were then mosaicked together using the seamless model from ENVI software. Moreover, the subsetting tool was applied to resize and remove neighbouring country regions from the mosaicked image.

### 2.2.4 Land cover classes and ground-truthing data

Ground-truthing data were collected during the dry season from the $7^{th}$ of July to the $11^{th}$ of September 2016, matching the acquisition period of Landsat 8 images used in this study. The purpose of locating and distinguishing different land cover types was to facilitate image classification and to understand the relationship between water hyacinth (the target plant) and other land cover types including papyrus around the water bodies. The major rivers and most of the lakes in Rwanda were visited and the locality of water hyacinth mats and other land covers types around water bodies were recorded using the Global Position System (GPS). A boat was used to navigate in the large rivers and lakes during the GPS point collection. The major land cover types identified in the study area were agricultural land, bare land, built-up areas, *Cyperus papyrus* (papyrus), savanna, open water and water hyacinth. A total of 1594 GPS points were collected and then overlaid on the Landsat 8 image to train and validate the RF and SVM classifiers by dividing the ground-truthing data into 70% training and 30% testing data sets (Table 2.2). The training dataset was used to generate spectral signatures for each land cover type to support the image classification, while the testing dataset was used to assess the accuracy of classifications.

Table 2.2: Ground-truthing data divided into training and testing data used in the study. Training data were used for image classification; testing data were used for accuracy assessment.

| Names of Land cover types | Codes | Total points | Training data | Testing data |
|---|---|---|---|---|
| Agricultural Land | AL | 170 | 119 | 51 |
| Bare Land | BL | 145 | 102 | 43 |
| Built-Up | BU | 140 | 98 | 42 |
| Papyrus | P | 158 | 111 | 47 |
| Savanna | S | 201 | 141 | 60 |
| Open Water | OW | 297 | 208 | 89 |
| Water Hyacinth | WH | 483 | 338 | 145 |

Prior to classification, spectral signatures were used to detect and determine the spectral separability between land cover types by calculating the Transformed Divergence (TD). The Transformed Divergence is a measure of the statistical separation between land cover types or classes-response patterns computed for all pairs of classes (Richards and Jia, 2006). These are presented in the form of a matrix. It is based on the covariance of the samples for each class at the pixel level and provides an estimation that exponentially decreases to increase the distances between classes as described by Richards (2013). The TD values normally range from 0 to 2. Good spectral separability occurs when the values of TD are >1.9, moderate when it is between 1.7 and 1.9, and poor when it is <1.7 (Jensen, 1996).

### 2.2.5 Image classification

The classification of images was carried out using RF and SVM. These two classifiers are advanced algorithms with the capability to minimize misclassification during the process of image classification. They are nonparametric algorithms able to handle analysis of continuous data and categorical data and are also able to deal with the outliers in training data (Breiman, 2001).

#### *Random Forest*

Random Forest (RF) is a novel learning approach that enhances better image classification. It is a family method that combines many decision trees by binary decisions where each decision tree develops depending on random sampling with replacement of the original training data (Breiman 2001). RF is generally characterized by important parameters such as bagging, bootstrapping and random subspace selection (Lin *et al.*, 2010). In combination with these characteristics, RF combines several techniques into one predictive model. The idea behind the bootstrap is to use data for sampling to roughly calculate the sample distribution of the statistics and data resampling from the sample data. Bootstrapping plays a part in the stability of statistical classification and regression (Breiman, 2001; Lin *et al.*, 2010). With the bagging approach, RF is able to construct a large number of trees with bootstrap samples from the training data set. This is done when each tree is constructed by taking a random sample of prediction before splitting each node, whereby the fitted values in all trees are independent. For each decision tree, a random subset of input predictors is used for splitting at each node (Ghosh and Joshi, 2014). A number of input variables (mtry) were randomly selected at each node from a random subset of the features. Each single tree was grown without reducing the original bootstrap sample to minimize similarity between the individual trees, which would increase the bias (Genuer *et al.*, 2010; Lin *et al.*, 2010). Furthermore, to get accurate classification, the two essential parameters in RF, input variables (mtry) and decision trees (ntrees), must be maximized. The default number of trees is 500, while the number of variables is equal to the number of predictors. Moreover, the out-of-bag samples which are approximately 30% of the total data must be considered to make an estimate of misclassification error and variable importance.

***Support Vector Machine***

Support Vector Machine(SVM) is a nonparametric supervised classifier based on statistical learning theory (Cortes and Vapnik, 1995), which contributes in determining the locality of decision boundaries or hyperplane between classes (Pal and Mather, 2004). It is a binary linear classifier capable of assigning pixels from known training samples to one or two possible classes, by defining optimal hyperplane. This contributes to the reduction of the misclassifications occurring during the training process (Mashao, 2003). The most representative samples can be identified by finding a hyperplane between classes. Therefore, the optimal hyperplane facilitates the separation of classes with the maximum distance between margins and the data points (Huang *et al.*, 2002). SVM optimizes the non-linear algorithm using a number of methods, one being the kernel method that assists to obtain the optimal hyperplane that separates classes (Oommen *et al.*, 2008). SVM has performed well in mapping terrestrial invasive species (Adam *et al.*, 2017; Atkinson *et al.*, 2017). Given the abovementioned characteristics, this study used RF and SVM to map water hyacinth in Rwandan water systems for testing their performance in mapping water hyacinth. This helped to find the best classifier that can enhance mapping of water hyacinth in water system.

### 2.2.6 Accuracy assessment

In evaluating maps of water hyacinth distribution and land cover types developed by the RF and SVM classifiers on Landsat images, an independent test in the form of confusion matrices was used. Thus, the overall accuracy, producer's and user's accuracies, and the Kappa coefficient were obtained as described by Congalton and Green (2008). The former was calculated according to correctly classified pixels divided by the total number of pixels. The producer's accuracy was calculated based on correctly classified pixels of each class in the map, divided by the total number of pixels in the reference image. The user's accuracy was obtained based on the correctly classified pixels divided by the total number of pixels of the class in the classified image. Furthermore, the Kappa coefficient was calculated to measure the difference between the reference data, actual agreement, and the classifiers (Congalton and Green, 2008). A Kappa coefficient close to one indicates strong agreement (Watson and Petrie, 2010).

## 2.3 Results

### 2.3.1 Spectral separability analysis

Spectral separability analysis of land cover types showed moderate to high values between all classes of land cover types (Table 2.3). These results indicate good separation between the land cover types used in this study. For instance, the transformation divergence between water hyacinth and papyrus was 1.861, which shows a good separability between the two.

Table 2.3: The spectral separability analysis between the target plant, water hyacinth, and other land cover types using TD, showing separability among landcover types.

| Classes | AL | BL | BU | P | S | WB | WH |
|---|---|---|---|---|---|---|---|
| **AL** | 0 | | | | | | |
| **BL** | 2 | 0 | | | | | |
| **BU** | 2 | 2 | 0 | | | | |
| **P** | 1.5 | 2 | 2 | 0 | | | |
| **S** | 1.7 | 2 | 2 | 1.8 | 0 | | |
| **OW** | 2 | 2 | 2 | 2 | 2 | 0 | |
| **WH** | 1.9 | 2 | 2 | 1.9 | 2 | 1.7 | 0 |

AL= Agricultural Land, BL = Bare Land, BU = Built-Up, P = Papyrus, S = Savanna, OW= Open Water, WH = Water Hyacinth. Good separability has a TD value of >1.9; moderate separability = 1.9–1.7 and poor separability <1.7.

### 2.3.2 The Performance of Random Forest and Support Vector Machine

Both RF and SVM classifiers were able to provide the spatial distribution of water hyacinth in Rwandan water systems (Figure 2. 2).

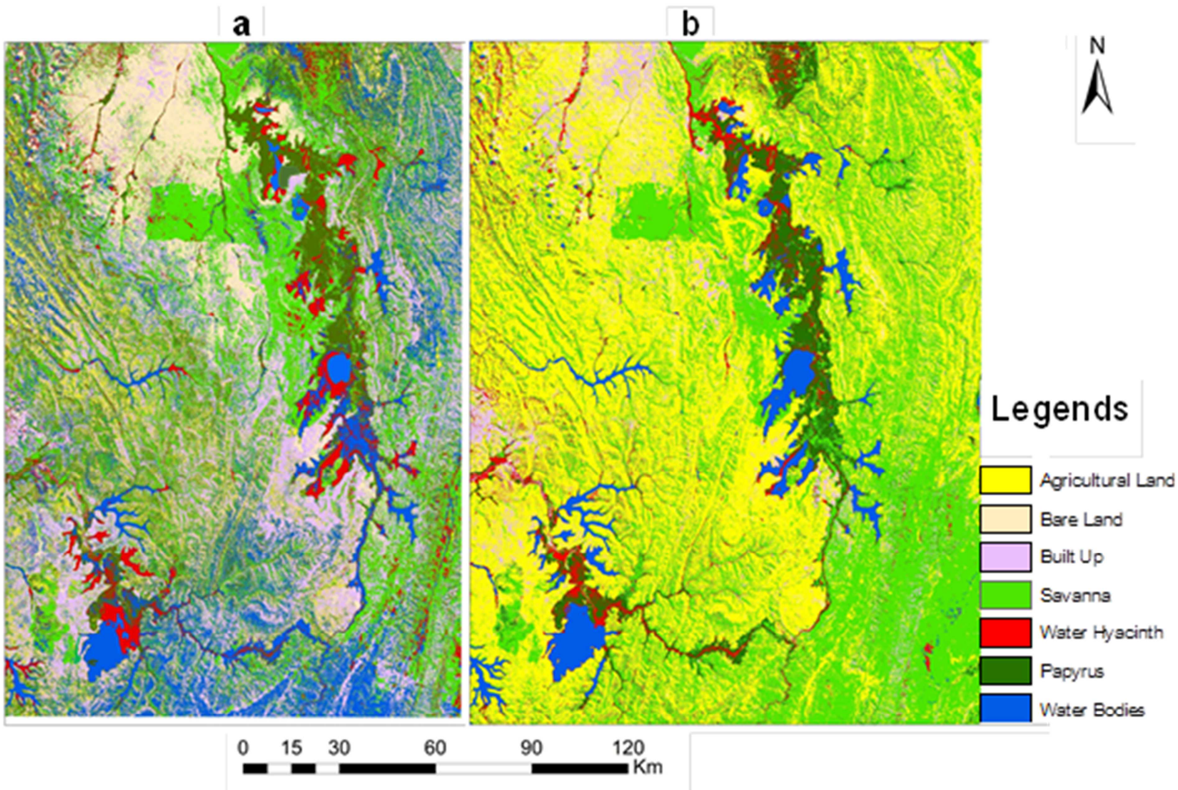


Figure 2.2: Spatial distribution of water hyacinth in the Rwanda water system using (a) Random Forest and (b) Support Vector Machine.

Both classifiers showed that most of the Rwandan lakes, especially those in the Eastern Province of the country, have substantial populations of water hyacinth. However, RF performed better in detecting and discriminating water hyacinth from other identified land cover types, specifically *Cyperus papyrus*, compared to the SVM classifier (Table 2.4). Area and percentage coverage of each land cover type were estimated from the image classified using RF and SVM algorithms (Table 2.4).

Table 2.4: Area occupied by water hyacinth and other land cover types in Rwanda and their respective percentage coverage obtained from two scenes of Landsat 8 images with low cloud cover (<3%) using Random Forest and Support Vector Machine classifiers.

| **Classes** | **Random Forest** | | **Support Vector Machine** | |
|---|---|---|---|---|
| | Area (ha) | (%) | Area (ha) | (%) |
| **Agricultural Land** | 282026 | 14.7 | 328393 | 15.3 |
| **Bare Land** | 173534 | 9.0 | 158754 | 7.4 |
| **Built-Up** | 317750 | 16.6 | 140183 | 6.5 |
| **Papyrus** | 207082 | 10.8 | 162509 | 7.6 |
| **Savanna** | 526659 | 27.4 | 852179 | 39.6 |
| **Open Water** | 304266 | 15.9 | 407457 | 19.0 |
| **Water Hyacinth** | 107767 | 5.6 | 100121 | 4.7 |

Rwandan water systems were clipped from the classified image to determine the percentage cover of water hyacinth compared to papyrus and open water. Much of the weed was found in the lakes located in the Akagera National Park (Figure 2.3). The highest water hyacinth coverage was found in Lake Hago (40%), followed by Lake Rwanyakizinga (36%) and Lake Rweru (29%), while the lowest was found in Lake Birira (3%) (Figure 2. 3).

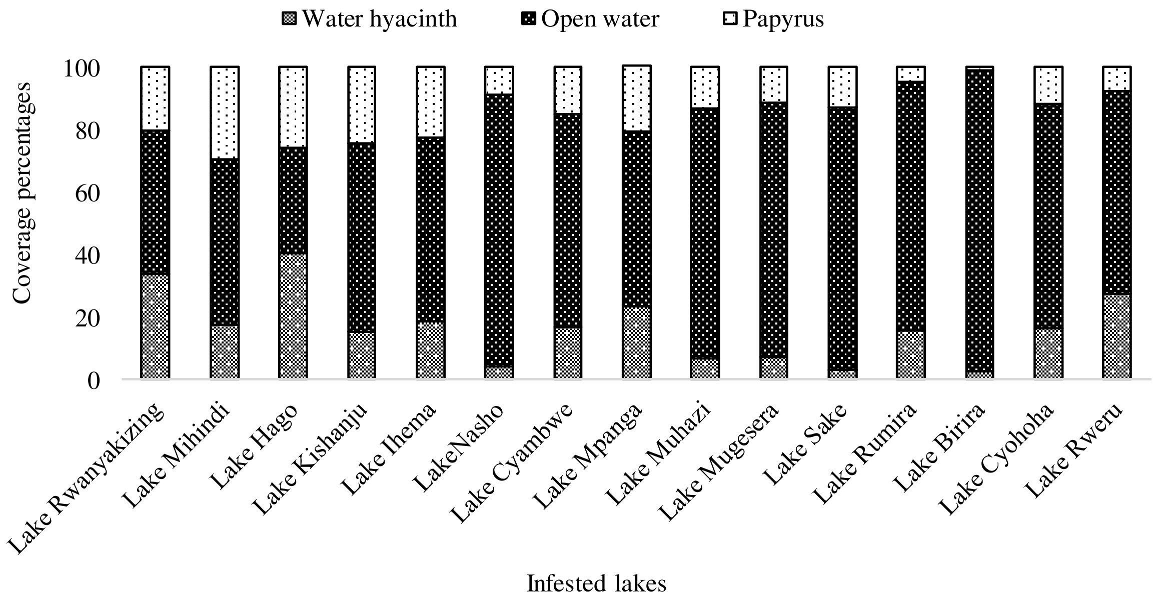


Figure 2.3: Extent of water hyacinth coverage (%) in Rwandan lakes compared to the open water and papyrus in each lake.

Of the rivers, the Akagera River had the highest level of water hyacinth infestation with 28% coverage (Figure 2.4). Water hyacinth has also invaded some of the wetlands in the country with a percentage coverage ranging from 10% to 28% (Figure 2.5).

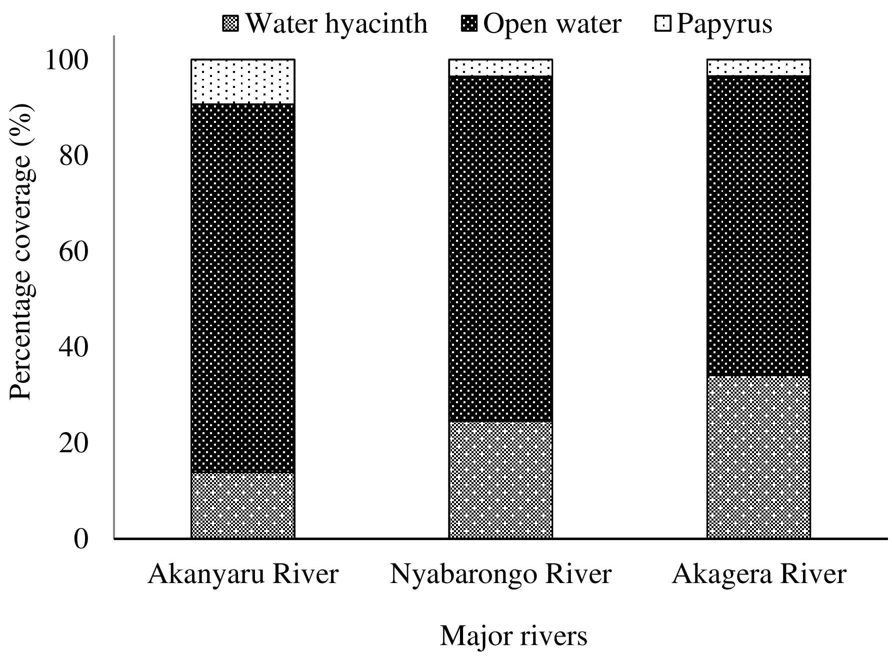


Figure 2.4: Extent of water hyacinth coverage in each of major Rwandan rivers compared to open waters and papyrus.

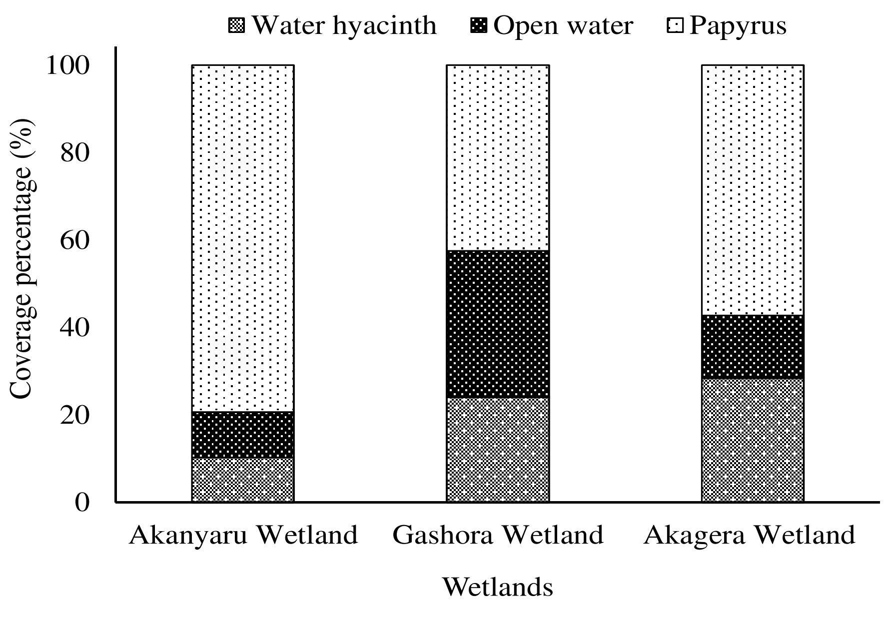


Figure 2.5: Extent of water hyacinth coverage in Rwandan wetlands through which the three main rivers pass.

### 2.3.3 Accuracy assessment

RF yielded an overall accuracy of 85% and a Kappa coefficient of 0.81 (Table 2.5); while SVM produced an overall accuracy of 65% and a Kappa coefficient of 0.57 (Table 2.6). All land cover types attained a user's accuracy of above 80% except for papyrus, which was only 52%. In contrary, the producer's accuracy achieved for all landcover types was above 70%, except for the agricultural land that was only 69% (Table 2.5).

The assessment of classification based on the SVM classification revealed that there was a spectral confusion between papyrus and water hyacinth, yielding a lower user's accuracy of 38% and 58%, respectively. The SVM yielded user accuracies lower than 57% and 49% for papyrus and water hyacinth, respectively (Table 2.6).

Table 2.5: Confusion matrix obtained using Random Forest classifier for land cover types Agricultural Land (AL), bare land (BL), built-up (BU), papyrus (P), savanna (S), Open Water (OW) and water hyacinth (WH). Overall accuracy (OA), Kappa statistic, producer's accuracy (PA) and user's accuracy (UA) were developed on the test dataset.

| | **Classes from Ground-Truthing Data** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Classes from Images** | **AL** | **BL** | **BU** | **P** | **S** | **WB** | **WH** | **Total row** | **UA** |
| **AL** | 36 | 1 | 0 | 0 | 4 | 0 | 2 | 43 | 84% |
| **BL** | 0 | 39 | 2 | 0 | 0 | 0 | 0 | 41 | 95% |
| **BU** | 0 | 2 | 41 | 0 | 0 | 0 | 0 | 43 | 95% |
| **P** | 4 | 0 | 0 | 24 | 5 | 0 | 14 | 47 | 52% |
| **S** | 5 | 2 | 0 | 3 | 48 | 0 | 2 | 60 | 80% |
| **WB** | 2 | 2 | 0 | 1 | 0 | 89 | 2 | 96 | 93% |
| **WH** | 5 | 1 | 0 | 5 | 2 | 5 | 100 | 118 | 85% |
| **Total column** | 52 | 47 | 43 | 33 | 59 | 94 | 120 | 448 | |
| **PA** | 69% | 83% | 95% | 72% | 81% | 94% | 83% | | |

Overall accuracy (OA) is 84%, Kappa coefficient is equal to 0.81

Table 2.6: Confusion matrix from SVM classifier for land cover types Agricultural Land (AL), bare land (BL), built-up (BU), papyrus (P), savanna (S), Open Water (OW) and water hyacinth (WH). Overall accuracy (OA), Kappa statistic, producer's accuracy (PA) and user's accuracy (UA) were developed on the test dataset using the ENVI 5.3 confusion matrix workflow.

| | **Ground truthing classes** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Classes from Image** | **AL** | **BL** | **BU** | **P** | **S** | **WB** | **WH** | **Total raw** | **UA (%)** |
| **AL** | **32** | 1 | 5 | 2 | 2 | 2 | 6 | 50 | 64% |
| **BL** | 1 | **40** | 16 | 0 | 3 | 1 | 0 | 61 | 66% |
| **BU** | 2 | 0 | **31** | 0 | 0 | 0 | 0 | 33 | 93% |
| **P** | 8 | 0 | 1 | **30** | 8 | 7 | 24 | 78 | 38% |
| **S** | 2 | 0 | 0 | 4 | **45** | 1 | 5 | 57 | 79% |
| **WB** | 0 | 0 | 0 | 0 | 0 | **68** | 22 | 90 | 76% |
| **WH** | 1 | 0 | 0 | 17 | 1 | 20 | **54** | 93 | 58.7% |
| **Total column** | 46 | 41 | 52 | 53 | 59 | 99 | 111 | 462 | |
| **PA (%)** | 70% | 97% | 59% | 57% | 76% | 69% | 49% | | |

Overall accuracy is 65%, Kappa coefficient is equal to 0.54

## 2.4 Discussion

The study proved the capability of Landsat 8 in detecting and mapping water hyacinth in Rwandan water systems. By applying nonparametric regression ensembles, Landsat 8 significantly discriminated water hyacinth from other riparian vegetation in Lake Chivero, Zimbabwe, compared to Landsat 7 ETM, with overall accuracies of 92% and 67%, respectively (Dube *et al.*, 2017). The current study applied RF and SVM advanced classifiers to Landsat 8 imageries to detect and map water hyacinth distribution in Rwandan water systems. Overall and individual accuracies obtained in this study showed both algorithms were able to detect and discriminate water hyacinth from papyrus, the other common aquatic plant in Rwandan riparian systems. However, the classification tests (accuracies and Kappa coefficient) for both classifiers showed a significant difference between their accuracies. Random Forest performed better, with a high overall accuracy of 85%, than Support Vector Machine (65%). This study suggests that Random Forest is the best classifier when mapping water hyacinth in water systems.

**Implications of the study for the management of water hyacinth**

Multispectral imageries of MODIS, MERIS, IKONOS and Landsat have been successfully used to identify and map water hyacinth in many regions of the world. Among these are those used in the water systems of Southern Texas in USA, for example Lake Texana near Edna, the Frio River near Tilden, and Rio Grande River in the Lower Rio Grande Valley (Everitt *et al.*, 1999); the Yelahanka, Doddabommasandra, Rachenahalli, Jakkur, Nagavara and Hebbal Lakes located in the northern parts of Bangalore, India (Verma *et al.*, 2003); Lake Kariba at the border of Zambia and Zimbabwe (Pettersson and Namakando 2002); Lake Victoria on the Tanzanian, Ugandan and Kenyan sides (Albright *et al.*, 2004; Ouma *et al.*,. 2005; Cheruiyot *et al.*,. 2014); Brisbane River, Australia (Schmidt and Witte 2010); and inland lakes of Zimbabwe (Dube *et al.*, 2017). Results from current study showed RF applied to free Landsat 8 satellite imageries is able to effectively.detect and map water hyacinth distribution and its extent in water systems.

The results of this study revealed that water hyacinth is distributed in the three major Rwandan rivers such as, Nyabarongo, Akanyaru and Akagera Rivers, the wetlands through which these rivers pass, and in most lakes, particularly those found in the Eastern province of the country. This finding contradicts the results of a previous study reported by Albright *et al.*, (2004) that showed the presence of water hyacinth only in Lake Ihema and Lake Mihindi and made no quantification of the extent of the weed coverage.

Compared to other land cover types considered in this study, water hyacinth covers only 5.6% of the total study area (1919084 ha) considered for investigation using two mosaicked Landsat 8 imageries. However, by masking other land cover types and clipping only the water bodies, the water hyacinth coverage in Rwandan water systems ranged from 3% to 40%. Normally, the acceptable coverage of water hyacinth at which its impacts are not considered detrimental to aquatic ecosystems and its biodiversity is <10% (Jones, 2009). However, coverage of water hyacinth above 20% will impact ecosystem health and should be controlled (Jones, 2009). Ten water hyacinth plants can theoretically produce 655360 individuals in one growing season (Penfound and Earle, 1948), two plants can multiply and produce 1200 daughter plants in 120 days (Jones, 2009). Such an exponential increase in water hyacinth was also indicated by Everitt *et al.* (1999) who reported a twofold increase in water hyacinth populations every 6–18 days. Thus, in the absence of sustainable control measures, water hyacinth can seriously disrupt local aquatic ecosystems (Jones, 2009). Hence, satellite images such as these, will allow real-time assessment and management intervention when and where it is required.

This study confirms that the Rwandan water systems are the most likely source of the water hyacinth infestation in Lake Victoria because some of the Rwandan rivers, such as the Akagera River, eventually join Lake Victoria. Nevertheless, one of the three Landsat images used in this study that covers some parts of the Mukungwa River and the upper and the middle parts of the Nyabarongo River in the Northern Province of the country was excluded from the analysis because of high cloud cover. The ground-truthing data, however, confirmed the presence of water hyacinth in the downstream section of the Mukungwa River in the Musanze district. Water hyacinth mats were also recorded in the Mukungwa Wetland close to the hydroelectric power station. These water hyacinth mats were seen moving from the Mukungwa River to the Nyabarongo River. The latter is directly linked to the Akagera River, which means that these mats will eventually reach the Akagera River, from which the lakes in Eastern Province are thought to be infested. Thus, these findings suggest that the origin of the water hyacinth in the rest of the water systems in Rwanda is the Mukungwa River, located in the Musanze district of Rwanda, in the northern region of the country. Locating the source of the water hyacinth invasion will help to prioritize water hyacinth management efforts for an effective and sustainable solution in Rwanda and the countries in the eastern regions affected by the weed.

**Conclusions**

The primary aim of this chapter was to determine the extent of water hyacinth invasion in Rwanda using Landsat 8 and to investigate how both Random Forest and Support Vector Machine can discriminate and classify water hyacinth from other land cover types. Overall, the results of the study showed that Random Forest performed well compared to SVM. RF was able to (1) accurately detect and discriminate water hyacinth from papyrus, with overall accuracies of 85%; (2) determine the level of water hyacinth invasion in Rwandan water bodies, which varied from 3% to 40%; and (3) determine the most infested water bodies such as Lake Hago, Lake Rwanyakizinga and Lake Rweru. This study also suggests that the Mukungwa River located in the Musanze district of Rwanda is the origin of water hyacinth infestation for the rest of the country and most likely the water bodies of neighbouring countries, among which is Lake Victoria. The findings of this study will help the Rwandan government and other policy makers to formulate effective and sustainable water hyacinth control measures and prioritize resource allocation based on the level and origin of infestation in different water systems of the country.

# CHAPTER 3:
# MAPPING SPATIO-TEMPORAL VARIATIONS IN WATER HYACINTH COVERAGE ON RWANDAN WATER BODIES USING MULTISPECTRAL IMAGERIES

***This chapter is under review in an international peer-reviewed journal for a possible consideration".***

**ABSTRACT**

Information on the spatial and temporal distribution of aquatic weeds helps to understand their extent, abundance, and propagation rates in invaded water systems. In the last three decades, few years, Rwandan fresh water systems have been defiled by the curse of water hyacinth invasion. Water hyacinth has led to a reduction in water quantity and threatened the livelihood of local communities that depend on the lakes for fishing and other socio-economic activities. To understand its status and to support sustainable management plans, it is necessary to obtain reliable information on water hyacinth's spatio-temporal distribution, density variation, magnitude, and rate of change dynamics in water systems. This was investigated using time-series Landsat satellite images for the years 1989, 2002, and 2017. Digital image classifications using the nonparametric classifier Random Forest (RF) as well as change detection analysis were carried out to process the satellite data. The results revealed that there was a fluctuation in the extent of water hyacinth over the period of the study. An annual increase of 1.9% in water hyacinth infestation was observed during the years 1989 and 2002; and thereafter, a decline of 1.7% per annum was observed between 2002 and 2017. The estimated average of water hyacinth infestation coverage over the time series of 1989, 2002 and 2017 was 17.7%, 22.4%, and 20.8%, respectively. Manual and biological control measures taken by the local governments to curb the water hyacinth population after the year of 2002 could be the reason for the decline seen by 2017. This study concludes that remote sensing is a valuable tool for change detection in the extent and distribution of invasive alien weeds, which are paramount in prioritizing resource allocation for management intervention and for pre- and post-control measure assessments to determine the efficacy of control methods undertaken.



**Key words**: change detection, invasive species, control, Rwanda, magnitude change

## 3.1 Introduction

Water resources have great ecological benefits and also benefits for agricultural, domestic and industrial activities worldwide (De Troyer *et al.*, 2016). The sustainable use of water is however affected by climate change, anthropogenic activities and invasive alien plant species (De Troyer *et al.*, 2016). Water hyacinth is one of the aquatic invasive plant species whose growth and multiplication are directly linked to water with high levels of nutrients; and consequently, the weed has become the dominant floating aquatic weed in the tropical and subtropical regions of the world (Cilliers *et al.*, 2003; Sotolu, 2013).

Since its introduction, water hyacinth has caused socio-economic and environmental havoc in Rwandan water bodies (REMA, 2016). The lack of effective and sustainable control methods has allowed water hyacinth to thrive and spread further despite intensive manual removal campaigns by the government (REMA, 2016). Thamaga and Dube (2016) found that lack of contemporary and consistent temporal and spatial information on water hyacinth distribution may further obfuscate monitoring and management plans of the weed invasion. The Rwandan government and other policy makers are committed to protect Rwandan water resources by controlling water hyacinth and other pollutants Rwanda Natural Resources Authority (RNRA), (2012). However, the success of this depends on updated and accurate information on the spatial distribution of water hyacinth and weed dynamics in water systems (Shekede *et al.*, 2008). Currently this information is compiled from traditional field surveys by visiting invaded rivers and lakes in the country (REMA, 2009; 2016). However, field surveys are laborious, costly, and often constrained by inaccessibility (Hoshino *et al.*, 2012). Thus, they are incapable of providing update information on temporal and spatial distribution and dynamic of water hyacinth in Rwandan water systems. However Geospatial technologies such as remote sensing techniques can quickly provide this information (Hoshino *et al.*, 2012).

Remote sensing techniques are economically effective, not time consuming and unconstrained by the size of water bodies or any other geographical barriers. They are able to identify and map plant species and other associated changes over time (Giardino *et al.*, 2014; Palmer *et al.*, 2015). Remote sensing techniques have proved useful in the mapping and management of biological invasions because of its capability to offer a well-documented synoptic view of an invasive alien plant species (Van der Meer *et al.*, 2002; Lawrence *et al.*, 2006). They allow the discrimination of invasive weeds from other plants (Huang and Asner, 2009). They are also better able to precisely detect dynamic changes in the invasive alien plant species in the environment over time than the classical ground-based surveys (Joshi *et al*., 2006; Cheruiyot *et al*., 2014; Penatti *et al*., 2015). Repeated sampling by satellite sensors provides information for long-term monitoring, which help to decide what control measures are most effective (Penatti *et al*., 2015). Such archived information is important for investigating the spatial and temporal distribution of the weed. This information is valuable for local communities, government, environmental management agencies and decision makers.

Multispectral sensors such as Medium Resolution Imaging Spectrometer (MERIS) and Medium Resolution Imaging Spectrometer (MODIS) were used to quantify and map the spatial and temporal distribution of water hyacinth in Lake Victoria (Cavalli *et al*., 2009; Fusilli *et al*., 2013). Albright *et al*., (2004), used LANDSAT ETM+ images to investigate changes in the water hyacinth coverage on Lake Victoria from 1999 to 2004. Jakubauskas *et al*. (2002) analysed a time series of three ASTER images to detect change of water hyacinth coverage in the Rio Grande (Texas, USA). In addition, the airborne digital colour-infrared video imagery in the green, red and near-infrared wavelengths was used to determine the spatial extent of aquatic macrophytes based on an unsupervised classification (Everitt *et al*., 1999). Although the aforementioned sensors have successfully provided information on variations in water hyacinth infestations, Landsat data namely Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI), are the most suitable sensors for detecting and assessing changes in ecosystems (Wulder *et al*., 2008). Landsat sensors have a spatial resolution of 30m, a revisit period of 16 days, plus a wide spatial coverage (Gómez *et al*., 2016). Rigorous calibration and consistency in the radiometry of the Landsat sensors, in particular the Operational Land Imager OLI, ETM+ and TM, make the Landsat image archive a durable example of the benefits of calibration and data interoperability (Gómez *et al*., 2016). For example, Dube *et al*. (2014) used Landsat Thematic Mapper and Enhanced Thematic Mapper imagery to investigate changes of water hyacinth coverage in Lake Mutirikwi, Zimbabwe, using the Normalized Difference Vegetation Index (NDVI).

The main aim of this chapter was to assess the spatial and temporal variation of the water hyacinth invasion in Rwandan water bodies over a period of 27 years (1989–2017) using multispectral Landsat imageries. The study assessed the variation in the extent of water hyacinth coverage and the annual rate of water hyacinth coverage compared to other land cover types, such as agricultural land, bare land, built-up areas and other riparian vegetation, including *Cyperus papyrus*, which may also have an influence on the water systems. The results from this study will inform policy makers on the dynamics and fluctuation of water hyacinth infestations in Rwandan water systems. They will also provide information on the control methods for water hyacinth used to date in the country.

## 3.2 Methods and materials

### 3.2.1 Description of the study area

(see details in 2.2.1)

### 3.2.2 Data description

Cloud-free images from Landsat 5, 7 and Landsat 8 were acquired from the Landsat archive via the GloVis web-link (http://glovis.usgs.gov/). Images were only acquired from the dry seasons of the years 1989, 2002 and 2017, as images from the rainy season were obscured by clouds. The time series were chosen based on different reasons: (1) the year 1989 was chosen to assess the extent of water hyacinth in ten years before the weed was officially recognized as a problem in the country, (2) the year 2002 was chosen to quantify the level of water hyacinth the invasion since all reports indicated that it was severe t in that year, compelling the government to initiate manual removal after the failure of biocontrol using *Neochetina* weevils (biocontrol agents of water hyacinth) first attempted in 2000. (3) The year 2017 was chosen to evaluate the efficiency of the intensified manual removal effort that started in 2002. To cover the above mentioned rivers, wetlands and lakes, two images with a path number of 172 for the two and a row number of 61 and 62 for each were acquired for the three periods to cover the area of interest with the target rivers, wetlands and lakes. They were thereafter projected to 36 Universal Transverse Mercator (UTM) with the World Geodetic System 1984 (WGS-84) datum to correct geometric distortions that occurred when the satellite was taking the image and to define the coordinate systems (latitude and longitude) of each pixel. This allows the correct correspondence of the images dataset and ground-truthed data Global Positioning System (GPS) points. All images used in this study were downloaded on 24 February 2018.

Table 3.1: Characteristics of the Landsat images acquired for each study year (1989, 2002 and 2017) from the Landsat archive of the United States Geological Survey to cover Rwanda.

| Satellite data | Path | Row | Acquisition date | % of cloud cover |
|---|---|---|---|---|
| Landsat 5 | 172 | 61 | 05/02/1989 | 0 |
| | 172 | 62 | 23/07/1989 | 1 |
| Landsat7 | 172 | 61 | 30/07/2002 | 7 |
| | 172 | 62 | 17/08/2002 | 0 |
| Landsat 8 | 172 | 61 | 01/07/2017 | 1 |
| | 172 | 62 | 01/07/2017 | 7 |

### 3.2.3 Image pre-processing

Weather conditions, variations in illumination, and sensor noise are responsible for distortions of remotely sensed images. Pre-processing improves the image data quality by removing unwanted distortion and improving features relevant for further processing analysis. Environment for Visualizing Images (ENVI) 5.3 software was used on both images from each year to rectify radiometric and atmospheric distortions. Radiometric calibration was important to ensure a uniform illumination on all comparable geometrically corrected images. Fast Line-of-sight Atmospheric Analysis of Spectral Hypercube (FLAASH) was applied to correct atmospheric errors. Then the two images for each year were mosaicked together using the ENVI software seamless model. The subsetting tool was applied to resize and remove unwanted regions from the mosaicked images. In addition, the shapefile of the Rwandan water systems was used to create a buffer zone of 1000 m alongside the lakes and rivers, and then only the images of the water systems were extracted using a masking process.

### 3.2.4 Reference data and image classification

The reference data used in this study were obtained from ground-truthing data collected during both the dry and rainy seasons in 2016. Locating and distinguishing different land cover types facilitated image classification. It also helped to understand the relationship between water hyacinth (the target) in the study area and other land cover types around the water bodies. To correctly and accurately distinguish water hyacinth from *C. papyrus* (papyrus), and riparian vegetation found during ground surveys, the selective spectral reflectance 0.7–0.9 µm as response for water hyacinth was used (Ritchie *et al.*, 2003). As there were no aerial photographs that could help to obtain reference data, especially for the images of 1998 and 2002, image enhancement techniques were used to support the visual interpretation of images. Image enhancement facilitates alteration of the appearance of an image in such a way that information from that image is more readily visualized and interpreted for the viewer's particular needs (Mather, 1987). In this study, the focus was on improving the visual interpretability of all Landsat images by varying brightness, contrast and the gamma parameters using the stretching function provided in Arc Map software. Furthermore, Google Earth was used to verify the identified land cover types. The major land cover types identified in the study area were agricultural land, bare land, built-up areas, papyrus, savanna, open water and water hyacinth. A total of 1336 ground-truthing points for each image in each year were obtained and then overlaid on each Landsat image to train and validate the classifiers. Ground-truthing data were split into a training dataset (70%) for image classification purposes and a testing dataset (30%) for accuracy assessment of the image classification process.

After categorizing the land cover types, a supervised classification using the Random Forest (RF) algorithm was conducted on all the Landsat images. RF is a novel learning approach for improving classification of images. It has the capability of handling highly non-linear interactions and is able to discriminate species from each other. It combines many decision trees by binary decisions where each decision tree depends on random sampling with the replacement of the original training data (Breiman 2001). By combining bagging, bootstrapping and random subspace selection (Lin *et al.*, 2010), RF combines several techniques into one predictive model, which other classifiers cannot do. In addition to this, Random Forest was obtained to be the best algorithm for mapping water hyacinth (chapter 2, figure 2.2). Therefore, this study used RF to accurately determine the changes in water hyacinth coverage over a period of 28 years on surface water systems compared to other land cover types, including papyrus, in the Rwandan water systems.

### 3.2.5 Accuracy assessment

To evaluate the map of water hyacinth distribution and land cover types developed by Random Forest using Landsat images, an independent test dataset in the form of confusion matrices was used to compare the true classes of ground-truthing dataset with the classes assigned by RF classifier. Thus, the overall accuracy, user's and producer's accuracies, and the Kappa coefficient were obtained as described by Congalton and Green (2008). The overall accuracy was obtained using the sum of correctly classified pixels, dividing the total number of pixels. The producer's accuracy was calculated based on correctly classified pixels in each class of the map, divided by the total number of pixels in the reference or ground truthing data. The user's accuracy was obtained based on the correctly classified pixels divided by the total number of pixels of the class in the classified image. Furthermore, the Kappa coefficient was also calculated to measure the difference between the reference data, actual agreement, and algorithm used for image classification (Congalton and Green, 2008).

### 3.2.6 Change detection

Change detection is a process that uses multi-temporal datasets to identify the state of an object or any phenomenon by observing it over a period of time (different years or months) (Chen *et al.*, 2012). The changes in land cover types are characterized by spatial and temporal dimensions. Temporal extent shows the period of time through which the change in land cover type took place, while spatial location and extent identify the geographical location of an area in which the change happens. The main purpose of conducting change detection analysis is to identify the extent of changes in land cover types, to describe the nature of the changes, and to determine the spatial and temporal pattern of the changes (Macleod and Congalton, 1998). Different techniques such as image rationing, image digitization, image overlaying, change vector analysis, background subtraction, image differencing and post classification comparison have been used for different purposes to monitor changes in land cover types, with all of them producing good results (Singh, 1989; Sunar 1998). Thus, change detection is a suitable approach for investigating the spatial and temporal variation in abundance and extent of water hyacinth invasions in water systems.

This study used change detection statistics based on cross tabulation techniques, which provides the amount of change among the defined land cover types. This change detection was generated between images in the combination of years 1989–2002 and 2002–2017 by providing the differences in the images where the latter image is known as initial state and the former known as the final state (Canty, 2009). Additionally, the magnitude change, and annual rate change for each land cover type of the study were obtained using the formulas developed by Islam *et al.* (2018). The magnitude change for each land cover type was calculated based on area coverage of landcover type from that final year subtracting area coverage of landcover type from initial year. Percentage in magnitude change (trend) for each land cover type was then obtained as indicated in Eq 1

Magnitude percentage $= \frac{Magnitude\ change * 100}{base\ year\ (initial\ year)}$ (Eq.1)

Annual rate of change for each land cover type was obtained as shown in equation 2.

Annual rate change $= \frac{\%\ of\ landcover\ type\ from\ year - \%\ of\ landcover\ type\ from\ initial\ year}{No\ of\ years}$ (Eq2)

### 3.3 Results and discussion

### 3.3.1 Landsat image classification

The classification results showed that water hyacinth cover in the Rwandan water bodies varied from 1989 to 2017 (Figure 3.1).

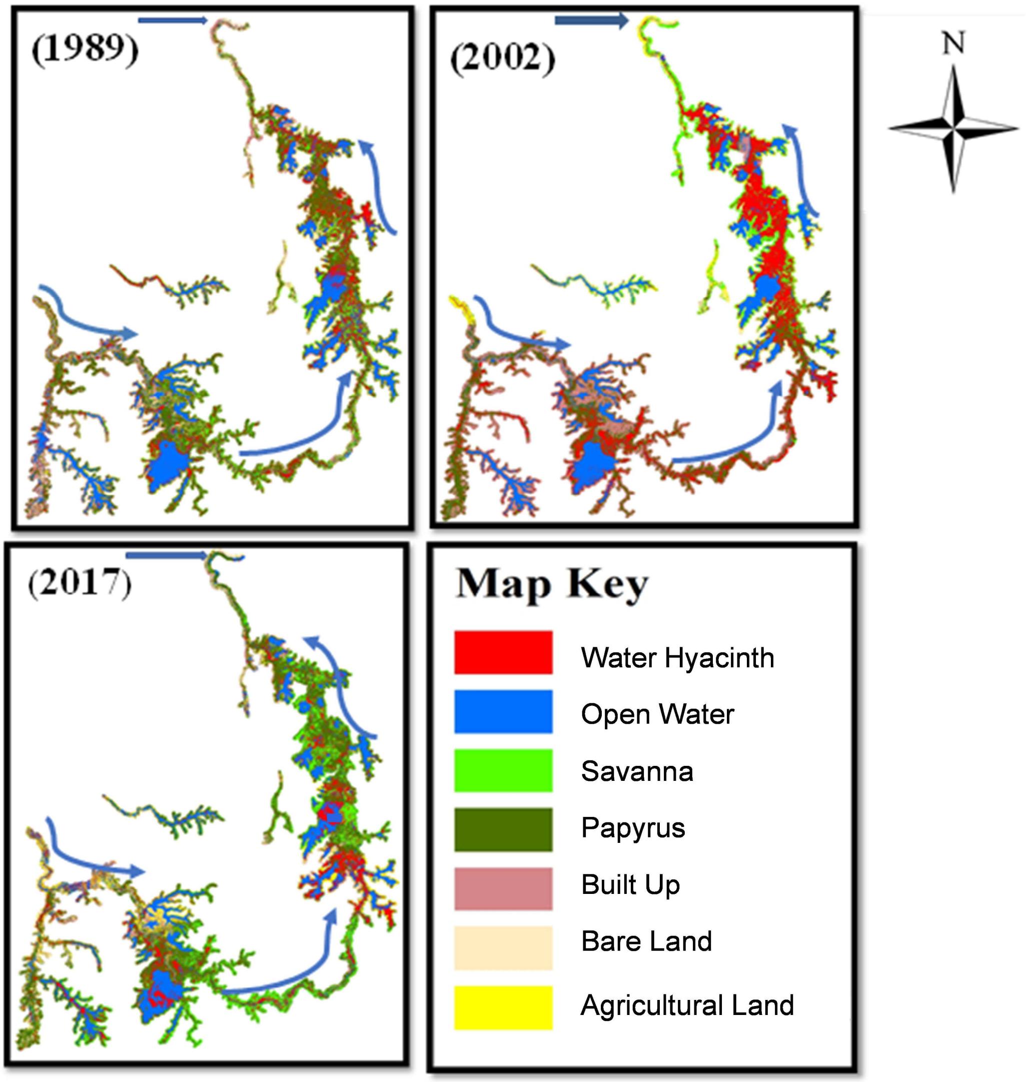


Figure 3.1: The variation in the extent and distribution of water hyacinth invasion in Rwandan water systems from 1989–2017.

When comparing the coverage of water hyacinth between the different time series considered in this study, it is clear that the largest surface area covered by water hyacinth occurred in 2002 and the lowest occurred in 2017 (Table 3.2).

Table 3.2: Area occupied by water hyacinth and other land cover types and their percentage cover obtained from 1989, 2002 and 2017 classified Landsat images of Rwanda using Random Forest algorithm.

| Land Cover Types | 1989 | | 2002 | | 2017 | |
|---|---|---|---|---|---|---|
| | Area (ha) | % | Area (ha) | % | Area (ha) | % |
| Agricultural Land | 7487.28 | 2.3 | 11911.95 | 3.2 | 22608.72 | 5.8 |
| Bare Land | 26707.2 | 8.1 | 20199.2 | 5.6 | 20882.3 | 5.3 |
| Built Up | 18756.3 | 5.7 | 74111.7 | 20.5 | 45525.9 | 11.6 |
| Papyrus | 114608.3 | 34.6 | 73099.9 | 20.2 | 122796 | 31.4 |
| Savanna | 49328.6 | 14.9 | 35446.1 | 9.8 | 56101.6 | 14.3 |
| Open Water | 64868.4 | 19.4 | 64567.3 | 17.8 | 73726.4 | 18.9 |
| Water Hyacinth | 49872.9 | 15 | 82840 | 22.9 | 49330.4 | 12.7 |

The infestation of water hyacinth in 2002 in some Rwandan lakes was reported by Albright *et al.* (2004) by analysing images from the years 2001 and 2002. However, that study did not quantify the extent of water hyacinth or measure an increase of water hyacinth coverage. In addition, that study focused only on Lake Mihindi and Lake Ihema found in the Akagera National Park. The greatest water hyacinth extent in the year 2002 by the current study was also reported by the Rwanda Environment Management Authority (REMA, 2009). This situation provoked the Rwandan government, environmental agencies and other partners to launch campaigns to control water hyacinth manually. Since the year 2002, manual removal has been intensified across the country, leading to the decrease in water hyacinth extent. However, regardless of these efforts to reduce water hyacinth infestations, the weed remains the number one scourge of the country's water systems (REMA, 2016). This is because manual removal is only suitable and effective in small water bodies and when quick, short-term results are required (Hill, 2003). The method is labour intensive, expensive and unsustainable. It requires repeated seasonal intervention because new water hyacinth populations grow from seeds embedded in the substrate in favourable conditions (Perez *et al.*, 2011). In addition, two plants can multiply and produce approximately 1200 daughter plants in 120 days in the absence of sustainable control methods (Jones, 2009).

Therefore, any plants missed in the cleaning operation can seriously disrupt local ecosystems in the absence of sustainable control measures.

### 3.3.2 Accuracy assessment

Random Forest applied on Landsat images, produced an overall accuracy of 77 to 87%. These ranges fall within the recommended overall accuracy ranges indicated by Anderson *et al.* (1976). In all three study time series (1989, 2002 and 2017) investigated, the land cover types achieved a user's accuracy of over 72%. In contrast, producer's accuracy achieved was above 65%, except for papyrus, which was only 57%. This was due to 36 pixels of papyrus that were misclassified as water hyacinth for the 2002 study period. The Kappa coefficient ranged from 0.73 to 0.87 (Table 3.3). These values of Kappa coefficient indicate a good image classification (Yang and Lo, 2002; Van Vliet *et al.*, 2011).

Table 3.3: Confusion matrix obtained from Random Forest classifier for the land cover types agricultural land, bare land, built-up, papyrus, savanna, open water, and water hyacinth in Rwanda. The accuracies such as overall accuracy, Kappa statistic, Producer's Accuracy and User's Accuracy were obtained using a testing dataset.

| Time Series | Overall Accuracy (%) | Kappa Coefficient | Individual accuracy (%) | Agricultural land | Bare Land | Built-Up | Papyrus | Savanna | Water hyacinth | Open water |
|---|---|---|---|---|---|---|---|---|---|---|
| **1989** | 87 | 0.84 | Producer | 79 | 87 | 71 | 74 | 82 | 97 | 92 |
| | | | User | 73 | 73 | 87 | 88 | 87 | 96 | 87 |
| **2002** | 77 | 0.73 | Producer | 89 | 87 | 81 | 58 | 73 | 91 | 74 |
| | | | User | 87 | 74 | 90 | 73 | 84 | 83 | 68 |
| **2017** | 81 | 0.77 | Producer | 66 | 74 | 88 | 73 | 83 | 91 | 82 |
| | | | User | 87 | 77 | 78 | 87 | 77 | 76 | 86 |

Therefore, this study suggests that the RF algorithm is a reliable classifier that can correctly distinguish water hyacinth from other riparian vegetation, including papyrus, temporally over an extended period of time.

### 3.3.3 Change detection

In all the time periods chosen for this study, there were transitions from one land cover type to another (Table 3.4 and 3.5). Some land cover types increased in the area of coverage while others decreased. Between 1989 and 2002, there was an increase in built-up areas reaching 168017ha, followed by water hyacinth with 36537ha, while other land cover types such as papyrus, savanna and open water decreased (Table 3.4). After genocide against Tutsi occurred in Rwanda in 1994, there was a considerable increase in built-up areas across the country (Mugiraneza *et al.*, 2017). This was due to Rwandan refugees returning to their home country from neighboring countries, and they occupied available open spaces, including spaces around wetlands, lakes and rivers (Ministry of Natural Resources, 2014). The decrease in savanna area was probably due to the removal of construction materials such as trees for pillars, and grass for thatch. In the same period (1989–2002), the area occupied by water hyacinth also increased and led to a decline of open water and papyrus (loss of 15726 ha and 97770 ha, respectively). Similarly, REMA (2009) reported that in the year 2002 there was an increased water hyacinth infestation in the Rwandan water bodies, and this pushed the Rwandan government to use manual removal to combat the weed

The increase of water hyacinth along with an increase of residential and other types of construction in the year 2002 across the country, particularly near the rivers and lakes, affected the quantity and quality of the Rwandan fresh water system (REMA, 2009).

Table 3.4: Changes in water hyacinth coverage (ha) in Rwandan water bodies and associated land cover types between the years 1989 and 2002. Totals in rows indicate the total area for each land cover type in 1989, while totals in columns indicate the area in 2002. The numbers in bold are unchanged pixels within the period of initial and final state. Negative values show a decrease in the area of a certain land cover types and positive values indicate an increase.

| | **Initial Time (1989)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Land Cover types | Agricultural Land | Bare Land | Built Up | Papyrus | Savanna | Open Water | Water Hyacinth | Total |
| **Final Year (2002)** | Agricultural Land | **4676** | 9563 | 17390 | 12685 | 18506 | 1157 | 3775 | 67752 |
| | Bare Land | 13540 | **21399** | 11616 | 348 | 34403 | 1490 | 9459 | 92255 |
| | Built-Up | 5118 | 8965 | **111575** | 2363 | 8449 | 516 | 5557 | 142543 |
| | Papyrus | 44710 | 24197 | 27916 | **267806** | 10121 | 22956 | 129466 | 527172 |
| | Savanna | 2134 | 32871 | 81561 | 99224 | **95104** | 6503 | 42486 | 359883 |
| | Open Water | 4169 | 189 | 4234 | 28382 | 19237 | **435614** | 109735 | 601560 |
| | Water Hyacinth | 13196 | 12051 | 56266 | 18594 | 46236 | 117598 | **297367** | 561308 |
| | Total | 87543 | 109235 | 310558 | 429402 | 232056 | 585834 | 597845 | |
| | Image difference | 19791 | 16980 | 168015 | -97770 | -127827 | -15726 | 36537 | |

Surprisingly, comparison of land cover types from 2002 and 2017 showed a different situation. Between these years, water hyacinth coverage decreased, while the areas of open water and papyrus increased (Table 3.5). This increase in open water was not only due to a decrease in water hyacinth but was also due to a decrease of the built-up areas. Since 2002, the construction of houses and roads and agricultural activities near rivers, lakes and wetlands was prohibited across the country (REMA, 2009). The restriction buffer zone of 50–100m around Rwandan water bodies contributed to the restoration of natural water resources in the country (Hategikimana and Twarabamenye, 2007).

As the area occupied by water hyacinth decreased, the surface area occupied by *Cyperus papyrus*, an important component of riparian vegetation for biodiversity, water quantity and quality regulation (Van Dam *et al.*, 2014), increased in the water bodies.

Table 3.5: Changes in water hyacinth coverage (ha) in Rwandan water bodies and associated land cover types between 2002 and 2017. Total in rows indicate the total area for each land cover type in 2002, while total areas in columns indicate the area in 2017. The numbers in bold are unchanged pixels within the period of initial and final state. A negative sign shows a decrease in the area of a certain land cover type and positive values indicate an increase.

| | | **Initial time (2002)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Land Cover Types | Agricultural Land | Bare Land | Built-Up | Papyrus | Savanna | Open Water | Water Hyacinth | Total |
| **Final time (2017)** | Agricultural Land | **1126** | 19580 | 8640 | 46526 | 19416 | 6576 | 7163 | 109027 |
| | Bare Land | 2022 | **40745** | 25194 | 62622 | 24681 | 3713 | 2585 | 161562 |
| | Built-Up | 7192 | 83841 | **64888** | 27653 | 13160 | 2883 | 2075 | 201692 |
| | Papyrus | 61246 | 20419 | 17144 | **266875** | 11372 | 62457 | 118726 | 558239 |
| | Savanna | 18615 | 27230 | 18250 | 130744 | **87834** | 16152 | 19509 | 318334 |
| | Open Water | 4199 | 1926 | 1392 | 24491 | 61881 | **451863** | 90251 | 636003 |
| | Water Hyacinth | 16872 | 2751 | 4302 | 32289 | 136868 | 93342 | **186831** | 473255 |
| | Total | 111272 | 196492 | 139810 | 591200 | 355212 | 636986 | 427140 | |
| | Image difference | 2245 | 34930 | -61882 | 32961 | 36878 | 983 | -46115 | |

In addition, further analysis confirmed the variability of water hyacinth coverage by estimating the magnitude and annual rate of change of the weed coverage compared to associated land cover types (Table 3.6). The period 1989–2002 showed an annual increase of 1.9% in water hyacinth coverage. In contrast, the annual rates of change for open water and papyrus declined by 0.018% and 1.7%, respectively. However, water hyacinth infestations declined at an annual rate of 1.7% between the years 2002 and 2017. This decrease was due to the intensive manual removal of water hyacinth, particularly in the large lakes after 2002. Nevertheless, manual removal of water hyacinth was always followed by reinfestation, making the continued spread of water hyacinth biomass inevitable until a sustainable control method is in place.

Table 3.6: Rwandan gains and losses of water hyacinth coverage and its associated land cover types over the study period of 1989, 2002 and 2017, based on the results obtained from Landsat images' classification that cover Rwanda.

| Land cover types | 1989–2002 | | | 2002–2017 | | |
|---|---|---|---|---|---|---|
| | Magnitude | Percentage (%) | Annual Rate Change (%) | Magnitude | Percentage (%) | Annual Rate Change (%) |
| Agricultural Land | 4424.7 | 22.8 | 1.6 | 10696.8 | 30.9 | 2.1 |
| Bare Land | -6508.1 | -13.9 | -1.1 | 683.1 | 1.7 | 0.1 |
| Built-Up | 55355.4 | 59.6 | 4.6 | -28585.8 | -23.9 | -1.6 |
| Papyrus | -41508.5 | -22.1 | -1.7 | 49696.1 | 25.4 | 1.7 |
| Savanna | -13882.5 | -16.4 | -1.3 | 20655.5 | 22.6 | 1.5 |
| Open Water | -301.1 | -0.2 | -0.02 | 9159.1 | 6.6 | 0.4 |
| Water Hyacinth | 32967.2 | 24.8 | 1.9 | -33509.7 | -25.4 | -1.7 |

The extent of water hyacinth compared to other riparian vegetation in each of the lakes, rivers and wetlands identified as invaded by the weed was quantified for each year considered in this study to determine the water hyacinth invasion pattern (Figures 3.2, 3.3 and 3.4). The lakes in the Akagera National Park were invaded even before the government officially recognized water hyacinth as a problematic weed in 1999. For instance, 29% of Lake Mihindi and 28% of Lake Ihema were already covered with water hyacinth by 1989. The greatest water hyacinth infestation was recorded in 2002 when 52% of Lake Mihindi and 30% of Lake Ihema were covered by the weed (Figure 3.2). This was the turning point when Rwandan government decided to intervene and control water hyacinth using manual removal technique. It is impressive to see the water hyacinth population declining in 2017, although the method does not guarantee the non-resurgence of the weed in future. There was a decrease in water hyacinth in the bigger lakes after the manual control intervention; however, the small lakes that had been regarded as weed free or had lower infestation levels showed outbreaks of water hyacinth. For instance, in Lake Hago the water hyacinth infestation increased from 2002 to 2017. Lake Kidogo is another example where the water hyacinth coverage increased to 47% by 2017 (Figure 3.2) while it was never been reported as a problem before.

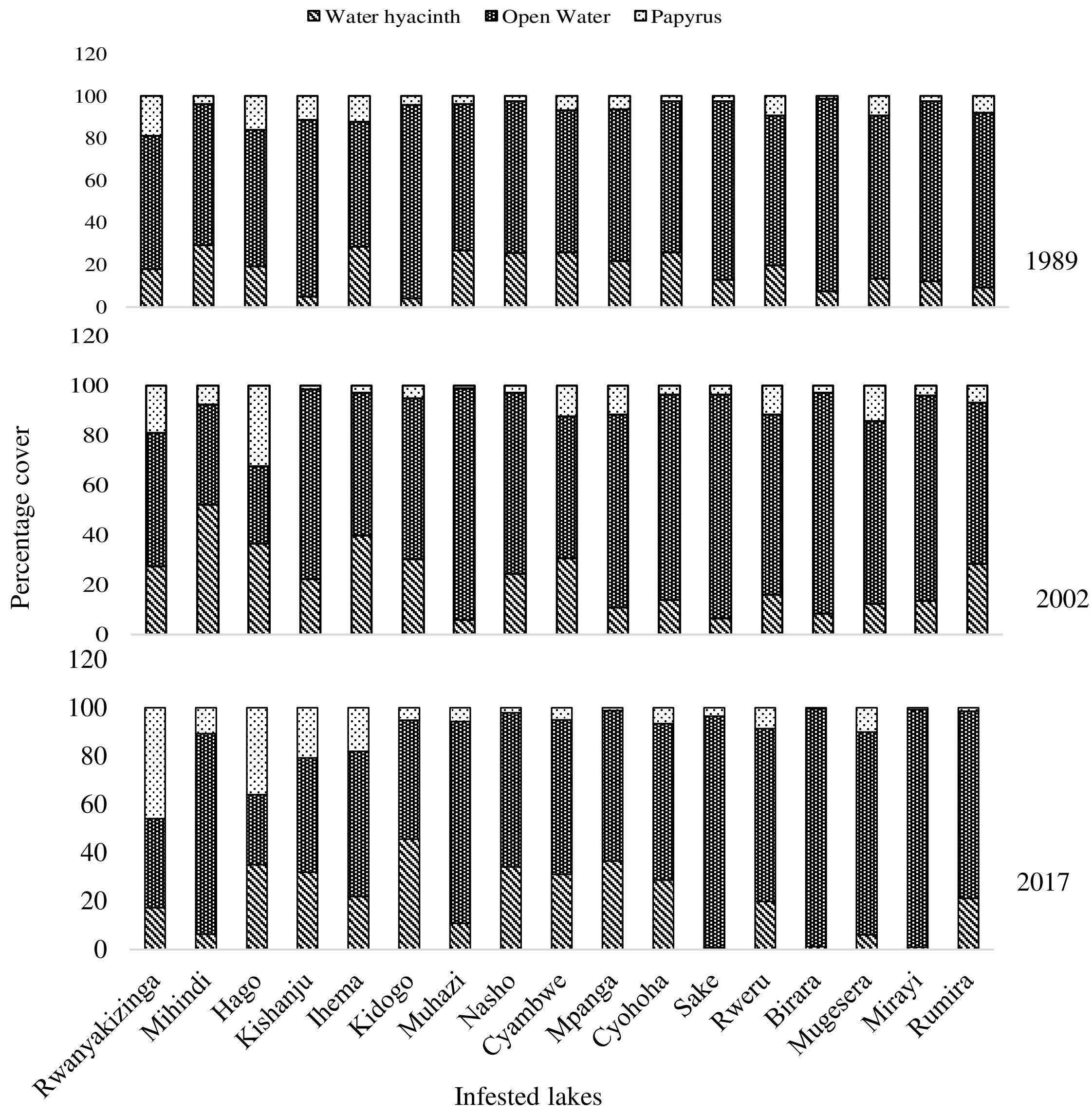


Figure 3.2: Extent of water hyacinth coverage over a period of 28 years in 17 Rwandan lakes located in the eastern region of the country. Water hyacinth percentage cover is compared to the percentage cover of open water and papyrus in each lake for each year.

This study found that water hyacinth was present in the three major rivers of the country and continues to be problematic (Figure 3.3).

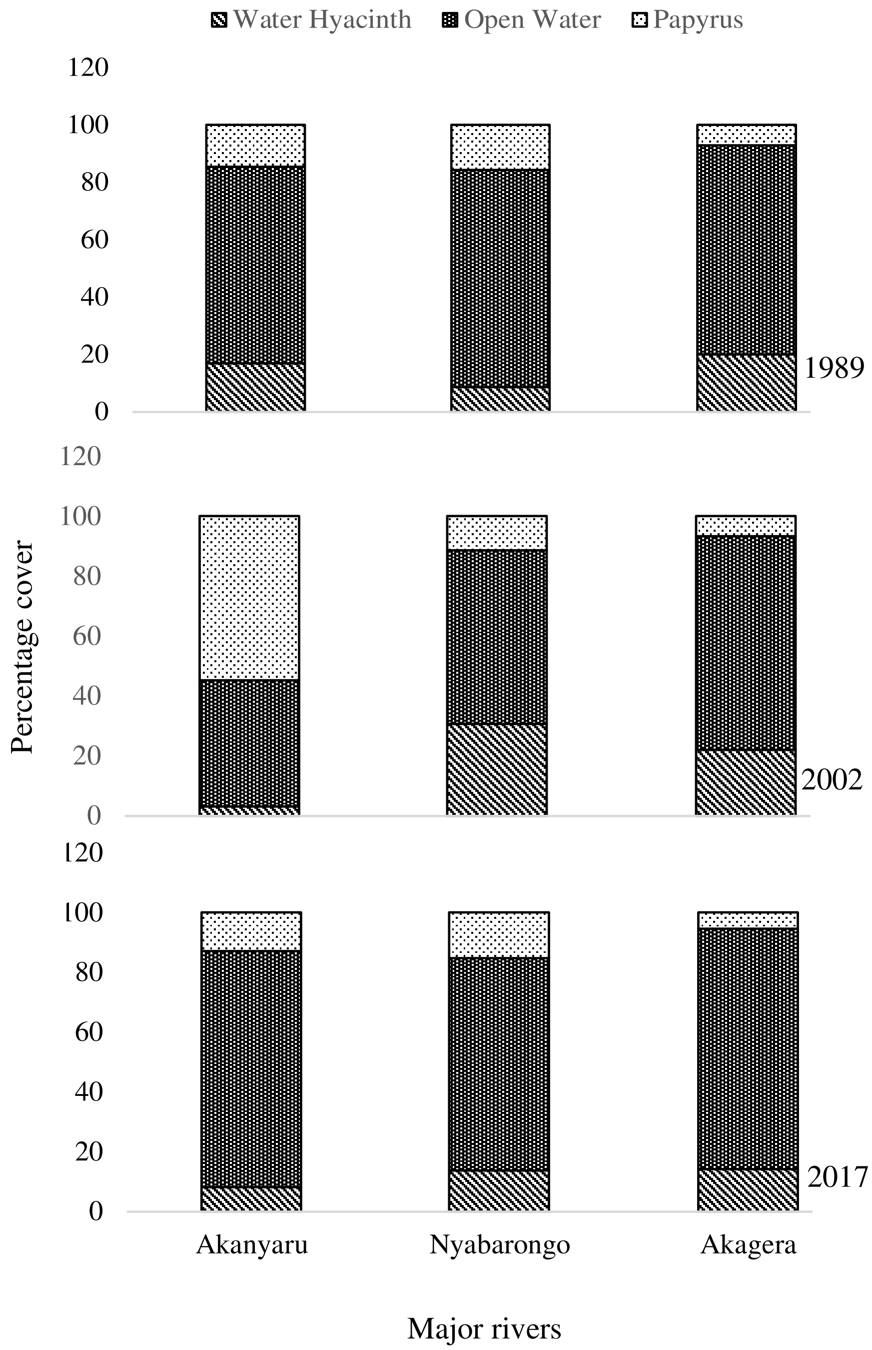


Figure 3.3: Extent of water hyacinth coverage over a period of 28 years in the Rwandan major rivers identified to be infested by the weed. Water hyacinth percentage cover is compared to the percentage cover of open water and papyrus in each lake for each year.

The greatest infestation of water hyacinth in the past was recorded in the Akagera River, which is thought to be the source of the weed spreading into most lakes in the eastern region of the country. Although Ogwang and Molo (2002) did not quantify the extent of water hyacinth in Rwanda, they reported major infestations of water hyacinth in the Akagera River, particularly in the downstream portions of the river. This has been ascribed to high concentration of nitrogen in the water (>25mg/l) and the absence of sustainable control measures for the weed reported in the Akagera River, the longest river in the country (Twongo *et al*., 2002).

In addition, the Gashora, Akanyaru and Akagera Wetlands through which the Nyabarongo, the Akanyaru and the Akagera rivers pass were also infested by water hyacinth prior to 1999 when water hyacinth was officially recognized as a problem in the country. The Akagera Wetland showed the highest percentage cover of water hyacinth over the three periods of the study (1989, 2002 and 2017) (Figure 3.4). The studies investigating threats to the Akagera Wetland from 1987 to 2015 showed water hyacinth to be the main problem, particularly in the 2000–2002 period (Twongo *et al*., 2002; Ndayisaba *et al*., 2017). However, these studies did not quantify the coverage of water hyacinth in the Wetland during this period.

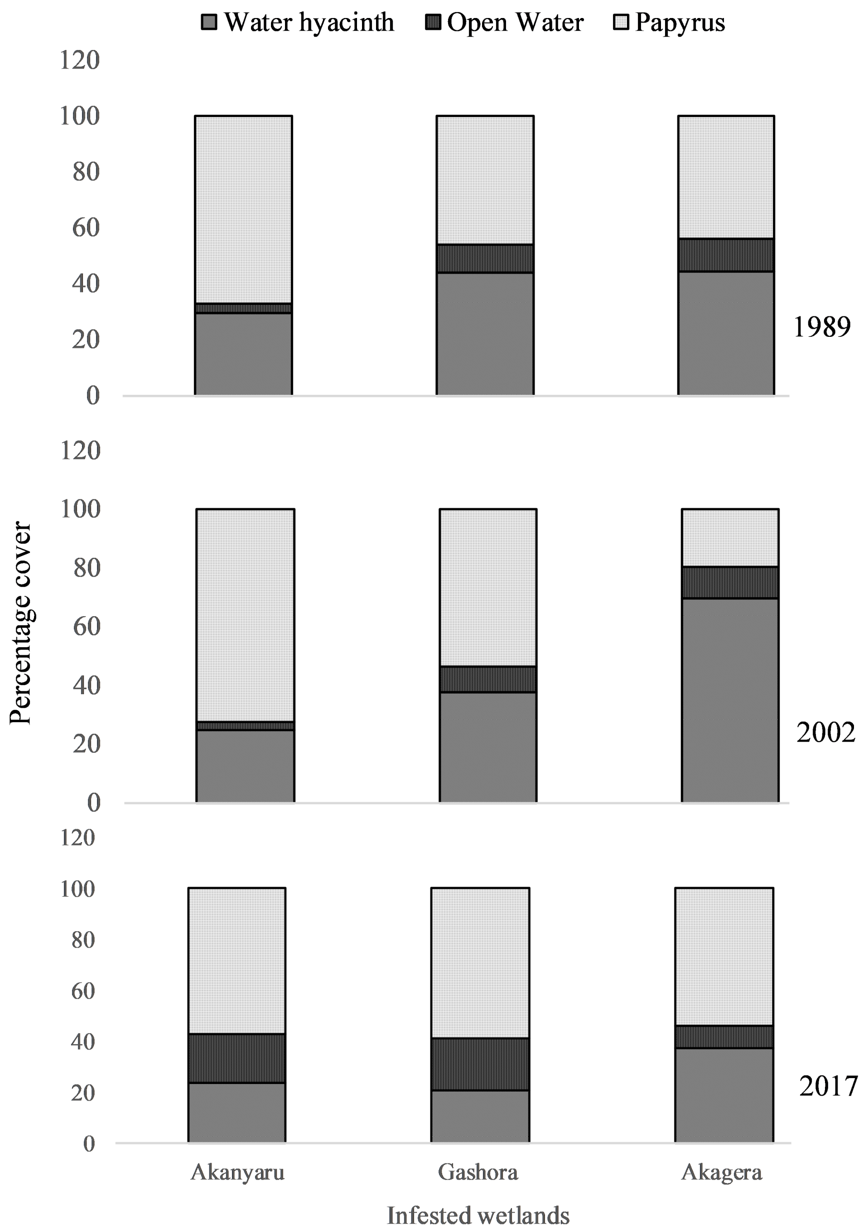


Figure 3.4: Extent of water hyacinth coverage over a period of 28 years in Rwandan wetlands through which the three main rivers pass.

**Implications of this study**

Remotely sensed imageries have been successfully used to identify and map spatio-temporal changes in water hyacinth infestations in many regions of the world (Thamag and Dube, 2018). However, Rwanda has not embraced this technological advancement because of the cost and the technical expertise required. Therefore, the quantification of the spatio-temporal variation of water hyacinth in a time series of satellite images confirmed the usefulness of Landsat images for following chronological changes in water hyacinth distribution and abundance in Rwanda. The Random Forest algorithm and the change detection analysis applied to the Landsat images (5, 7 and 8) were able to provide reliable information on the water hyacinth invasion status in Rwandan water bodies. The current study showed that water hyacinth has been invading the Rwandan water systems since at least 1989. The average weed percentage cover was 17.7% in 1989. By 2002, there was an increase in the weed coverage with an average percentage cover of 22.4%. However, in 2017 weed coverage decreased to 20.8% due to a manual water hyacinth management intervention. Regardless of the intensive manual removal across the country (REMA, 2016), water hyacinth remains a problem in the county.

**Conclusions**

The purpose of this chapter was to investigate change in water hyacinth coverage using Landsat images from 1989, 2002 and 2017. Overall, the results showed that the nonparametric classifier Random Forest was able to (1) accurately detect and discriminate water hyacinth from papyrus, with accuracies ranging from 77% to 87%; and (2) determine changes in water hyacinth extent. This includes magnitude and annual rate of change before water hyacinth was officially recognized as a weed in the country and after intensified manual removal measures were taken as well as its current status. (3) Determine the extent of water hyacinth and its level of invasion in each of the water systems identified to be infested by the weed. Therefore, this study suggests that remote sensing should be considered as a tool for mapping and monitoring the spread of water hyacinth and evaluating pre- and post-management interventions undertaken to control the weed so that the allocation of resources and continuity of the control methods are guaranteed based on the efficiency of the methods implemented.

# CHAPTER 4:

# MAPPING WATER QUALITY PARAMETERS OF RWANDAN WATER SYSTEMS THAT CONTRIBUTE TO WATER HYACINTH GROWTH USING LANDSAT 8 MULTISPECTRAL IMAGERY

***This chapter has been prepared to be submitted to the Journal of Water Resource Research***

## ABSTRACT

Water plays significant role in an aquatic ecosystem by regulating global scale ecosystem processes, linking biosphere, lithosphere and atmosphere, enabling chemical reactions and facilitating the movement of substances. It displays its own biotic and abiotic characteristics that indicate the quality of the aquatic ecosystem, such as lakes, rivers, dams, wetlands, oceans, streams and estuaries. Thus, it is crucial to assess and monitor the quality of water to ensure that it remains functional. Field-based methods have been used to assess and quantify water quality indicators such as temperature, nitrogen and phosphorus and turbidity levels. However, such methods are intrinsically labour intensive, expensive and incapable of providing broad scale spatial and temporal variations of biotic and abiotic characteristics of water. On the other hand, remote sensing techniques can offer information on surface water quality parameters that are not readily available when using field surveys, hence making it possible to monitor the landscape, identify and quantify water quality parameters. The main aim of this study was to determine the spatial distribution of temperature, nitrogen, phosphorus and turbidity in Rwandan water bodies infested by water hyacinth. Images from Landsat 8 acquired in August and November 2016 were processed according to individual band, band rationing as well as band combination. Maps were produced according to the correlation between the measured water parameters and the reflectance values of the Landsat 8 image. Rwandan water bodies are more turbid (2500 (NTU) and eutrophied (11.4 mg/l N, 1.12mg/l P) and warm (28 °C) in the wet season compared to the dry season. The results revealed that Rwandan water bodies with high level of water hyacinth coverage are those with high level of turbidity, nitrogen and phosphorus. These results can help Rwandan water resource management and research institutions to create a permanent geographically located database for future research. The use of satellite imagery is recommended for frequent and continuous scrutiny of Rwandan water systems.

**Key words**: water quality, turbidity, nutrients, water temperature, remote sensing, spatial distribution.

## 4.1 Introduction

Water is the most precious natural resource that sustains life on earth (UNEP, 2008). Without a good quality of water, sustainable development is impossible (UNICEF, 2008; UNEP, 2010). Globally, water is a basic need of the entire population as well as for most developmental activities (Biswas, 2004). However, its quality and quantity are threatened by pollution, which comes from both non-point and point sources (Gumbo *et al*., 2008; UNEP, 2010). Point sources include industrial discharges, poor sanitation practices, domestic sewage, disposal of solid waste, release of liquid from refuse dumps, and discharge of food processing waste (Gumbo *et al.,* 2008; UNEP, 2010). Non-point sources include runoff from agricultural activities, erosion that causes land degradation, and urban runoff such as gasoline, motor oil, heavy metal and other pollutants from roadways and parking lots (Gumbo *et al*., 2008; Viman *et al*., 2010; Ferronato and Torretta, 2019). The problem of poor water quality has become a major social and economic concern globally (WWDRP, 2012). Increasing pressures from different human developments aggravate the deterioration of surface water, such as lakes, rivers, dams, and the quality of groundwater (Meybeck and Vörösmarty, 2005). Many parts of the world today are challenged by problems associated with poor water quality and the use and control of water resources, which may imperil the sustainable development of these resources (Cook and Bakker, 2012). Discharge of sewage and stormwater runoff are the common ways by which nutrients enter the aquatic ecosystems resulting in pollution (Adeyemo, 2008; UNEP, 2008), and this is a serious problem in many African countries, including Rwanda (UNEP, 2008). Increased urbanization in the county has led to the mismanagement of water quality. Thus, the World Bank and United Nations Environmental Program encourage all countries to regularly assess water quality indicators such as turbidity, temperature, nitrogen, phosphorus, total suspended solids, dissolved oxygen, dissolved organic carbon, chlorophyll a concentration, and pH (UNEP, 2008). This will help to demonstrate progress towards the targets of meeting international agreements by plotting trends in water quality parameters over time and space (UNEP, 2008).

### 4.1.1 Water resources and water quality in Rwandan water systems

Rwanda has a dense hydrographical network: rivers cover an area of 7260 ha, lakes occupy 128190 ha, while the wetlands and valleys cover a total area of 77000ha (Habiyakare and Zhou

2015). However, the quality of water in these water systems is a concern because of the risk from anthropogenic activities (RNRA, 2012).

The poor quality of Rwandan water systems is due to (i) the agricultural practice of using fertilizers containing NPK such as Diammonium phosphate (DAP) and urea and pesticides such as glyphosate IPA, Paraquat, Lambda-cyhalothrin, Mancozeb, 2,4-D-dimethylammonium, Imidacloprid, and Atrazine (Rutikanga, 2015) to improve productivity, which then reach the surface water by runoff (Nahayo *et al.*, 2016), (ii) the disposal of domestic and industrial discharges (Usanzineza *et al.*, 2011; Mukanyandwi *et al.*, 2018); and (iii) erosion driven sediment transport and suspended matter that result in high water turbidity, which is considered as a common cause of water quality deterioration in Rwanda (Karamage *et al.*, 2016; Mukanyandwi *et al.*, 2018). High turbidity and an increase of nitrogen and phosphorus in Rwandan water bodies have been reported by the Rwanda Natural Resources Authority (RNRA, 2012). Since 2010, the problem of water quality became a focus in Rwanda when the government developed Law No. 53/2010 for managing natural water resources by establishing the Rwanda Natural Resources Authority (MINIRENA, 2011). Since then, the country has adopted the Integrated Water Resources Management (IWRM) approach that assists in the coordination and management of water resources and monitors their degradation (Aboniyo *et al.*, 2017). Research institutions were called on to help with the continuous assessment of water quality parameters at least once a year (Aboniyo *et al.*, 2017). The monitoring and evaluation of water quality parameters in the country is based on field surveys through which the aforementioned water parameters are determined through in-situ measurements and analysis of samples in the laboratory (RNRA, 2012; Aboniyo *et al.*, 2017). This is costly and time consuming, not consistent, and sometimes it is not easy to access all areas of certain water bodies (He *et al.*, 2008). In addition, field-based techniques do not allow a view of spatial and temporal variations of water quality parameters for the whole water body and cannot provide the spatial information on water parameters on large inaccessible water bodies (He *et al.*, 2008). Field surveys cannot rapidly provide information on water quality indicators, which is crucial for planning and evaluating health management of water bodies (Wang and Ma, 2001). To surmount these problems, researchers use remote sensing techniques that allow the large-scale evaluation of water quality indicators (Usali and Ismail 2010; Gholizadeh *et al.*, 2016).

### 4.1.2 Application of remote sensing in assessment of water quality parameters

Remote sensing techniques are able to (i) determine spatial variability of water parameters that are not readily available when using field based methods over large geographic areas, (ii) determine temporal trends of water parameters over a given period of interests, and (iii) provide the information on the conditions of water bodies in remote areas (Schaeffer *et al.*, 2013; Gholizadeh *et al.*, 2016). Various sensors mounted on satellites and other platforms detect the quantity of radiation at various wavelengths reflected from water surfaces, which are used directly or indirectly to determine water quality parameters.

Hyperspectral remote sensing is considered as the most effective tool for detecting and identifying water quality problems on small or large-scale water bodies (Govender *et al.*, 2007; Kutser *et al.*, 2009; Santini *et al.*, 2010; Mbuh, 2018; Jensen *et al.*, 2019; Mbuh, 2019; Moses *et al.*, 2019). However, the data can be exorbitantly expensive to acquire and difficult and time consuming to process and analyse. Thus, many researchers consider the use of multispectral remotely sensed data for assessing water quality indicators (Koponen, 2007; Gholizadeh *et al.*, 2016).

Many multispectral sensors are available to estimate water quality indicators (Hellweger *et al.*, 2004) (Table 4.1), and their selection depends on their temporal, spectral, and spatial resolutions (Gholizadeh *et al.*, 2016). Among these, Landsat 8, with a moderate revisiting time and spatial resolution of 30m, was found to be the most suitable sensor to provide information on spatial distribution of water quality parameters like nitrogen, phosphorus, temperature and turbidity. MODIS and MERIS have been successfully used to map water quality parameters in most sub-Saharan countries (Dube *et al.*, 2015), but, they have low spatial resolution (250m) compared to Landsat sensors with a moderate spatial resolution (30m) (ESA, 2015). SPOT has good spatial resolution (5m) but few bands (4 bands), and data are not always available to the public. IKONOS also has high spatial resolution (4 m) and can capture water surface conditions; however, data are not available for public use and are costly (Goetz *et al.*, 2003). Landsat is available free of charge from an archive hosted by the US Geological Survey Earth Resources Observation and Science Centre using the USGS Globalization Visualization Viewer (GLoVis) tool available at http://glovis.usgs.gov, and it provides the longest continuous data of the earth, since 1972 to present, from Landsat 1 to Landsat 8 (USGS, 2013).

Table 4.1: Multispectral sensors used to study and monitor water quality indicators worldwide (adapted from Gholizadeh *et al.*, 2016).

| Sensors | Spatial resolution (m) | Spectral resolution (number of bands) | Revisiting time (days) |
|---|---|---|---|
| MODIS | 250 | 36 | 15 |
| MERIS | 240 | 15 | 25 |
| SPOT | 5–20 | 5 | 26 |
| IKONOS | 2 | 5 | 3 |
| LANDSAT | 30 | 7–11 | 16 |

Landsat data have been acquired routinely to monitor water parameters in inland water systems (Giardino *et al.*, 20141). The first Landsat used in this way was Landsat 4 TM, which assessed chlorophyll a, turbidity and temperature, key water quality parameters, (Khorram *et al.*, 1989). The images of Landsat 5 TM were used to provide spatial and temporal information on turbidity and chlorophyll a in Reelfoot Lake, Tennessee (Wang *et al.*, 2006). Since its launch in 2013, Landsat 8 has been explored and widely used to map water quality (Gholizadeh *et al.*, 2016). Compared to the previous generations of Landsat 5 and 7, Landsat 8 is 12bit, which enhances the sensor for proper detection of water properties (Roy *et al.*, 2014).

Although detecting and mapping water quality indicators are very important, it is also crucial to understand their relationship with aquatic living organisms (Christine *et al.*, 2018). This has been a global focus in biological invasions to determining their role in the multiplication and spread of invasive species, including water hyacinth. Water parameters, such as nutrients and temperatures, were found to be the key influencers of water hyacinth growth and proliferation (Byrne *et al.*, 2010). Reddy *et al.* (1989; 1990) showed that water hyacinth grows quicker at high water nutrient levels (50mg/l N, 10mg/l P) than at low nutrient levels (0.5mg/l N, 0.06mg/l P). High nutrients are now considered a constraint in biological control of water hyacinth because in high nutrient waters, it over or equally compensates for insect damage, which affects the effectiveness of biological control (Bownes *et al.*, 2013; Mukarugwiro *et al.*, 2018). Extreme temperatures also affect water hyacinth growth as well as its biocontrol agents (Byrne *et al.*, 2010). However, water hyacinth has the ability to regrow after stressful extreme temperatures

(Perez *et al*., 2011), while the biocontrol agents take longer to recover from extremes (Byrne *et al*., 2010). Another water parameter that is thought to contribute to water hyacinth growth as well weed biological control is water turbidity, which was further investigated in this study (Chapter 5). Thus, knowledge of water quality indicators in Rwandan water bodies can be used to assess the potential for water hyacinth distribution and spread in water systems as well as the potential for biological control success in Rwanda. Therefore, this chapter aimed to determine the spatial distribution of water turbidity, nitrogen, phosphorus and water temperatures using Landsat 8 images. The study hypothesized that the Rwandan rivers and lakes with a high infestation of water hyacinth are those with high turbidity, temperature and nitrogen and phosphorus levels.

## 4.2 Methods and materials

### 4.2.1 Description of study area

Study area was described in Chapter 2 (section 2.2.1).

### 4.2.2 Selection of sampling sites and field data collection

Fieldwork was conducted from July to December 2016. Four main rivers and two lakes invaded by water hyacinth (see Chapter 2) were selected of ground-truthing data. A Global Positioning System (GPS) receiver (Garmin GPSMAP 64s) with the position accuaracy of 3 to 15m was used to determine the position of each sampling location. Nine sampling locations were chosen from the Mukungwa River, 15 sampling locations from each of the Nyabarongo and Akanyaru rivers, and 30 from the Akagera River. Ten sampling locations were also chosen from each of Lake Rweru and Lake Hago (Figure 4.1). All sampling locations were selected by randomly depending on their accessibility

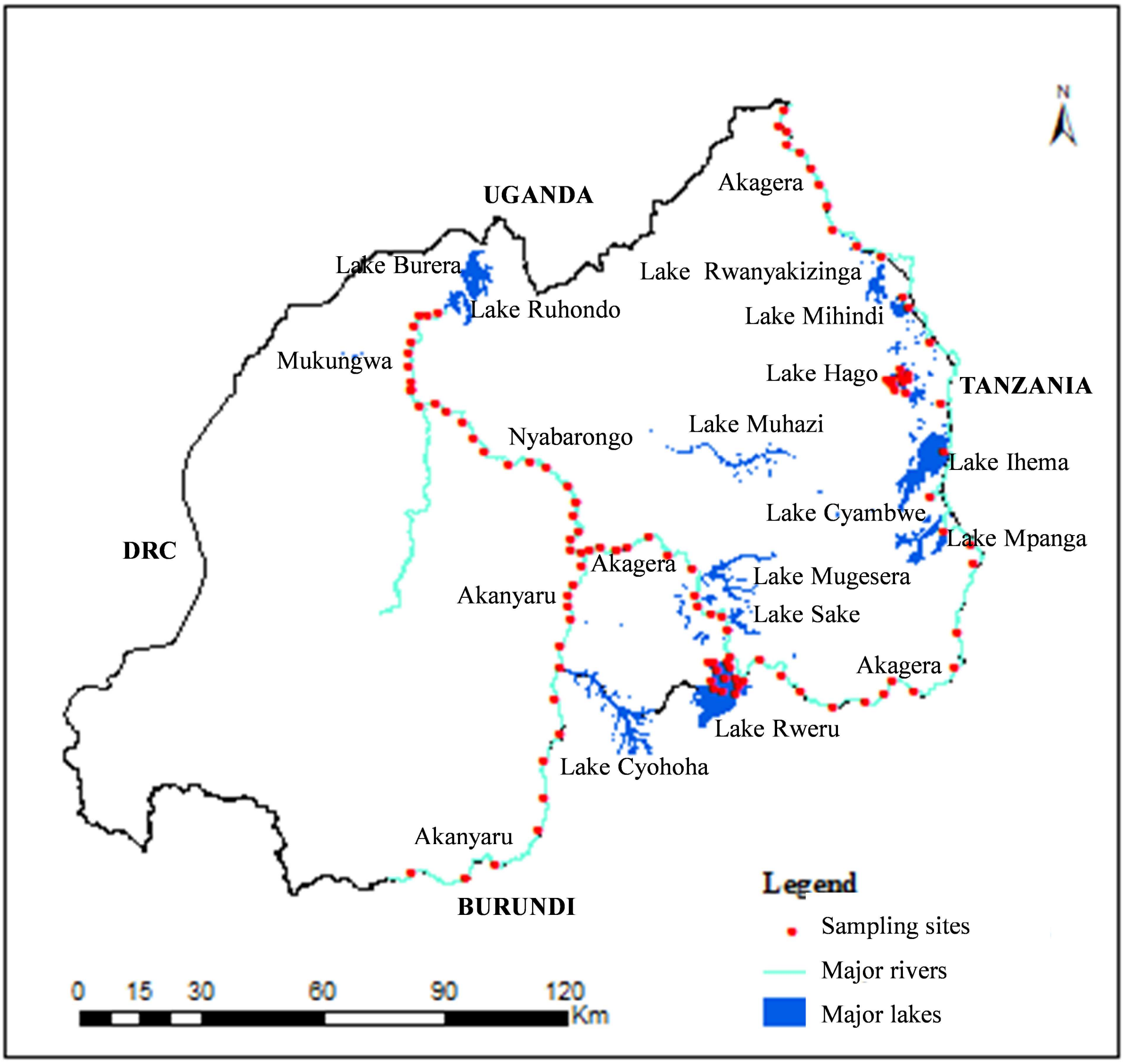


Figure 4.1: The sampling collection sites in four main Rwandan rivers and two lakes where water parameters were measured. These sites were chosen for field surveys based on extent water of water hyacinth (chapter 2).

Different in-situ instruments were used to record water quality parameters such as turbidity, nitrogen, phosphorus and temperature, investigated in this study. Water turbidity was measured using a Secchi disc; nitrogen and phosphorus were measured using a Hach calorimeter (model 2100Q). Water temperature was measured using YSI Professional Plus handheld multiparameter (model 6600). The fieldwork was planned so that the water characterization matched with the days on which the Landsat 8 sensor woul take an image of the sites in Rwanda. This was done to lessen the variability in water quality parameters between the ground-truthing in-situ data and those acquired using the satellite. This allowed a better calibration of generated algorithms to estimate the water quality parameters.

### 4.2.3 Analysis of field data

Descriptive statistics such as the mean, standard deviation, minimum and maximum values for nitrogen, phosphorus, temperature and turbidity determined and compared to National standard levels and international level. These include the Rwandan Water Guidelines for Evaluation of Raw Water for Drinking Water treatment, Canadian Guidelines for Recreational Purposes (2012), ECE Standards Statistical Classification of Surface Freshwater Quality for Maintenance of Aquatic Life and the FAO Water Quality for Agriculture (1994).

### 4.2.4 Landsat 8 images acquisition and processing

Two Landsat 8 images were acquired in August and November 2016 from the Landsat archive of the US Geological Survey. Although ground-truthing data included the Mukungwa River and the upper part of the Nyabarongo River, it was not possible to get clear images without cloud or less cloud that included the aforementioned rivers. Thus, the acquired images covered part of the Nyabarongo River, the whole Akanyaru River, the Akagera River and other invaded lakes from the Eastern Province. Images were downloaded from the USGS database through the Global Visualization Viewer link (http://glovis.usgs.gov/). Images were then pre-processed to improve the image data by suppressing unwanted distortion and enhancing features relevant for better processing analysis using Environment for Visualizing Images (ENVI) 5.3 software. Radiometric calibration was important to ensure a uniform illumination on all comparable, geometrically corrected images. This characteristic allows estimating and comparing the field measurements of biophysical parameters in space and time (Chavez, 1988). FLAASH was applied to correct any atmospheric errors that occurred during image acquisition, after which the two images were mosaicked using ENVI software's seamless model. Using a shapefile of the Rwandan water systems, the image was masked to keep only the water bodies. Furthermore, reflectance values of each band (visible and near-infrared bands) of Landsat 8 on every image at each sampling point were determined using Arc GIS (option of 'extract multi-values') for each water parameter.

### 4.2.5 Development of regression models

To develop the models, firstly the reflectance values of each band and value of each water quality parameter at a specific sampling point were regressed. Individual bands, band ratios which involve the division of two bands (one band is considered as numerator and one is denominator) and band combinations were tested to determine which of these provided the highest correlation value with particular water parameters. Thereafter, regression models were developed using Ordinary Least Square (OLS) regression according to the band ratios, raw bands, or bands combinations with high $R^2$. $R^2$ values range from 0 to 1 and values above 0.6 signify a strong correlation, those between 0.6 and 0.5 a moderate correlation, while values below 0.5 are considered weak, showing no difference between the predicted and actual values (field data values) (Alparslan *et al.*, 2007). Apart from the coefficient of determination $R^2$, created models were also developed and selected according to P values and Root Mean Square Error (RMSE). To assess a more detailed spatial distribution of turbidity, nitrogen, phosphorus and temperature in the Rwandan water systems, maps were generated using Arc GIS 10.5 software by applying obtained algorithms (with high $R^2$, P values $<0.05$ and low RMSE) to the Landsat 8 images. Furthermore, the correlations between water hyacinth percentages cover and water parameters to investigate their relationship as well as the influence of Rwandan water parameters on the extent of water hyacinth.

## 4.3 Results

### 4.3.1 Field assessment of water quality parameters

Results in this section are based on field measurements of turbidity, nitrogen, phosphorus and temperature in dry the months (July and August) and in wet season (October, November and December). All water parameters have increased during wet season (Table 4.2).

Table 4.2: Descriptive statistics of water quality parameters measured during the dry and wet seasons 2016 from each of the four main rivers and two lakes invaded by water hyacinth in Rwanda

| | | **Water parameters collected in dry season, 2016** | | | | **Water parameters collected in wet season** | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Sites** | | Turbidity (NTU) | Nitrogen (mg/l) | Phosphorus (mg/l) | Temperature (ºC) | Turbidity (NTU) | Nitrogen (mg/l) | Phosphorus (mg/l) | Temperature (ºC) |
| **Mukungwa** | Mean | 19.71 | 0.49 | 0.016 | 18.26 | 264.02 | 1.55 | 0.0065 | 21.09994737 |
| | Standard deviation | ±5.18 | ±0.14 | ±0.03 | ±0.63 | ±62.16 | ±0.123 | ±0.043 | ±0.79 |
| | Maximum | 26.7 | 0.92 | 0.034 | 19.2 | 355 | 2.62 | 0.046 | 22.8 |
| | Minimum | 10.89 | 0,21 | 0.001 | 17 | 106 | 1.5 | 0.012 | 20.1 |
| **Nyabarongo** | Mean | 103.5 | 1.32 | 0.33 | 21.72 | 1732.92 | 6.23 | 0.54 | 22.5 |
| | Standard deviation | ±18.78 | ±0.58 | ±0.18 | ±0.57 | ±329.26 | ±0.32 | ±0.051 | ±1.34 |
| | Maximum | 115.41 | 2.98 | 0.18 | 22.6 | 2849 | 7.2 | 1.7 | 26 |
| | Minimum | 45.34 | 0.72 | 0,019 | 21.1 | 614 | 4.6 | 0.32 | 20.6 |
| **Akanyaru** | Mean | 73.45 | 1.35 | 0.28 | 21.67 | 1293 | 5.87 | 0.64 | 22.8 |
| | Standard deviation | ±12.57 | ±0.38 | ±0.15 | ±0.64 | ±211.73 | ±1.68 | ±0.32 | ±0.85 |
| | Maximum | 84.6 | 1.85 | 0.12 | 22 | 731 | 6.4 | 1.44 | 25.9 |
| | Minimum | 37.4 | 0.62 | 0.01 | 20.1 | 615 | 4.1 | 0.42 | 21.7 |
| **Akagera** | Mean | 108.54 | 1.96 | 0.28 | 22.22 | 1861.5 | 8.75 | 0.83 | 25.2 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Standard deviation | ±25.34 | ±0.57 | ±0.16 | ±0.91 | ±559.85 | ±0.72 | ±0.17 | ±1.78 |
| | Maximum | 124 | 3.8 | 0.33 | 23.1 | 3509 | 11.1 | 1.9 | 28.2 |
| | Minimum | 62.2 | 0.79 | 0.024 | 20.5 | 639 | 5.6 | 0.26 | 21.8 |
| **Rweru** | Mean | 29.76 | 0.59 | 0.004 | 20.4 | 301.53 | 2.63 | 0.21 | 24.29 |
| | Standard deviation | ±3.02 | ±0.14 | ±0.003 | ±0.35 | ±46.98 | ±0.71 | ±0.19 | ±2.04 |
| | Maximum | 25 | 0.92 | 0.071 | 21.2 | 316 | 2.9 | 0.38 | 27.8 |
| | Minimum | 12 | 0.37 | 0.001 | 20.1 | 132 | 0.83 | 0.032 | 21.1 |
| **Hago** | Mean | 19.54 | 0.2 | 0.002 | 20.6 | 149 | 1.22 | 0.11 | 25.8 |
| | Standard deviation | ±1.61 | ±0.17 | ±0.05 | ±0.71 | ±13.13 | ±0.27 | ±0.08 | ±1.21 |
| | Maximum | 17.8 | 0.17 | 0.02 | 21.9 | 165 | 1.8 | 0.32 | 27.8 |
| | Minimum | 12.29 | 0.03 | 0.001 | 20.1 | 77 | 0.35 | 0.0243 | 23.5 |

### 4.3.2 Predictive models of water quality parameters

Turbidity and temperature were predicted using models that combined seven bands of Landsat 8 (visible bands, near-infra red and shortwave infrared band) for both November and August with a good coefficient of determination ranging from 0.7 to 0.78, respectively and small Root Mean Square Error (RMSE) (Table 4.3 and 4.4). Phosphorus in both August and November was predicted using a model that involved band ratio with a moderate correlation ($R^2$ from 0.60 to 0.63). Moreover, nitrogen was predicted using a model that combined visible, near-infrared bands and short near-infrared bands in August, and band rationing in November with a moderate coefficient of determination ranging from 0.62 to 0.64 (Table 4.3 and 4.4).

Table 4.3: Developed models of nitrogen, phosphorus, temperature and turbidity obtained by regressing reflectance values from Landsat 8 and ground-truthing data of August 2016.

| **Water Parameter** | **Bands** | **Regression Models** | **$R^2$** | **P values** | **RMSE** |
|---|---|---|---|---|---|
| **Nitrogen** | All bands | Y=1.046-(b1*0.17)+(b2*0.06)+(b3*0.03)+(b4*0.013)+(b5*0.2)-(b6*0.91)-(b7*0.9) | 0.64 | 0.001 | 0.39mg/l |
| **Phosphorus** | b4/b6 | Y= 0.21+(b2/b4*0.185) | 0.63 | 0.001 | 0.15mg/l |
| **Temperature** | All bands | Y= 20.96+(b1*0.17)+(b2*0.21)-(b3*0.27)+(b6* 0.26)+ (b7* 0.11) | 0.72 | 0.000 | 0.41 °C |
| **Turbidity** | All bands | Y=26.369b1*0.7312)+(b2*5.6659)+(b3*4.8138)+(b4*1.3305)+(b5*7.014)+(b6*0.2126)+(b7*0.854)-(NDTI*5.9) | 0.7 | 0.002 | 13.1NTU |

Table 4.4: Developed models of nitrogen, phosphorus, temperature and turbidity obtained by regressing reflectance values from Landsat 8 and ground-truthing data of November 2016.

| Water parameter | Bands | Models/equations | $R^2$ | P value | RMSE |
|---|---|---|---|---|---|
| Nitrogen | b5 | Y= 0.3+(b5* 0.0018) | 0.62 | 0.001 | 1.46mg/l |
| Phosphorus | b6/b5 | Y= 0.25-(b5/b7 * 0.00307) | 0.6 | 0.013 | 0.11mg/l |
| Temperature | All bands | Y=23.4252-(b1*0.008)-(b2*0.0775)-(b3*0.00192)+(b4*0.005326)-(b5*0.003273)+(b6*0.002843)-(b7*0.001452) | 0.67 | 0.001 | 1.14 °C |
| Turbidity | All bands | Y=50+(b1*0.1401)-(b2*0.3517)+(b3*0.2591)+(b4*0.02)+(b5*0.205669)+(b6*0.015)-(b7*0.021176) | 0.78 | 0.000 | 141.3NTU |

### 4.3.3 Estimated spatial distribution of water parameters

Estimated nitrogen levels were high in the rivers and along the shores of the lakes in November (Figure 4.2). The lakes, through which the Akagera River passes, such as Lake Rweru, Lake Mpanga, Lake Ihema and Lake Mihindi, had high nitrogen compared to other lakes in both months. However, this occurred on the shores of the lakes where the Akagera River is in contact with the lakes. Further more, open-water surfaces of the Akagera Wetland through which the Akagera River passes also had high nitrogen in November.

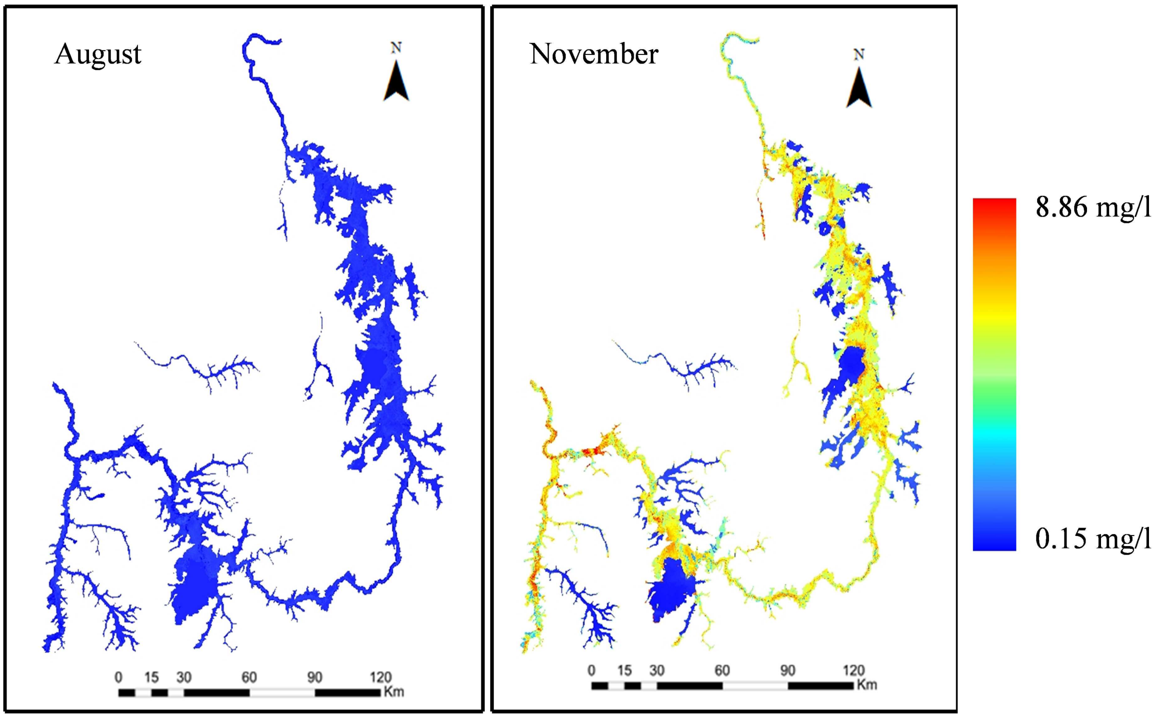


Figure 4.2: Estimated spatial distribution of nitrogen in Rwandan water bodies for August and November 2016. These maps were generated using regression models that involved band combination for November image and individual band (b5) for the August image.

The the relationship between the predicted nitrogen levels and field measurements was moderate for both August and November (Figure 4.3).

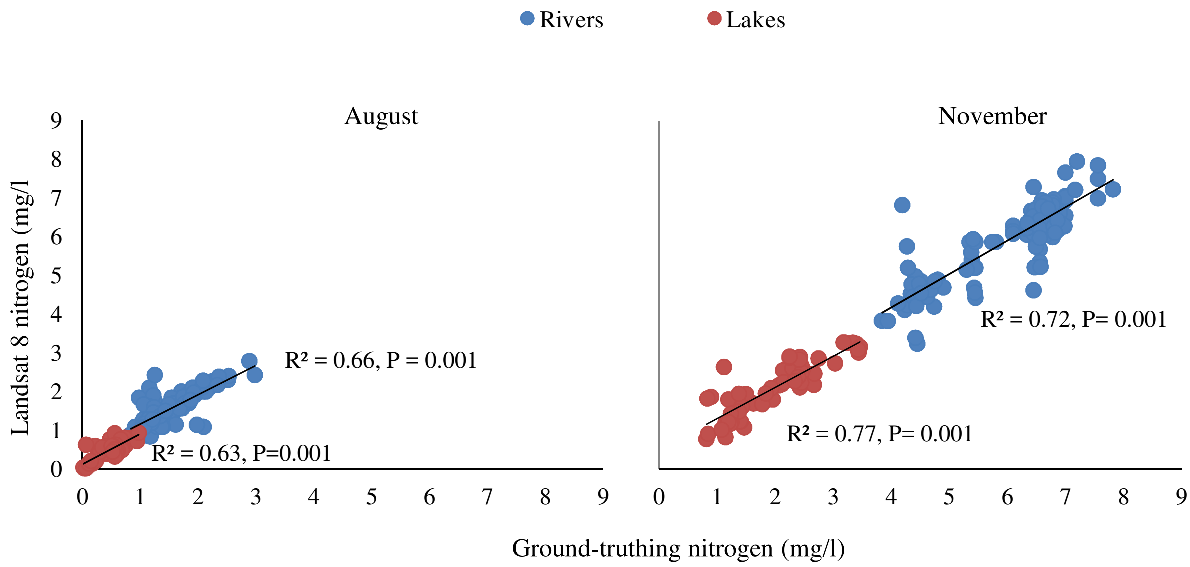


Figure 4.3: Relationship between predicted water nitrogen by Landsat 8 imagery and measured water nitrogen levels using in-situ instrument in Rwandan water systems, during August and November 2016.

Estimated phosphorus levels in August were generally lower compared to November in all the water bodies, except some portions of a few lakes. All the rivers had relatively high concentration of phosphorus during November compared to the lakes. Lake Rweru, Lake Mpanga, Lake Ihema and Lake Mihindi, had high estimated phosphorus compared to other lakes especially at their shores during the month of November (Figure 4.4). This is because those are lakes through which the Akagera River with high levels of phosphorus passes.

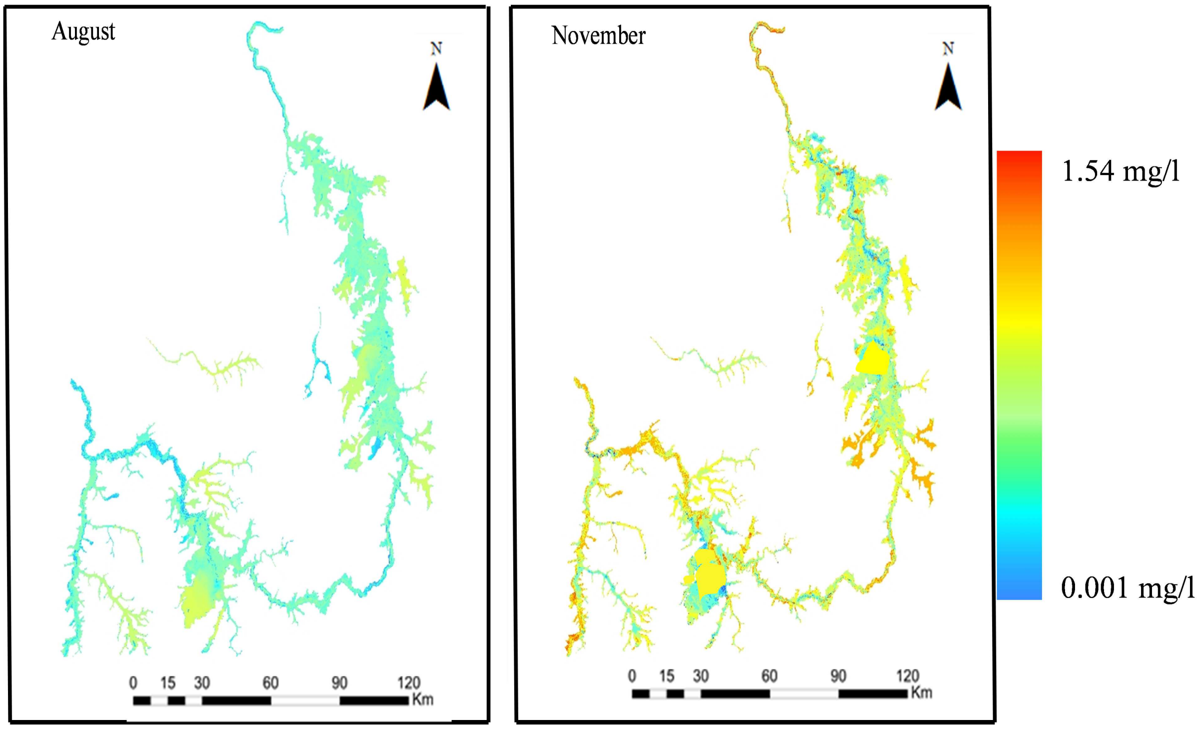


Figure 4.4: Estimated spatial distribution of phosphorus in Rwandan water bodies for August and November. The images were acquired in 2016 to match the dates of ground-truthing. These maps were generated using regression empirical models that involved band rationing.

The correlation between phosphorus levels obtained from ground-truthing measurements and those achieved from Landsat 8 was strong in November but moderate in August (Figure 4.5).

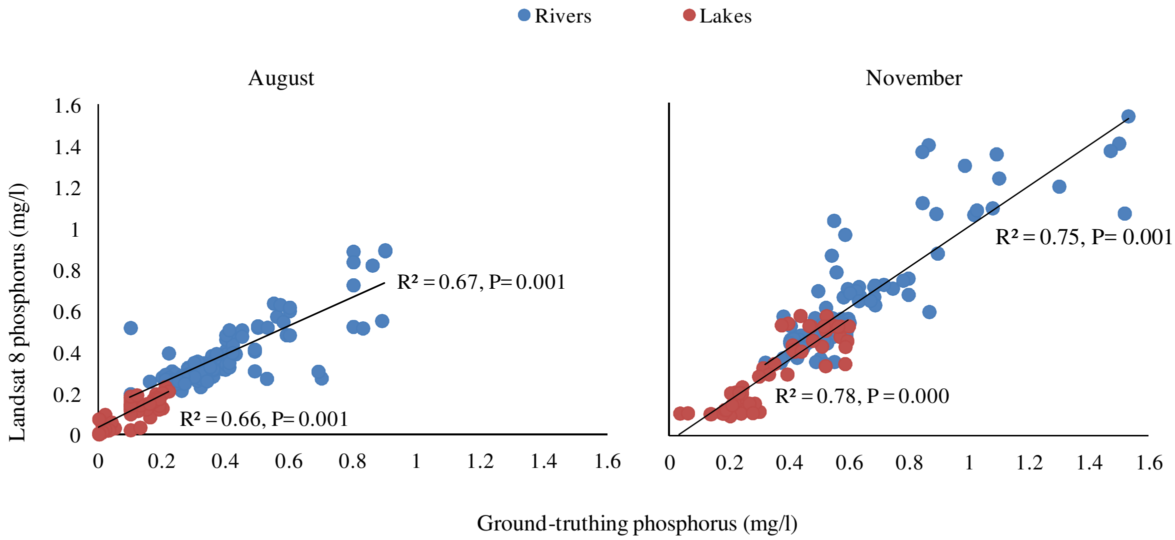


Figure 4.5: Relationship between predicted phosphorus by Landsat 8 imagery and measured phosphorus levels using in-situ instrument in Rwandan water systems, during August and November 2016.

Estimated water temperatures in the lakes were generally lower in August compared to water temperatures in the rivers (20–21 ℃). However, estimated water temperatures in lakes steeply increased in November (Figure 4.6). On other hand, the Akagera River had relatively high water temperatures in both months compared to other rivers.

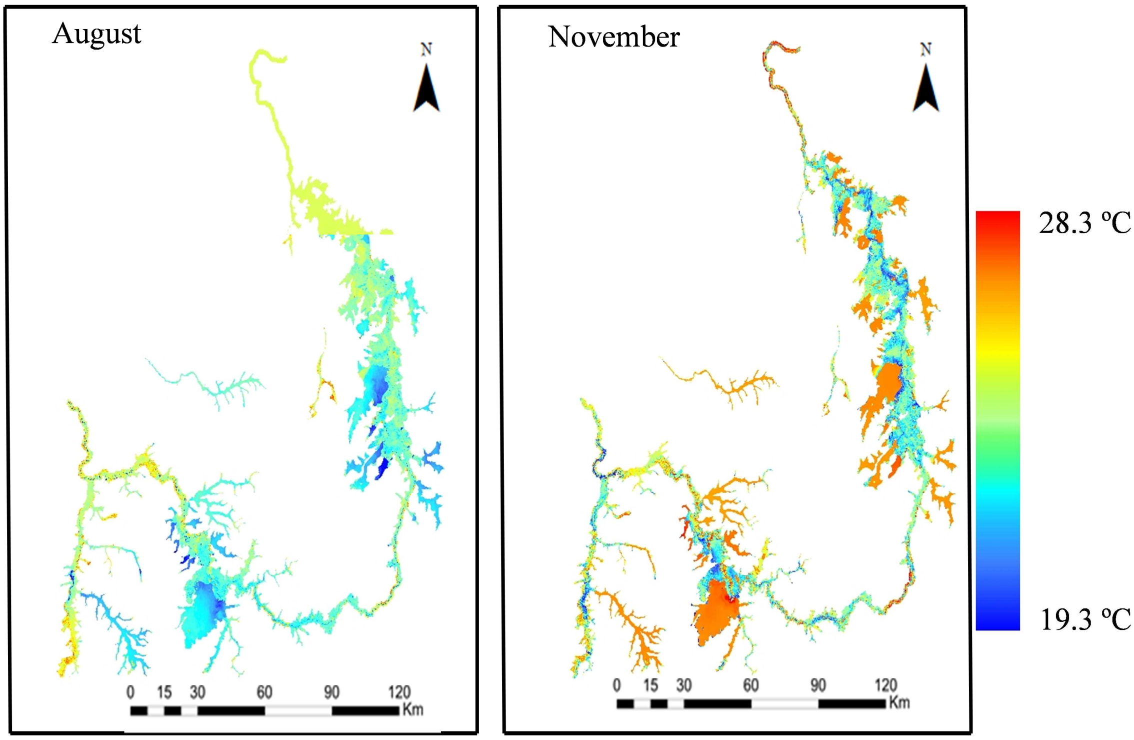


Figure 4.6: Spatial distribution of estimated water temperature in Rwandan water systems for August and November 2016. These maps were generated using regression models that involved band combination for August and November images.

A strong correlation was observed between field measurements of temperature and temperature estimated by Landsat 8 for both months (Figure 4.7).

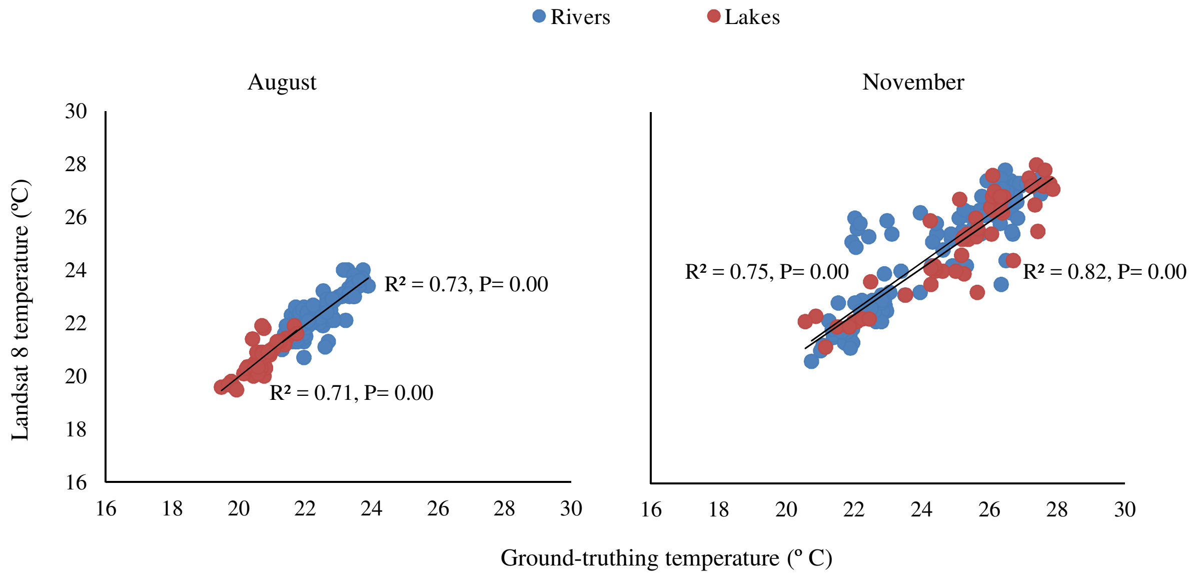


Figure 4.7: Relationship between predicted water temperature by Landsat 8 imagery and measured temperatures using in-situ instrument in Rwandan water systems, during August and November, 2016.

Estimated turbidity levels were generally high in rivers and at the shores of some lakes such as Lake Rweru, Lake Nasho, Lake Ihema and Lake Mihindi, through which the Akagera River passes. Estimated turbidity levels had increased during November. However, Rwandan rivers were more turbid during November (Figure 4.8). Additionally, open–water surfaces of the Akagera Wetland were more turbid (Figure 4.8). Furthermore, there was a strong correlation between turbidity predicted by Landsat 8 and turbidity observed (Figure 4.9).

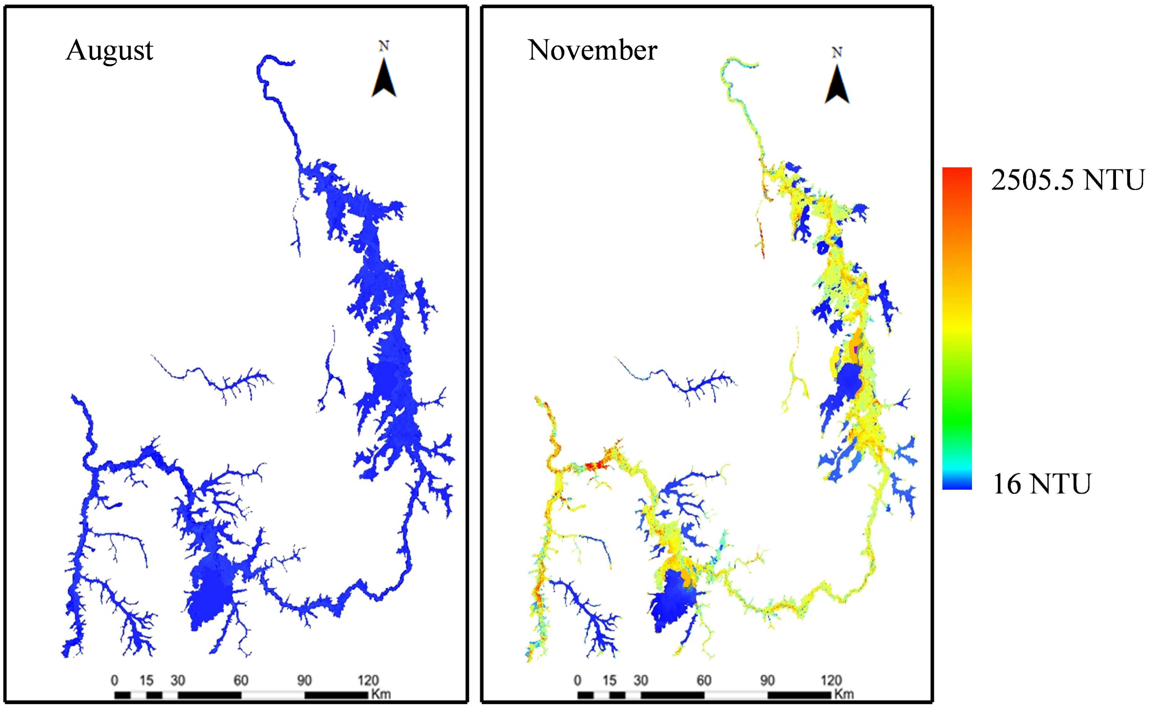


Figure 4.8: Distribution of turbidity in Rwandan water bodies in August and November 2016. Regression empirical models that involved band combination for August and November imageswere used.

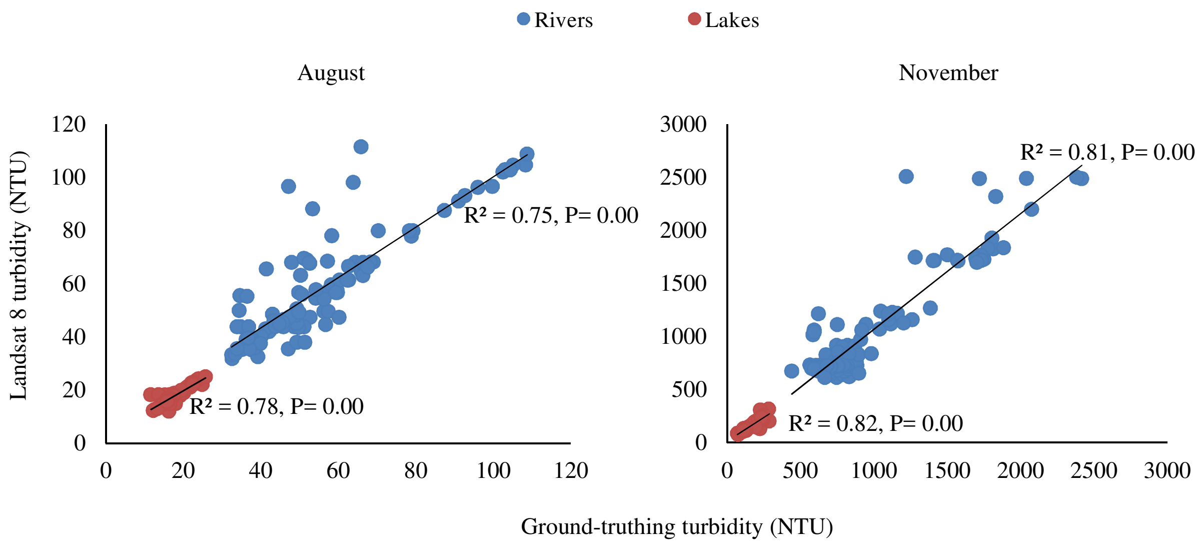


Figure 4.9: Relationship between predicted water turbidity by Landsat 8 imagery and measured turbidity using in-situ sampling in Rwandan water systems during, August and November 2016.

### 4.3.4 Relationships between water hyacinth coverage and water parameters in Rwandan water systems

The correlation between water hyacinth coverage and estimated water nitrogen levels was found to be strong in rivers for both August and November. However, the correlation between water hyacinth percentage cover and estimated water nitrogen levels in lakes was weak and not statistically significant (Figure 4.10).

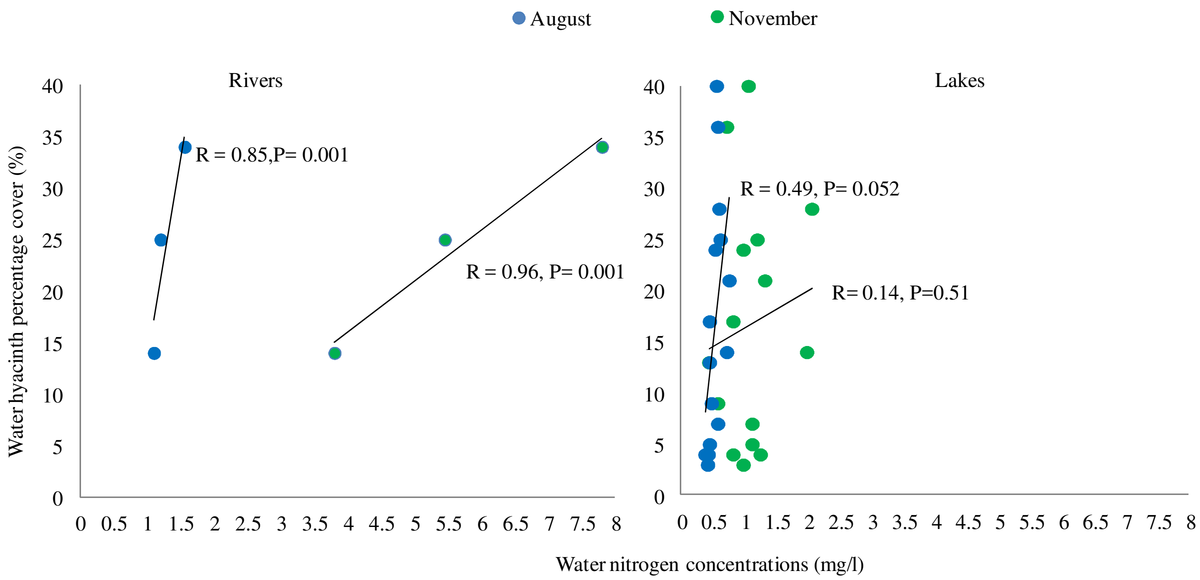


Figure 4.10: The correlation between water hyacinth percentage cover (%) and estimated nitrogen using Landsat 8 in August and November. Percentage cover of water hyacinth was obtained using Landsat 8 images

The correlation between water hyacinth coverage and estimated water phosphorus level in rivers was found to be strong for both August and November. However, the correlation between water hyacinth percentage cover and estimated water phosphorus in lakes was weak and not statistically significant (Figure 4.11).

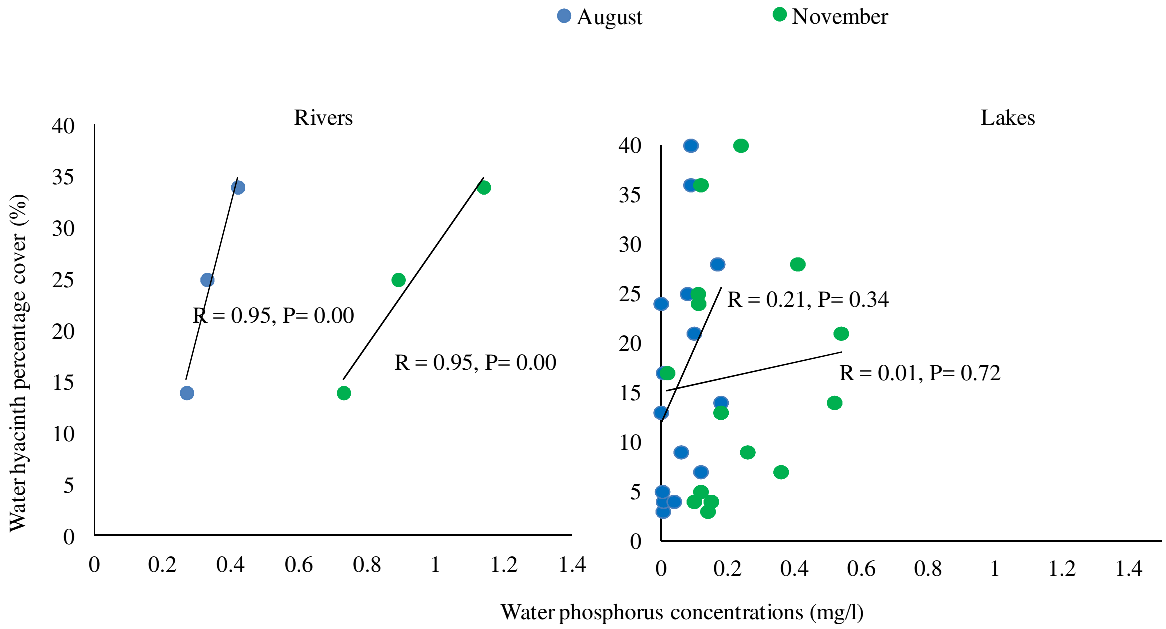


Figure 4.11: The correlation between water hyacinth percentage cover (%) and estimated phosphorus using Landsat 8 in August and November. Percentage cover of water hyacinth was obtained using Landsat 8 images.

The correlation between water hyacinth coverage and estimated water temperature in rivers obtained using Landsat 8 was found to be strong for both August and November. However, the correlation between water hyacinth percentage cover and estimated water temperature in lakes was weak and not statistically significant (Figure 4.12).

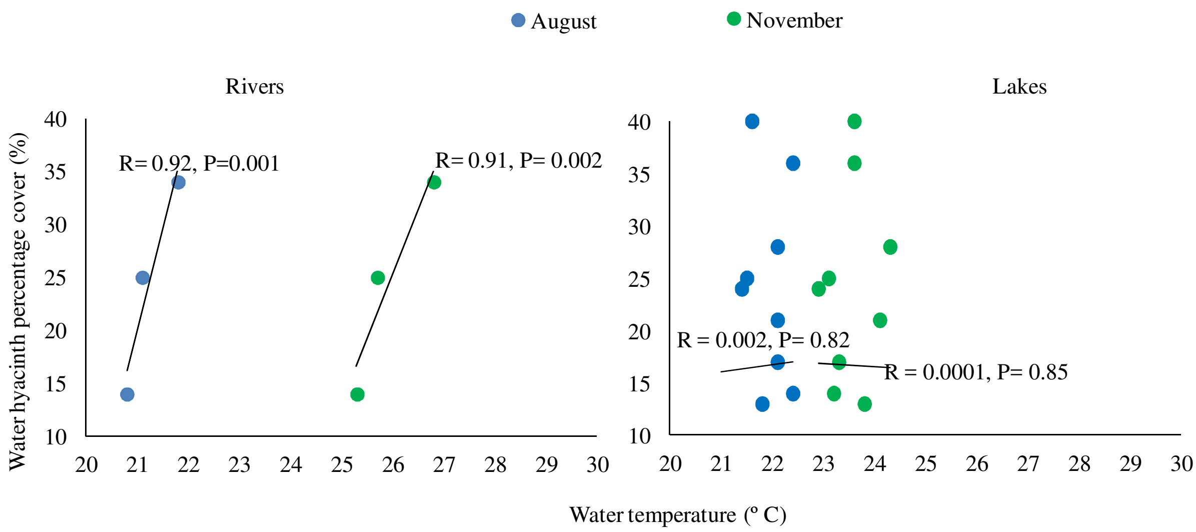


Figure 4.12: The correlation between water hyacinth percentage cover (%) and estimated water temperature using Landsat 8 images in August and November. Percentage cover of water hyacinth was mapped in Rwandan rivers and lakes using Landsat 8 images.

The correlation between water hyacinth coverage and estimated water turbidity in rivers, obtained using Landsat 8 was found to be strong for both August and November. However, correlation between water hyacinth percentage cover and estimated water turbidity in the lakes was weak and not statistically significant (Figure 4.13).

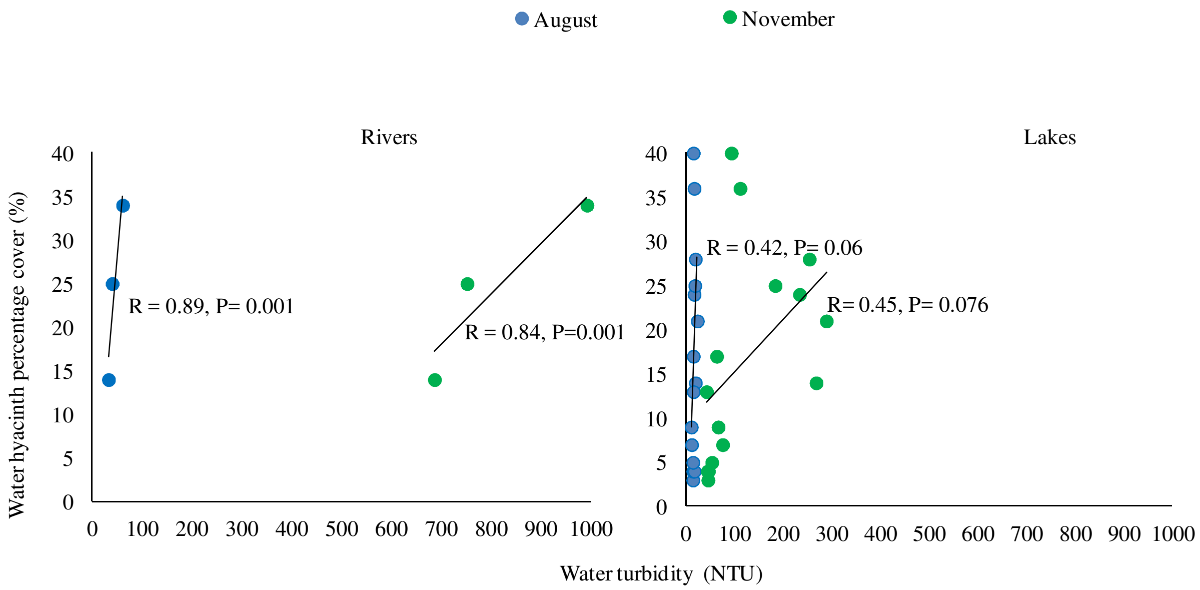


Figure 4.13: The correlation between water hyacinth percentage cover (%) and estimated water turbidity using Landsat 8 images in August and November. Percentage cover of water hyacinth was mapped in Rwandan rivers and lakes using Landsat 8 images.

## 4.4 Discussion

Remote sensing techniques used in this study, has generally enabled the detection and evaluation of the spatial distribution of nitrogen, phosphorus, temperature and turbidity in Rwandan water systems with the use of regression models that involved band combination and band rationing from Landsat 8. Landsat 8 showed that the abovementioned water parameters are high in the rivers compared to the lakes in both dry and wet season; however, their levels steeply increased during the wet season. Compared to other Landsat sensors (Landsat 5 TM and Landsat 7 ETM+), Landsat 8 has an additional channels in deep blue (430–450nm) and infrared (1360–1380nm) spectral regions that further enhance its capability to detect water parameters and monitor water resources in general (Joshi *et al.*, 2017). In addition, the red band of Landsat 8 has a better spectral resolution (640–670nm, bandwidth = 30nm) compared to the red band of Landsat 5 TM (630–690nm, bandwidth = 60nm), and this characteristic enables this band to properly capture water properties (Gholizadeh *et al.*, 2016). Thus, it was justified to use Landsat 8 to map the spatial distribution of the important water quality indicators in Rwandan water systems with the purpose of exploring their relationship with water hyacinth distribution in those Rwandan water systems.

***Nitrogen and phosphorus***

Nitrogen and phosphorus are indicators of water quality and their regular monitoring facilitates the management of eutrophication problems in complex water systems (Andersen *et al*., 2006). The current study applied Landsat 8 images to map nitrogen and phosphorus in Rwandan water bodies and found that a band combination is the best when mapping nitrogen than a single band. For instance, Zhai *et al*. (2013) found a weak correlation ($R^2$ = 0.46) when they estimated nitrogen using the raw band (NIR band) and good results ($R^2$ = 0.74) when combining the visible and near infra-red bands. Chen and Quan (2012) and Liu *et al*. (2015) also suggested that combining visible and near-infra red bands, is the best option for mapping nitrogen levels in water bodies. Band combination improves the relationship between water biochemical contents and spectral reflectance of water as each band detects its own information, the combination of which gives moderate and high regression coefficient (Liu *et al*., 2015). On the other hand, band ratio was found to be the best option for mapping phosphorus levels in water. The studies by Chen and Quan (2012); Liu *et al*. (2015) and Kaparanga (2015) found a moderate coefficient regression using band rationing when mapping water phosphorus.

Compared to the older generations of Landsat (4, 5 and 7), Landsat 8 can spatially map both nitrogen and phosphorus effectively. Using Landsat 7 and Landsat 8, Gholizadeh and Melesse (2017) found the derived regression models from Landsat 8 had high correlation coefficient ranged from 0.91 to 0.98 for both nitrogen and phosphorus, respectively, while derived empirical models from Landsat 5 had a low correlation coefficient (0.56 to 0.52). Low regression and correlation coefficient were also reported by Song *et al*. (2011) who obtained weak correlation for nitrogen and phosphorus (0.55, and 0.51, respectively) when using Landsat 5. Similarly, Alparslan *et al*. (2007) found lower $R^2$ for both nitrogen and phosphorus (<0.60) compared to those found in the current study ($R^2$ = 0.61–0.67) with Landsat 7. High $R^2$ values signify a high accuracy in predicting water quality indicators including nitrogen and phosphorus, which varies based on the sensor (Gholizadeh and Melesse, 2017). For example, MODIS has accurately mapped (high $R^2$ >0.92) nitrogen and phosphorus in large water bodies such as Lake Victoria in Africa and Lake Thahu in China (Gholizadeh *et al*., 2016). However, it cannot be used in the Rwandan water systems since its rivers are less than 250m wide (lower than the sensor spatial resolution). Thus, the current study suggests that Landsat 8 is the best multispectral sensor able to assess the levels of nitrogen and phosphorus and their spatial distribution in Rwandan water systems due to its better spatial resolution (30m).

The levels of nitrogen and phosphorus were found to strongly correlate to water hyacinth coverage in the rivers, while the correlation between nitrogen and phosphorus and water hyacinth coverage in the lakes was weak. This was probably caused by high variability of water nitrogen, water phosphorus and water hyacinth coverage percentage in the lakes. These correlations reveal water hyacinth's ability to opportunistically capitalise on any increase in available nutrients and respond rapidly with increased growth and biomass (Hill, 2014). This could affect the effectiveness of biological control of water hyacinth since water hyacinth plants are able compensate for herbivory damage (Bownes *et al.*, 2013). This was further investigated in chapter 6 of this thesis by investigating the effect of Rwandan water nutrients on the biological control of water hyacinth.

***Water temperature***

Water temperature is one of the parameters that influence chemical, physical, and biological processes in water systems (Webb *et al.*, 2008). Consequently, it plays a substantial role in a wide range of aquatic ecosystem functions, since it is correlated to energy fluxes through the water and atmosphere interface (Lamaro *et al.*, 2013). Hence, it is important to evaluate its ranges in complex water systems. For the past three decades, remote sensing techniques have been used to evaluate and determine spatial and temporal variations of water temperature in water systems worldwide (Gholizadeh *et al.*, 2016). Most previous studies, such as those by Wubet (2003), Rozenstein *et al.* (2014), Abdelmalik (2018) and Tavares *et al.* (2019) used thermal infrared bands to detect temperature and thus map its spatial distribution in water bodies. However, in the present study the reflectance of Landsat 8 thermal bands were not found to strongly correlate with observed temperature values, thus they were not used in this study. On the other hand, the study found a significant correlation when combining b2–b7 of Landsat 8, and the regression coefficients were good, $R^2$ = 0.72 and 0.68 for August and November respectively. Similarly, Abdelmalik (2018) found a good regression coefficient ($R^2$ = 0.95) when using the combination of visible bands and near-infrared bands of ASTER images. However, using a combination of thermal bands of the same sensor, Abdelmalik (2018) found a low correlation coefficient ($R^2$ = 0.53). The thermal bands of Landsat 8 have a 100m spatial resolution, while the Rwandan rivers are only 35to 60m wide. Thus, the Landsat 8 thermal bands could not be used in this study, since thermal bands tend to overestimate water temperatures when used on small water bodies (Bresciani *et al*., 2011).

The correlation between water hyacinth coverage and river water temperature was stronger than that found in the lakes. This probably reflects the greater variability of both water hyacinth coverage and all the water parameters measured in the lakes. Nevertheless, the temperatures recorded at all sites are suitable for water hyacinth growth and development of its biocontrol agents (Byrne *et al.,* 2010).

***Turbidity***

Water turbidity was detected by combining seven bands (b1–b7) of Landsat 8. Theoretically, a single band can provide information on turbidity levels in water systems (Novo *et al*., 1989; Kemker *et al*., 2014); however, this may only be effective in water bodies with low turbidity levels (Nechad *et al*., 2010; Joshi *et al*., 2017; Quang *et al*., 2017). This is because the complex substances in water affect the reflectance signal of water by shifting, for example, from visible reflectance to the near-infrared region (Doxaran *et al*., 2002; Nechad *et al*., 2010; Feng *et al*., 2014). Hence, it is worth considering a combination of bands when evaluating turbidity levels in more turbid water systems (Feng *et al*., 2014). Dekker *et al*. (2002), Brezonik *et al*. (2005), and Akbar *et al*. (2010) used band combinations (visible bands and near-infrared) to evaluate turbidity levels in Bow River of Alberta, Canada. Their results showed strong correlations between in-situ and Landsat data, and the fitting model was good with high $R^2$ values (0.85). Lim and Choi (2015) also found that a combination of seven Landsat 8 bands provided good results in predicting turbidity levels in Nakdong River, Korea.

Although Landsat 8 images from both August and November successfully determined the spatial distribution of turbidity in the Rwandan water systems, the results acquired in November were relatively more robust. Similarly, images from the wet season provided good results compared to images from the dry season when evaluating turbidity levels in Lake Naivasha, Kenya (Ndugu, 2014). Sediments, soil silt and other dissolved organic matter that contribute to water turbidity increase backscatter, change the light spectral distribution, and reduce average path length of the light. This leads to high reflectance in both visible and infrared wavelengths for water bodies with high turbidity (Moore *et al*., 1980; Dogliotti *et al*., 2015; Gidudu *et al*., 2017). Hence it is important to consider seasons when mapping turbidity in water systems, especially in areas, like Rwanda, where turbidity predominantly occurs as a result of silt and sediments runoff during the rainy season (Gidudu *et al*., 2017).

These results revealed a relationship between water turbidity and water hyacinth distribution in Rwandan rivers but there was no strong relationship between estimated water turbidity in the lakes and water hyacinth coverage in lakes. This was probably due to high variability in both water turbidity and water hyacinth coverage in the lakes. Where turbidity is high in both the dry and wet season, water hyacinth coverage is high. This is further investigated in Chapter 5. Turbidity is driven by sediments, soil silt and other dissolved organic matter that are known to enhance the multiplication of macrophyte plants (Kisson *et al*., 2013), which can constrain a control programme for water hyacinth. This constraint could operate through increased plant growth or direct effects on the biocontrol agents. This was investigated in details in chapter 5 by using estimated levels of turbidity from remote sensing and field measures to investigate impact of turbidity on water hyacinth growth as well as its biological control agent *Neochetina eichhorniae*.

**Implications of the study**

Remotely sensed imageries have been successfully used to assess water quality indicators and to determine their spatial distribution worldwide (Dube *et al*., 2015; Gholizadeh *et al*., 2016; Joshi *et al*., 2017, Abdelmalik, 2018). However, Rwanda has not embraced this technique because of cost and the technical expertise required. Thus, the results in this study indicate that the free Landsat 8 could provide datasets that can be used to detect turbidity, nitrogen, phosphorus and temperature; and determine their spatial distribution in Rwandan water bodies. Landsat 8 was used to map the aforementioned water parameters in more than 10 water bodies, which would have been difficult or even impossible using the traditional field survey methods. The predicted levels of water parameters in dry season were not high, except for turbidity levels in Akagera River, which were higher than the country standard turbidity levels (<16 NTU). In the wet season, the levels of all the investigated water parameters increased because of heavy erosion that causes soil runoff into rivers and lakes (RNRA, 2012, Karamage *et al*., 2016). Normally,

rainfall is the major cause of spatial variability of water quality parameters (McDowel and Trudgil, 2000; Simard *et al.*, 2000), and in regions where erosion is the key influence on soil runoff into water bodies, the magnitude and levels of water quality indicators also increase (Simard *et al.*, 2000). Thus, the results of the current study confirm the literature stating that the water quality in Rwandan water is exacerbated during the rainy season (RNRA, 2012; Karamage *et al.*, 2016). Since 2010, the Rwandan government has been committed to protect and manage its water resources (RNRA, 2012). To achieve this, the government has encouraged non-governmental organizations and research institutions to participate in the activities of water resource management. Studies that investigated water quality parameters in the country used field surveys and water sample analysis in laboratories collected at specific points or sites (Nhapi *et al.*, 2011; Aboniyo *et al.*, 2017; Dusabe *et al.*, 2019). None of these studies could give either the spatial or temporal view of turbidity, nitrogen, phosphorus, temperature or other parameters that the current study did. It is crucial to have a synoptic view of water quality parameters in each part of a certain water body (Ritchie *et al.*, 2003; Dube *et al.*, 2015). Thus, the current study suggests considering remote sensing techniques for accurate evaluation and management of Rwandan water systems.
The combination of these results with those from chapter 2 reveals a link between the distribution of water hyacinth and its extent in Rwandan water bodies with abiotic water parameters. Rivers with extensive water hyacinth coverage are those with higher levels of nutrients, turbidity and temperatures. This shows that aforementioned water parameters contribute to water hyacinth proliferation in Rwandan water bodies.

Although Landsat 8 mapped water quality indicators in the examined Rwandan water bodies, it is important to understand its challenges. Among those challenges are extensive cloud covers in some regions of the country, because cloud cover does not allow satellites to properly capture water properties. This challenge was notable in the region of the Northern Province of the country. The Mukungwa River and the upper pary of the Nyabarongo River were not included in this study because of high cloud cover. The same problem was encountered when looking for usable images from December, April and May, which could have been used to determine the level of these water parameters during these months of the wet season.

## Conclusions

This chapter aimed to map the spatial distribution of water quality indicators using Landsat 8 data and to determine their contribution to water hyacinth distribution in Rwandan water bodies. The results revealed that Landsat 8 offers an effective tool to assess turbidity, nitrogen, phosphorus and temperature, which are essential indicators of water quality. All water parameters increased in November, during the wet season. The three main Rwandan rivers are more turbid and have higher levels of nitrogen and phosphorus than the lakes. The longest Rwandan river, the Akagera River, is more turbid and nutrient enriched, especially during the wet season than other rivers. Landsat 8 was able to provide a spatial and temporal view of nitrogen, phosphorus and temperature and turbidity in the Rwanda rivers and lakes, and this study suggests that using satellite data will help achieve the country's goal of sustainable development in terms of monitoring and managing water resources. Remote sensing techniques will not replace in-situ measurements of water quality in the Rwandan lakes and rivers but will provide fast and reliable means of assessing the indicators of water quality and determine their spatial distribution. To achieve good monitoring of water resources in Rwanda, policy makers, research institutions and the Rwandan Natural Resource Management should consider remote sensing techniques when assessing water quality in the country. These results can be used by both government and non-governmental organisations involved in weed control. On other hand, the water catchmentsin Rwanda need to be protected, erosion needs to be reduced; fertilizer and pesticide use need to be reduced. The following chapters (Chapters 5, 6 and 7) focused on the effect of water parameters nutirents, temperature and turbidity on biological control of water hyacinth with the purpose of investigating the feasibility of biological control of water hyacinth in Rwanda.

# CHAPTER 5:

# THE EFFECT OF WATER TURBIDITY ON THE ESTABLISHMENT AND PERFORMANCE OF *NEOCHETINA EICHHORNIAE* (WARNER) (COLEOPTERA: CURCULIONIDAE), A BIOCONTROL AGENT OF WATER HYACINTH

***This chapter has been prepared to be submitted to the peer review International Journal***

**ABSTRACT**

Water hyacinth (*Eichhornia crassipes*) (C. Mart.) Solms (Liliales: Pontederiaceae) has been the target of nine biological control agents in South Africa including *Neochetina eichhorniae* (Warner) (Coleoptera: Curculionidae). Both *Neochetina* weevils have also been released against water hyacinth in Rwanda, but failed to control the weed, possibly as a result of high water turbidity levels in water. This study, therefore, investigated the influence of water turbidity on the performance and establishment of *Neochetina eichhorniae* in Rwanda. Turbidity levels were measured over two seasons in four Rwandan rivers and two lakes. Thoses values were then used in laboratory trials to investigate the effect of turbidity on the weevils' development. Water hyacinth plants were maintained in clear water and at three different turbidity levels: high [1500 Nephrometic Turbidity Unit (NTU)], medium (600 NTU) and low (85 NTU) for both treatment and control componets. There were ten tubs for clear water, and ten tubs for each turbidity level making a total of 40 tubs for the treatment and 40 tubs for the control components. Each treatment had one water hyacinth plant with three *Neochetina eichhorniae* larvae inoculated into the petioles of water hyacinth, one larva per petiole of leaf position1, leaf position 2 and leaf position 3 from the centre of plant outwards, while the control plants were free of insects. In total, 30 larvae were inoculated into the treatment plants for each turbidity level and the clear water treatment. Plant growth parameters were measured weekly for three months, while adult emergence was observed and recorded from the 56$^{th}$ day of the experiment. 24 emerged adults of *N. eichhorniae* were found from plants grown at clear water treatment, 21 were from the low turbidity treatment, 12 were from the medium treatment, while no emerged adults were found at high turbidity. Weevil larvae pupate on submerged the roots of water hyacinth and may be affected by the low dissolved oxygen recorded in the water at high and medium turbidity levels. In contrast, the wet plant weight, numbers of leaves, and length of petiole were significantly enhanced by increased water turbidity. Larval feeding was higher on plants growing in clear water and the low turbidity (to be checked) compared to medium and high turbidity treatments. The implications of this study are that *N. eichhorniae* may not establish or perform well in water bodies with high levels of turbidity, which in turn enhances the growth of water hyacinth.

**Key words**: Water turbid, biomass removal, leaf turnover; insect feeding, pupation, dissolved oxygen, insect emergence.

## 5.1 Introduction

Water hyacinth is known as the most notorious aquatic weed worldwide (Annang, 2012; Waithaka, 2013; Honlah *et al.*, 2019). Every year enormous amounts of money and effort are expended globally to reduce its impacts using physical, chemical, or biological control methods (Gutiérrez *et al.*, 2001; Byers *et al.*, 2002; Hill, 2003). However, only biological control is deemed sustainable to control water hyacinth invasions (Charudattan, 1998; Hoelmer and Kirk, 2005; Ray and Hill, 2012). Nine agents have been released to control water hyacinth worldwide (Coetzee *et al.*, 2011), with *Neochetina eichhorniae* (Warner) (Coleoptera: Curculionidae) being the first and the most common agent. The host-specific weevil feeds on the leaf lamina, petioles and stem bases (Spencer and Ksander, 2004). The larvae tunnel through the petiole toward the crown of the plant and destroy the petiole tissue (DeLoach and Cordo, 1976; Forno, 1981; Jianqing *et al.*, 2002), creating entry points for pathogens that lead to plant necrosis and subsequent death (Ripley *et al.*, 2008). After the third instar, larvae of *N. eichhorniae* migrate to the roots of the water hyacinth where they pupate (DeLoach and Cordo, 1976). The adults feed on the leaves of water hyacinth, creating characteristic feeding scars that reduce the plant's photosynthetic area (Franceschini *et al.*, 2010; Soti and Volin, 2010). Although *Neochetina* weevils can have a devastating effect on water hyacinth populations (Jayanth, 1988), they can be constrained by abiotic factors such as extreme temperatures, nutrients and turbidity levels. For instance, extremely cold conditions reduce the rate of development and growth, and subsequently, the weevil's population (Julien, 2001). Similarly, temperatures higher than the optimum 30°C reduce the weevil's egg production efficacy (Julien, 2001; Oke, 2008). Under eutrophic condition, water hyacinth plants are capable of compensating for the damage caused by the biocontrol agents, while their growth rates are at an optimal level (Bownes, 2008; Mukarugwiro *et al.*, 2018). This contributes to minimal effects of biocontrol agents on water hyacinth invasion as well their total failure (Coetzee and Hill, 2012).

In the case of Rwanda, despite the warm climatic conditions (Ntwari *et al.* 2017) and few eutrophic water systems (Usanzineza *et al.*, 2011), *Neochetina* weevils released against water hyacinth weeds in 2000 have failed to control the weed (Moorhouse *et al.*, 2001). However, the weevils were able to control water hyacinth in neighbouring countries such as Kenya, Uganda and Tanzania with similar climatic conditions to Rwanda (Mwende and Njoka, 2005; Wilson *et al.,* 2007).

Elevated water turbidity levels can negatively affect the lives of different aquatic organisms (Kjelland *et al.*, 2015), and the failure of the *Neochetina* is thought to be caused by the impacts of high water turbidity levels on the growth and life cycle of the weevils. Rwandan surface water systems are often affected by silt deposition carried by runoff from the adjacent hilly landscapes, particularly during the rainy season (REMA, 2009). Soil silt is known to increase water turbidity, which has a detrimental impact on aquatic organisms (Dunlop *et al.*, 2005; Kjelland *et al.*, 2015). Thus, investigating the impact of water turbidity on the reproduction and life cycle of the water hyacinth weevils such as *N.eichhorniae* might help to understand why these biocontrol agents failed to substantially reduce and control the water hyacinth population in Rwanda surface water bodies.

### 5.1.1 Description and characterization of water turbidity

Turbidity is described as a measure of water clarity in water bodies (Alcantara *et al.*, 2010). It is caused by the presence of suspended and dissolved organic and inorganic matter in the water column (ASTM International, 2003; Alcantara *et al.*, 2010). Turbidity is one of the water parameters used for measuring water quality to determine its health status for aquatic organisms (Davies-Colley and Smith, 2001; Alcantara *et al.*, 2010). It is usually measured in Nephelometric Turbidity Units (NTU), which are used as a surrogate for the less easily measured suspended sediment content (Davies-Colley and Smith, 2001). There are two types of turbidity in water systems: (i) Sediment turbidity that is influenced by runoff from a watershed and is usually soil runoff because of soil erosion, especially in regions of high hills and mountains (Stortz *et al.,* 1976; Uncles *et al.*, 1994; Li and Zhang, 1998). (ii) Algal turbidity that is caused by other water parameters such as eutrophication (high concentrations of nitrogen and phosphorus) and elevated temperatures (Paerl and Huisman, 2008). Agricultural activities, construction, deforestation, and exploitation of natural resources are some of the common causes of sediment and nutrient influxes into aquatic ecosystems (Baker and Richards, 2002; Ouyang *et al.*, 2005). The former is, however, the leading contributor to large amounts of sediment and nutrients that increase phytoplankton blooms (Heisler *et al.*, 2008). The effects of climate change are another factor that alters the turbidity regime of aquatic systems, either through changes in precipitation leading to alteration in runoff cycles from the surrounding watershed or through increasing temperatures affecting the timing and intensity of algal blooms (Samal *et al.*, 2013).

### 5.1.2 The impact of water turbidity on aquatic organisms

Water turbidity is caused by the presence of dissolved and suspended matter for instance soil silt, clay, finely divided organic matter, phytoplankton and dyes and organic acids (Myre and Shaw 2006). It is considered as a major contributor to the decrease in the diversity of aquatic organisms in ecosystems (Henley *et al.*, 2000). This is because (i) high turbidity in water reduces light penetration and the oxygen necessary for the growth of aquatic organisms. Reduction of light penetration negatively impacts photosynthetic organisms, which ultimately disrupts food webs and decreases populations in ecosystems (Lunt and Smee, 2014). (ii) The suspended matter in water binds directly with biological membranes, especially in fishes and aquatic insects that use gills for respiration, eventually killing them by asphyxia (Bond and Downes, 2003).

High turbidity levels have a direct physiological effect on aquatic organisms (Henley *et al.*, 2000). Ye-Ebiyo *et al.* (2003) found that the settled silts and organic matter at the bottom of rivers or streams smothered the eggs of aquatic insects and suffocated newly hatched larvae as well as insect pupae. Thus, there is a high probability that turbidity in Rwanda water systems could affect *Neochetina* weevils. This could be due to sediments covering the roots of water hyacinth, directly smothering the pupae of the weevils by reducing the dissolved oxygen level in the water (Visalakshy and Jayanth, 1996). This may suffocate the pupae, reducing the adult emergence and eventually the weevil's population (Tindall *et al.*, 2013). Surface water systems in Rwanda are heavily affected by high turbidity (Figure 5.1) as a result of silt deposition originating from heavy soil erosion and agricultural runoff (Muhirwa *et al.*, 2010; Nhapi *et al.*, 2011). Turbidity levels vary seasonally, depending on the biological activities in the water column and surface runoff carrying soil particles (Nhapi *et al.*, 2011). However, heavy rainfall is a major contributor to high turbidity levels in Rwandan water bodies (REMA, 2011).

Figure 5.1: Silt and dissolved organic matter from agricultural runoff in the Nyabarongo River, Rwanda (Photo of December, 2016).

An increase in turbidity results in the reduction of fish production in some Rwandan lakes, especially those in the Bugesera district, due to sediments and other soil materials carried along the Nyabarongo River (REMA, 2011). This has affected the socio-economic status of the local communities who depend on fishing for their livelihood. It is also believed that the high turbidity levels of these water systems could be the reason for the poor performance of the *Neochetina* weevils released in 2000 to control the water hyacinth infestation in Rwanda.

The aim of this study was to determine the effect of water turbidity on the success of the *Neochetina* weevils on water hyacinth.

The following questions are addressed in this chapter:

- Can turbidity affect the development and survival of *Neochetina eichhorniae*?
- Can elevated turbidity affect bettle feeding on water hyacinth?
- Is the high turbidity in the Rwandan water system one of the reasons behind the failure of *Neochetina* weevils?
- Can elevated turbidity affect water hyacinth growth?

## 5.2 Methods and materials

The study involved fieldwork to record water turbidity in selected Rwandan water bodies and laboratory experiments to test the effects of different turbidity levels on the feeding and establishment of *N. eichhorniae* on water hyacinth

### 5.2.1 Field work

Fieldwork was conducted from July to December 2016. Surveys were carried out twice a month at sampling sites in the Mukungwa, Nyabarongo, Akagera Akanyaru Rivers and Lake Rweru and Lake Hago (Figure 5.2). This selection was based on the distribution of water hyacinth and its extent in the Rwandan water systems (see Chapter 2). The number of sampling sites on each river varied because the rivers have different lengths and widths. There were 9 sampling locations for Mukungwa River (the smallest river), 15 sampling sites for each of Nyabarongo, and Akanyaru Rivers, and 30 sampling sites for the Akagera River (the longest river in Rwanda); while 10 sampling sites were chosen for each of Lake Rweru and Lake Hago. For all sites, sampling points were chosen according to accessibility and presence of water hyacinth in river or lake. At each site, turbidity was detected using a handheld portable Secchi disc, according to McCluney (1975).

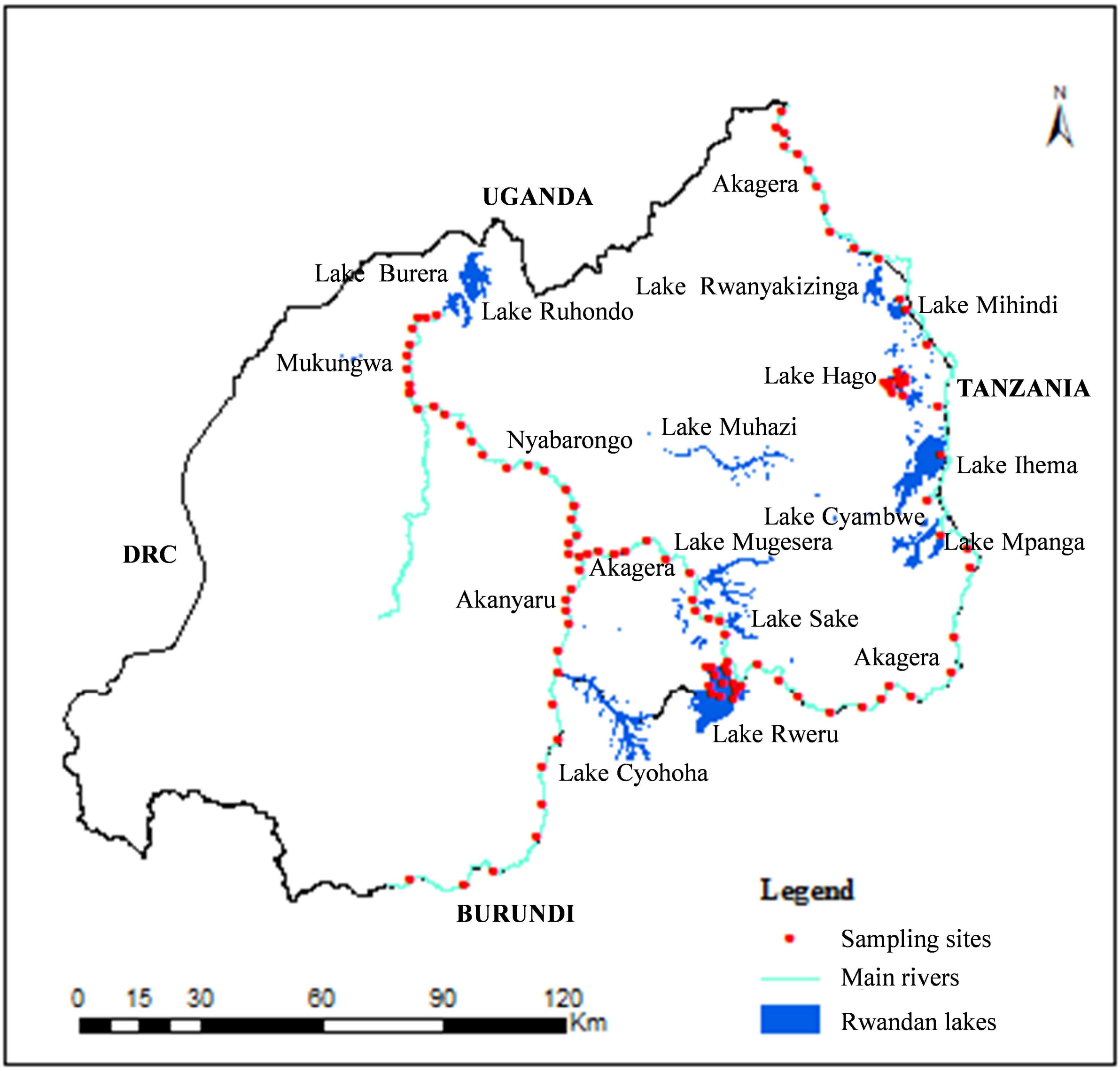


Figure 5.2: Map of Rwanda showing the sampling sites in the lakes and rivers where turbidity was measured.

Thereafter, the mean values of water turbidity recorded in the abovementioned selected Rwandan water system were calculated and turbidity levels were categorized according to the worldwide turbidity classification system as high (>1000 NTU), medium (950 to160 NTU) and low (150 to 6 NTU) (Table 5.1) (UNEPGEMS, 2007).

Table 5.1: The mean values of water turbidity levels (NTU) taken during the dry and rainy seasons, 2016 from each of the four main rivers and two lakes in Rwanda.

| Water Bodies | Turbidity (NTU) in dry season (Dry seaon | | Turbidity (NTU) in wet season (Rainy season) | |
|---|---|---|---|---|
| | Mean | Standard deviation | Mean | Standard deviation |
| Mukungwa River | 10.6 | ±5.18 | 264.5 | ±62.16 |
| Nyabarongo River | 103.5 | ±18.78 | 1732 | ±329.26 |
| Akanyaru River | 73 | ±12.57 | 1256.5 | ±211.73 |
| Akagera River | 94 | ±25.34 | 1861.5 | ±459.85 |
| Rweru Lake | 29 | ±3.02 | 301.5 | ±46.98 |
| Hago Lake | 19.5 | ±1.61 | 149 | ±13.13 |

### 5.2.2 Laboratory work

#### 5.2.2.1 Oviposition and larval inoculation

Water hyacinth leaves obtained from water hyacinth cultured at University of the Witwatersrand were excised and placed in a small plastic tub of 0.5 litres with *N. eichhorniae* adults (15 females and 15 males) for oviposition. Three days later, the leaves were dissected under a stereo microscope to collect eggs. All materials (forceps and scalpel) used during leaf dissection were sterilized using ethanol. The eggs were then placed on wet filter paper in petri dishes and maintained at 25°C. The eggs were checked daily for hatching, which occurred approximately on the 11$^{th}$ day. Newly hatched larvae were inserted into small punctures made in the petioles of the experimental water hyacinth plants. The larvae were inoculated into the first, second and third leaf of each treatment plant, counting outwards from the centre of the plants. No larvae were added to the control plants, and thus, they were not punctured. This procedure whereby the plants were punctured or not but no larvae were inoculated has been found not to have any effect on water hyacinth growth (Bokotomba, 2017).

#### 5.2.2.2 Simulated turbidity conditions

Laboratory experiments were carried out at the University of the Witwatersrand over a period of three months. Healthy water hyacinth plants of the same size with five leaves per plant were obtained from stock cultures grown in pools at the University. The laboratory experiment was set up as follows: high = 1800 NTU, medium = 600 NTU, low turbidity = 85 NTU turbidity levels and clear water (no turbidity, approximately 2 NTU) for treatment and control components. These levels were chosen according to turbidity levels recorded in Rwandan water bodies selected for this study (Table 5.1). To prepare the aforementioned turbidity levels, clay soil was mixed with tap water as follows: for high turbidity, 13.5 kg of clay soil was mixed with 45 of tap water; for medium turbidity, 6.76 kg of clay soil was mixed with 45 L of tap water; and for low turbidity, 1.5 kg clay soil was mixed with 45 L of tap water. One water hyacinth plant was placed in each of 15 L tub filled with 10 L of water from each of turbidity levels prepared. There were ten tubs for clear water, and ten tubs for each turbidity level making a total of 40 tubs for the treatment and 40 tubs for the control components. Each treatment had one water hyacinth plant with three *Neochetina eichhorniae* larvae inoculated into the petioles of water hyacinth, one larva per petiole of leaf position1, leaf position 2 and leaf position 3 from the centre of plant outwards, while the control plants were free of insects. In total, 30 larvae were inoculated into the treatment plants for each turbidity level and the clear water treatment. Nitrogen and phosphorus (2.8 mg/l N and 0.4 mg/l P) in the form of Hoagland's solution were added to each tub to assist the plant and insect growth. Every week, 5mg/l of chelated iron was added to each bucket (treatment and control) to avoid iron deficiency. A pumping system with submersible fish tank pumps was installed in each tub to agitate and maintain the turbidity level of each treatment and control. The growth media of the turbid solutions were changed weekly for all tubs. Turbidity levels were also checked twice a week using a turbidity-meter (2001A) to maintain the same turbidity level throughout the period of the experiment. Nutrient levels (nitrogen and phosphorus concentrations) were also tested twice a week in each tub using a Hach colorimeter (DR/870). In addition, dissolved oxygen was measured three times a week using a Dissolved Oxygen Meter (YSI Pro 20, model 55).

### 5.2.3 Data collection

The tubs were distributed according to a randomization table for the six conditions in order to share the light equitably, and the tubs were swopped through the different positions three times a week over the course of the experiments. From the $34^{th}$ day of the experiment onwards, plants were checked for pupae every wee, since larvae pupate in the roots of water water hyacinth in 30 days under the nutrient conditions used in the experiment (Mukarugwiro *et al.*, 2018). From the $54^{th}$ day of the experiment, all tubs were covered with nets to prevent emerged adult escaping or moving from one tub to another. The numbers of emerging adults were recorded for all treatment plants growing in the different turbidity levels.

The effect of water turbidity on insect feeding was evaluated by recording the loss or gain of the wet plant biomass weekly. Plants were removed from the tubs and weighed after five minutes to allow water draining from the plant. Wet weight was utilised because it allowed continued use of all the replicates on each sampling occurrence. New leaves growing on each plant were tagged weekly to measure the rate of leaf production from each turbidity treatment. Hence, leaf turnover was obtained by comparing the number of leaves added or lost from each week with the initial number of leaves per plant. Furthermore, the length of the longest petiole was measured weekly for all treatment and control plants to determine the plant growth rate.

### 5.2.4 Data analysis

The number of emerged *N. eichhorniae* found at each turbidity level at the end of the experiment, was compared using one-way ANOVA. The percentage of emerged *N. eichhorniae* at each turbidity level was calcurated using total number of emerged *N. eichhorniae* found at each turbidity level and total number of larvae inoculated at each turbidity level. One-way ANOVA followed by Least Significant Test post-hoc, was used to compare the means of the water hyacinth growth parameters between turbidity treatments with larvae and controls (without larvae). Probit analysis was conducted to predict lethal turbidity ($LT_{50}$) at which 50% *N. eichhorniae* will emerge. The data for plant growth parameters (wet plant biomass, number of leaves, and length of petiole) for all the three turbidity regimes and clear water treatment were first subjected to normality tests to determine the distribution of the data and the suitable analysis method. Repeated measures ANOVA was used to compare the difference in the plant growth parameters between control and treatment plants over time using the Statistica Software (version 12.6).

Linear regression was used to explore the relationship between turbidity and other water parameters such as temperature, dissolved oxygen, nitrogen, and phosphorus measured during the experiments. The purpose of this was to investigate if turbidity could have an impact on other water parameters. In addition, linear regression was also used to explore the correlations between turbidity and water parameters measured during field surveys. All analyses were performed at p-value of 0.05.

### 5.3 Results

#### 5.3.1 Effect of turbidity on the development and survival of *N. eichhorniae*

The negative impact of high levels of water turbidity on weevil development was greater than that in the medium and low turbidity levels as well as in the clear water treatment (Figure 5.3). No adult emergence was found in the high turbidity treatment.

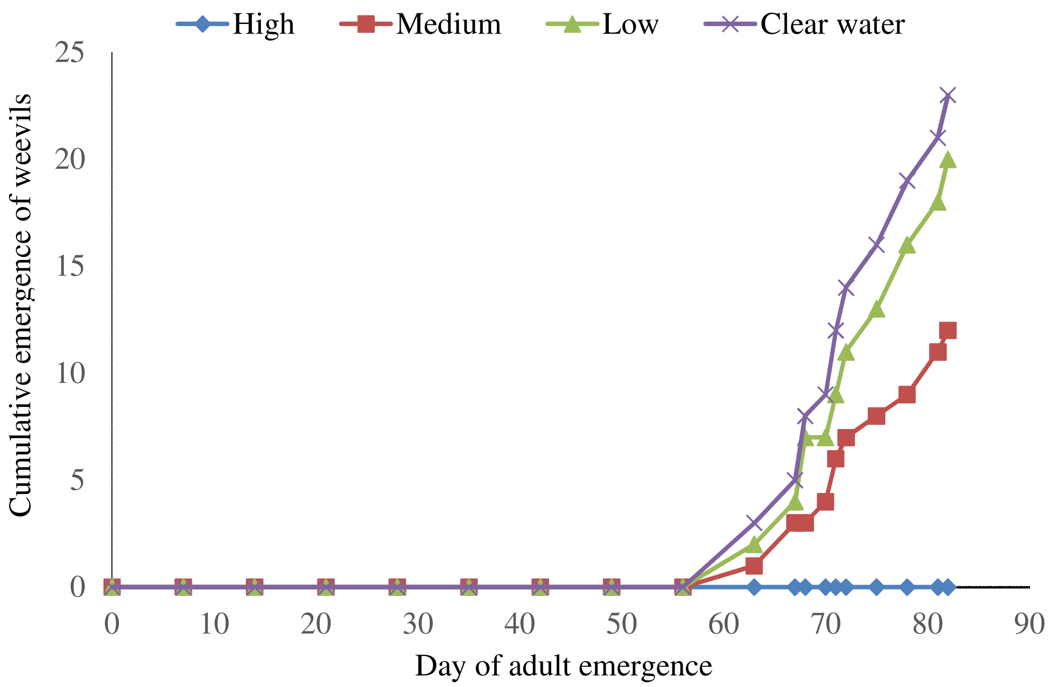


Figure 5.3: The effect of turbidity on the survival and emergence of *N. eichhorniae* weevils. The total number of adult emergences at each turbidity level (high = 1500 NTU, medium = 600 NTU, and low = 85 NTU) and clear water (2 NTU) treatments.

The percentage emergence of *N. eichhorniae* was highest from clear water, followed by low and medium turbidity levels, while at high turbidity treatment; there were no emerged adults (Figure 5.4).

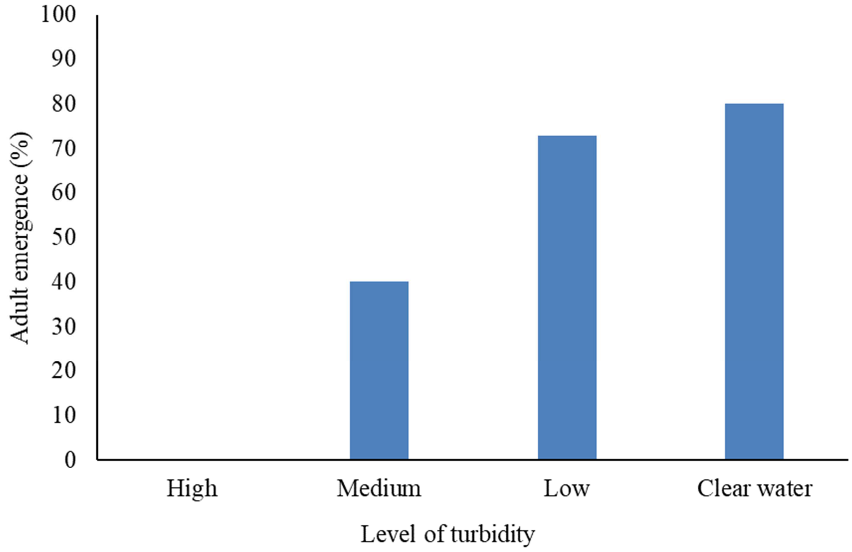


Figure 5.4: Percentage emergence of adult *N. eichhorniae* from water hyacinth grown at different turbidity levels (high = 1500 NTU, medium = 600 NTU, low turbidity = 85 NTU) and clear water (2 NTU) treatments.

The emergence (%) of adult *N. eichhorniae* was calculated from the number of larvae inoculated into the plants and total the number of emerged adult found at each turbidity level. In addition, a probit analysis showed that the lethal turbidity ($LT_{50}$) for *N. eichhorniae* immatures is 439.8NTU (Figure 5.5).

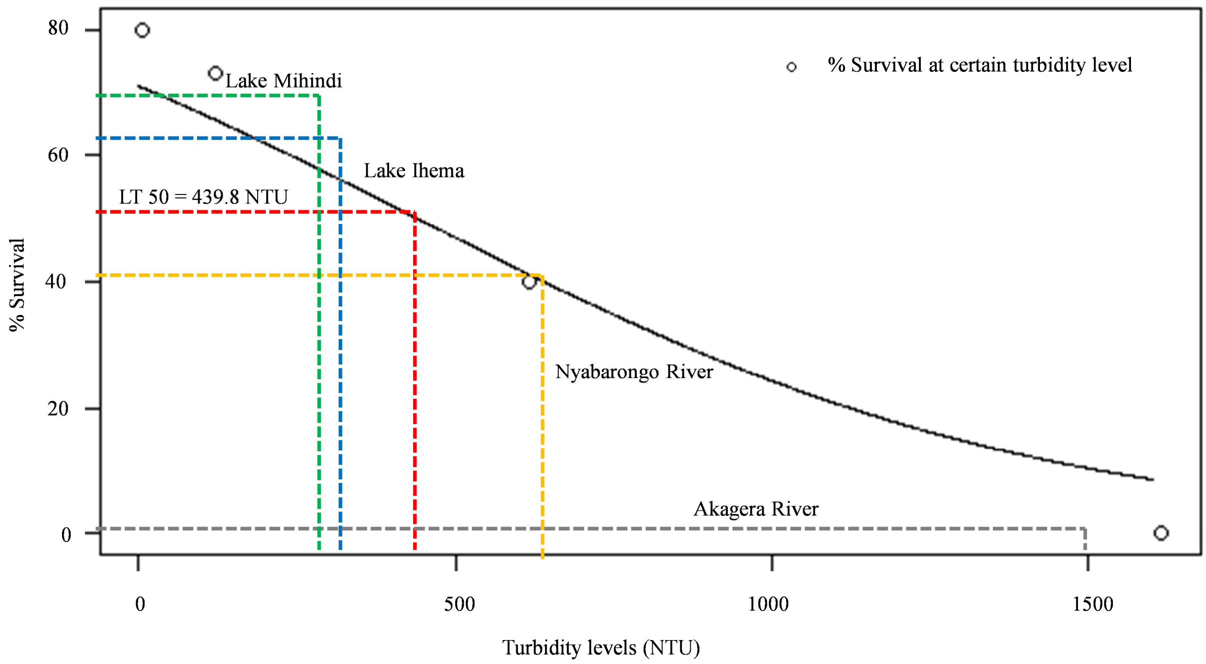


Figure 5.5: *N. eichhorniae* emerged adult survival (%) estimated using a probit function to predict lethal turbidity ($LT_{50}$), the turbidity at which 50% of *N. eichhorniae* will emerge and extrapolated to the turbidity levels found in Rwandan water bodies.

### 5.3.2 Effect of turbidity and *N. eichhorniae* on water hyacinth growth

All plants in the treatment group lost biomass except those plants grown at high turbidity levels, while the plants in the control group (without weevils) gained biomass (Figure 5.6). There were significant differences in plant biomass between the respective control and treatment groups at clear water ($F_{11, 198} = 205.93$, P = 0.003), the low turbidity ($F_{11, 198} = 92.064$, P = 0.001), medium turbidity ($F_{11, 198} = 29.892$, P = 0.001), and high turbidity ($F_{11, 198} = 19.34$, P = 0.001) levels. Comparison of plant biomass between the different treatments showed that the treated plants growing in clear water had a significantly greater loss of biomass ($F_{33, 396} = 36.396$, P < 0.01) than those grown at low, medium and high turbidity levels.

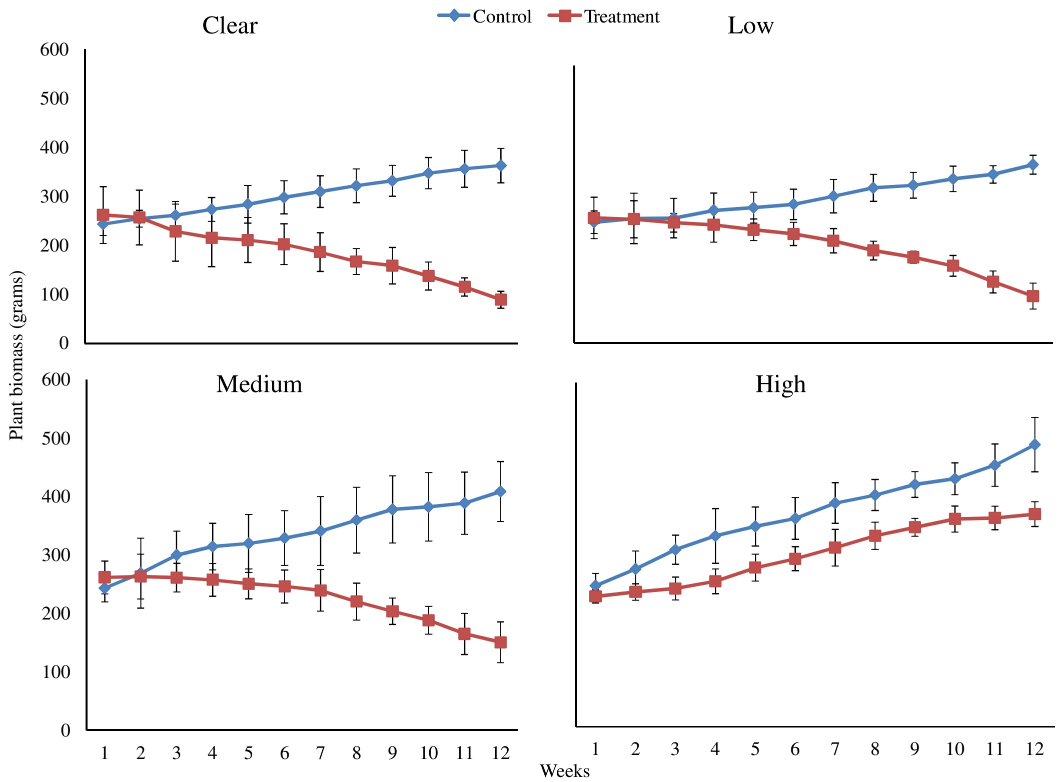


Figure 5.6: The effect of *Neochetina* weevils on water hyacinth biomass of plants grown at different turbidity levels, clear water = 2 NTU, low turbidity = 85NTU, medium turbidity = 600NTU, and high turbidity =1500NTU. Treatment plants had three *N. eichhorniae* larvae inoculated into them and control had none. Errors bars represent the standard errors of the mean.

The different turbidity levels as well as their respective interactions with the weevil showed a significant effect on the number of leaves per water hyacinth plant (Figure 5.7). The treatment plants in clear water and low turbidity levels lost more leaves ($F_{33, 396} = 7.512$, $P < 0.014$; $F_{33, 396} = 12.512$, $P < 0.02$ respectively) compared to those in the medium turbidity ($F_{33, 396} = 24.312$, $P < 0.034$), while the treatment plants in the high turbidity levels gained leaves (Figure 5. 7). Leaf turnover between the controls and treatments was significantly different in the clear water ($F_{11, 198} = 74.77$, $P = 0.001$), low turbidity ($F_{11, 198} = 50.488$, $P = 0.0022$), medium ($F_{11, 198} = 46.861$, $P = 0.014$) and high turbidity ($F_{11, 198} = 8.566$, $P = 0.045$) levels.

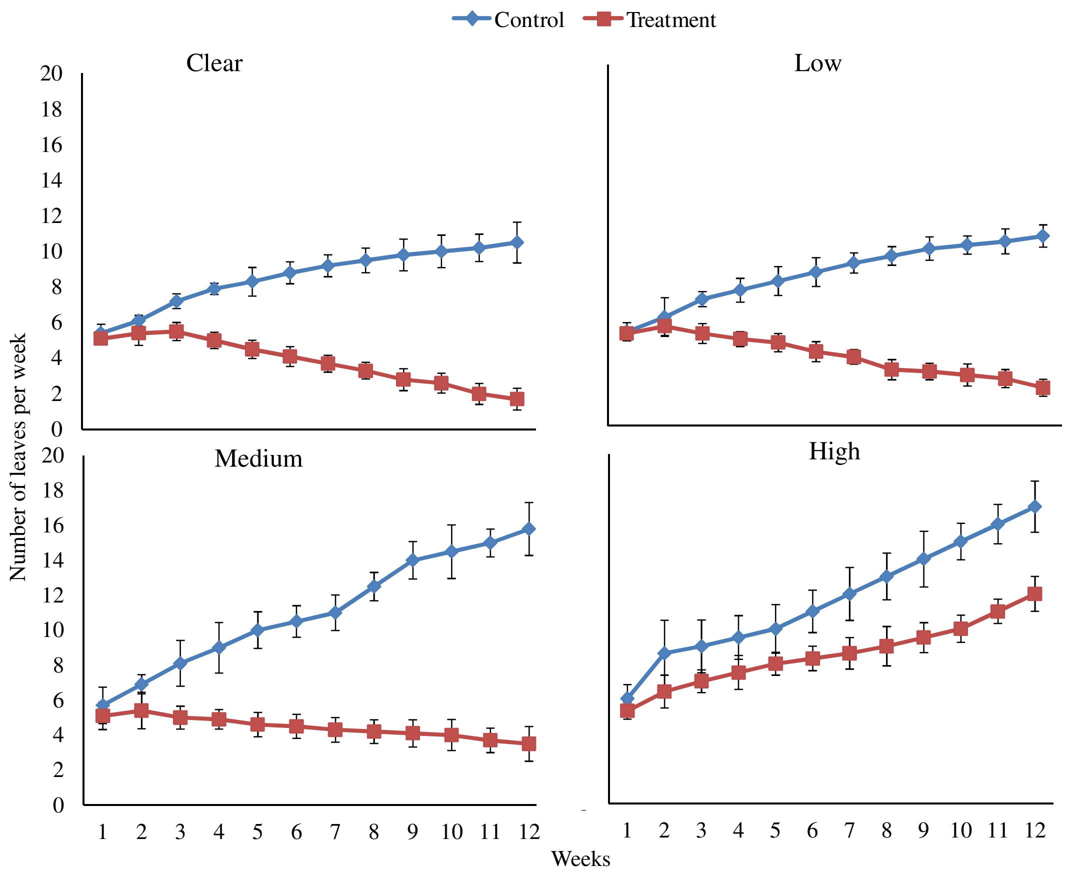


Figure 5.7: The effects of the water turbidity and *N. eichhorniae* feeding on water hyacinth leaves added or lost per week per plant, grown at different turbidity levels, clear water = 2 NTU, low turbidity = 85NTU, medium turbidity = 600NTU, and high turbidity =1500NTU. Treatment plants had three *N. eichhorniae* larvae inoculated into them and control had none. Errors bars represent the standard errors of the mean.

The length of the longest petiole increased in the controls and decreased in the clear water, low and medium turbidity treatments, but increased in the high turbidity levels (Figure 5.8). There was significant difference in length of longest petiole between control and treatment groups from week 4 to week 12 of the experiments in the clear water ($F_{11, 198} = 19.277$, $P < 0.012$), the low turbidity level ($F_{11, 198} = 27.726$, $P < 0.023$), medium turbidity level ($F_{11, 198} = 3.525$, $P < 0.042$), and high turbidity ($F1, 160 = 1.289$, $P < 0.05$).

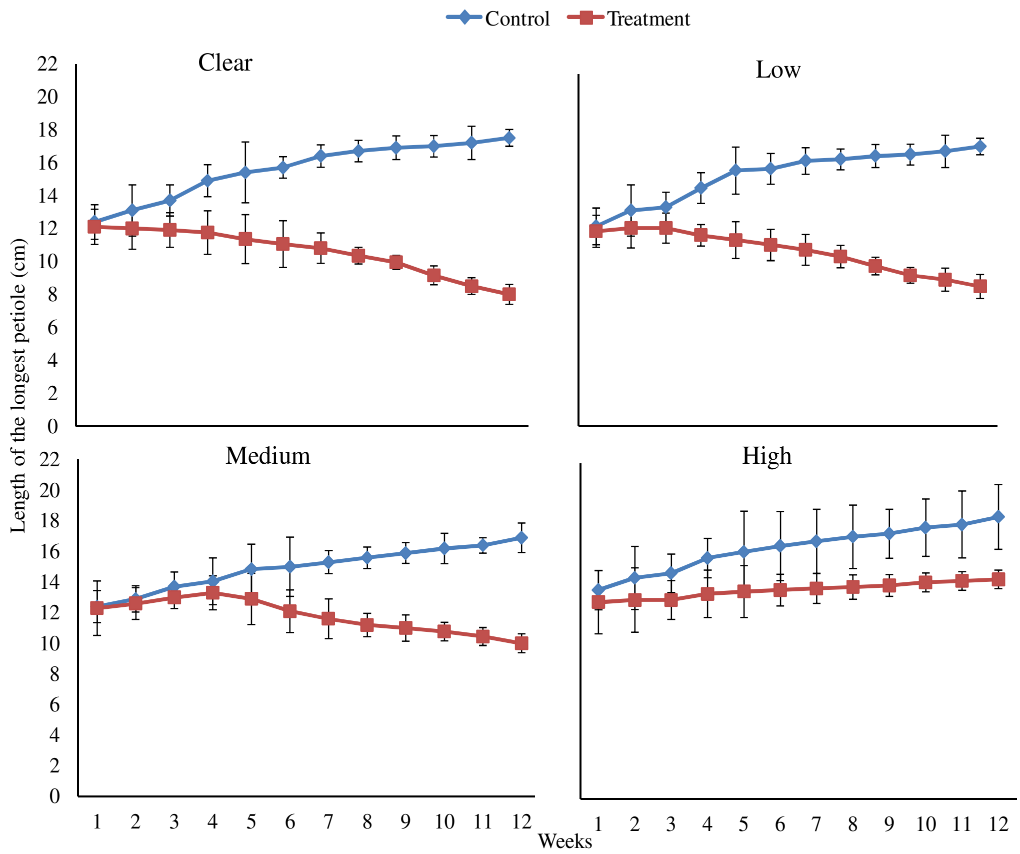


Figure 5.8: The effects of *N. eichhorniae* on the length of the longest petiole of water hyacinth grown at different turbidity levels, clear water = 2 NTU, low turbidity = 85NTU, medium turbidity = 600NTU, and high turbidity =1500NTU. Treatment plants had three *N. eichhorniae* larvae inoculated into them and control had none. Errors bars represent the standard errors of the mean.

### 5.3.3 Effect of turbidity on other water parameters

The increase in water turbidity in the laboratory trials and wet season field measures was associated with an increase in water temperature (Figure 5.9). Linear regression showed a strong positive relationship between turbidity levels and water temperatures in both laboratory and the field data from the wet season with $R^2$ = 0.95, but a weak relationship between turbidity and temperature recorded in the dry season with $R^2$ equal to 0.033 (Figure 5.9).

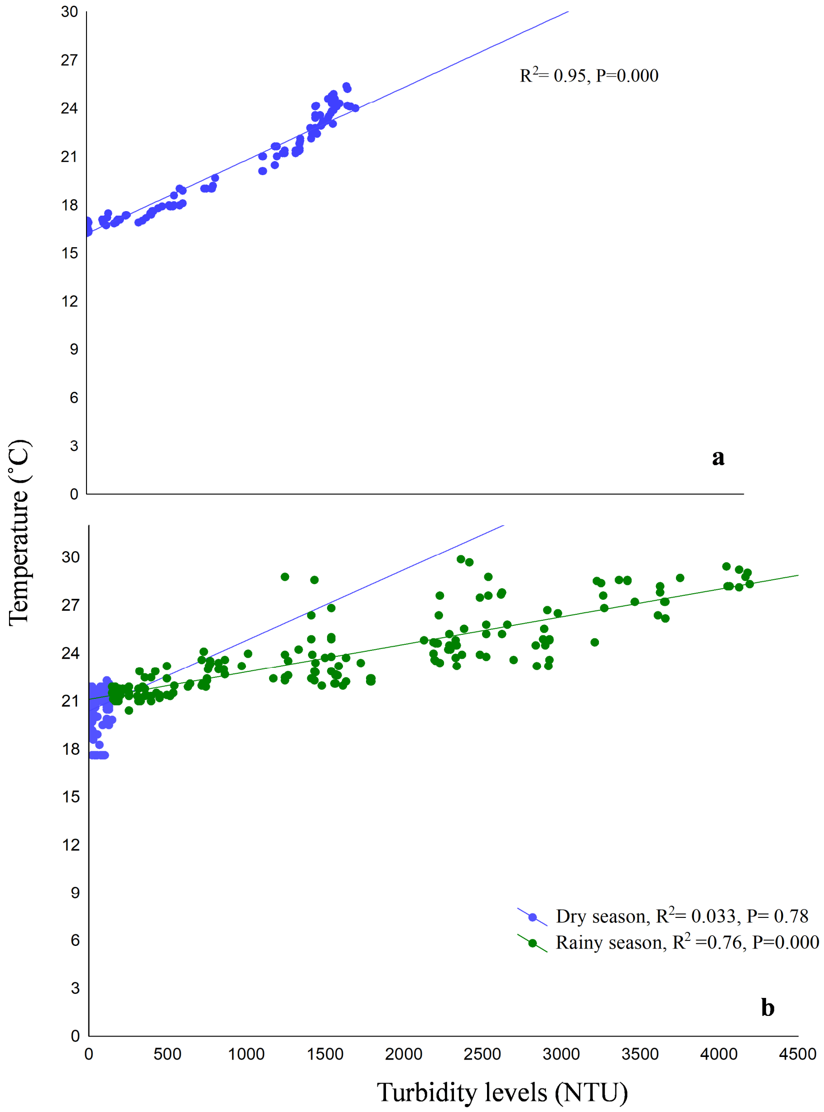


Figure 5.9: The relationship between turbidity levels and water temperature measured from (a) laboratory experiments and (b) field data from four Rwandan rivers and two lakes.

In contrast, there was strong negative linear relationship between turbidity and dissolved oxygen. This was observed in both laboratory experiments and field survey data for both seasons (Figure 5.10), and clearly indicated that as the water turbidity increased the dissolved oxygen decreased.

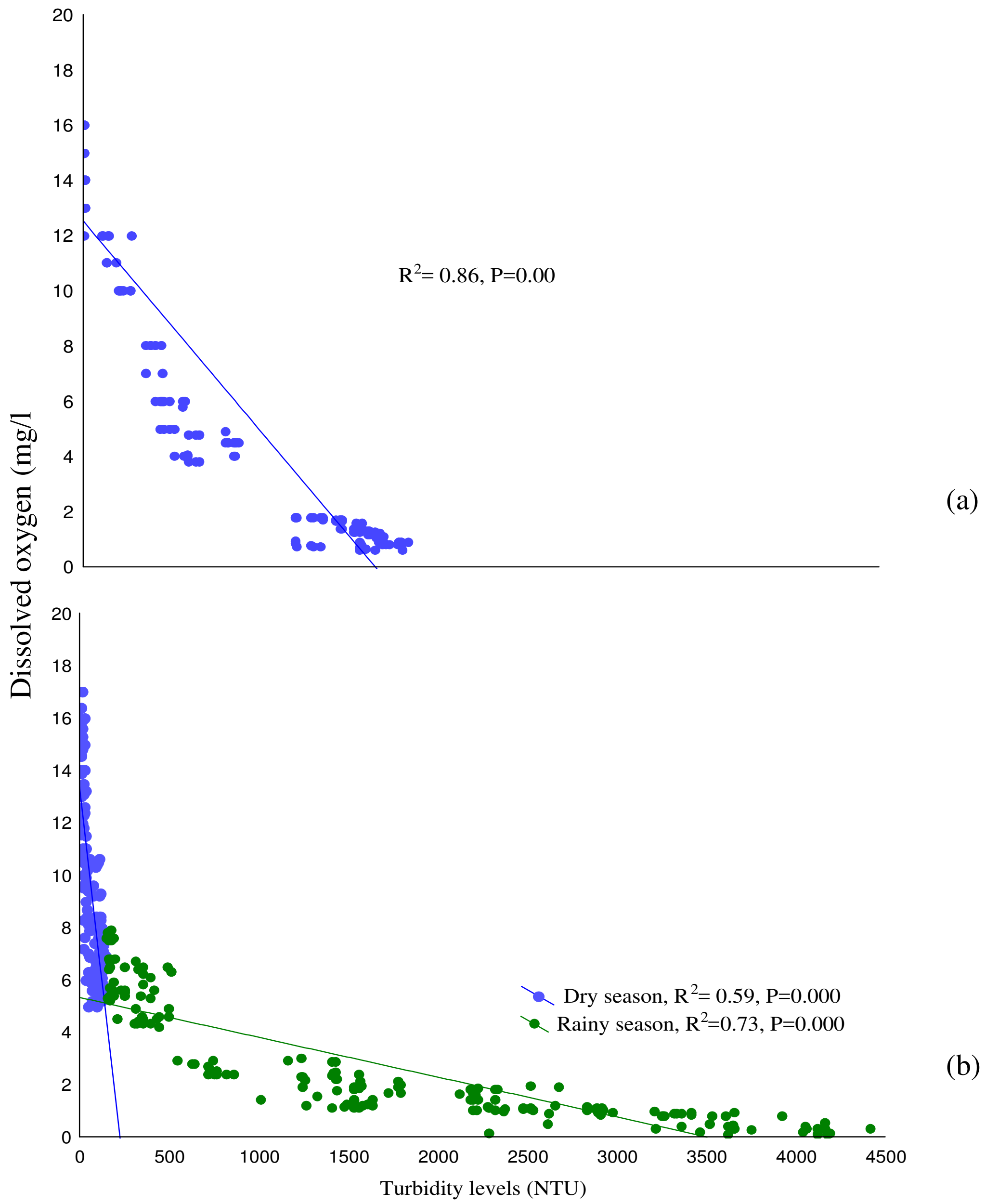


Figure 5.10: The relationship between turbidity levels and dissolved oxygen in (a) laboratory experiments and (b) field survey data from four Rwandan rivers and two lakes.

A strong positive relationship was found between turbidity and nutrient levels (both nitrogen and phosphorus) for laboratory and field data from the wet season. Nutrient levels in the dry season were relatively low (Figure 5.11 and 5.12).

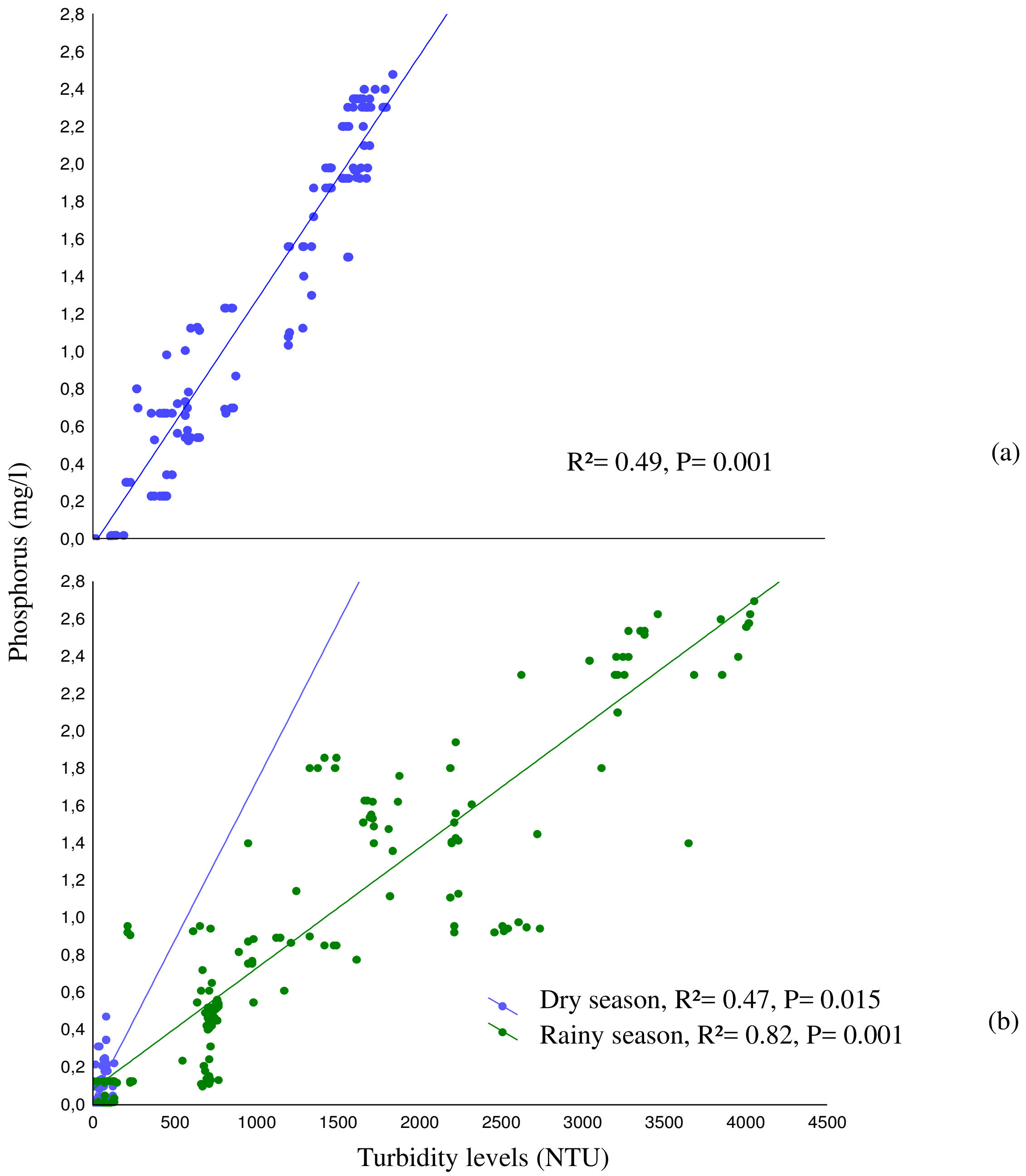


Figure 5.11: The relationship between turbidity levels and phosphorus concentration detected in (a) laboratory experiments and (b) field survey data from four Rwandan rivers and two lakes.

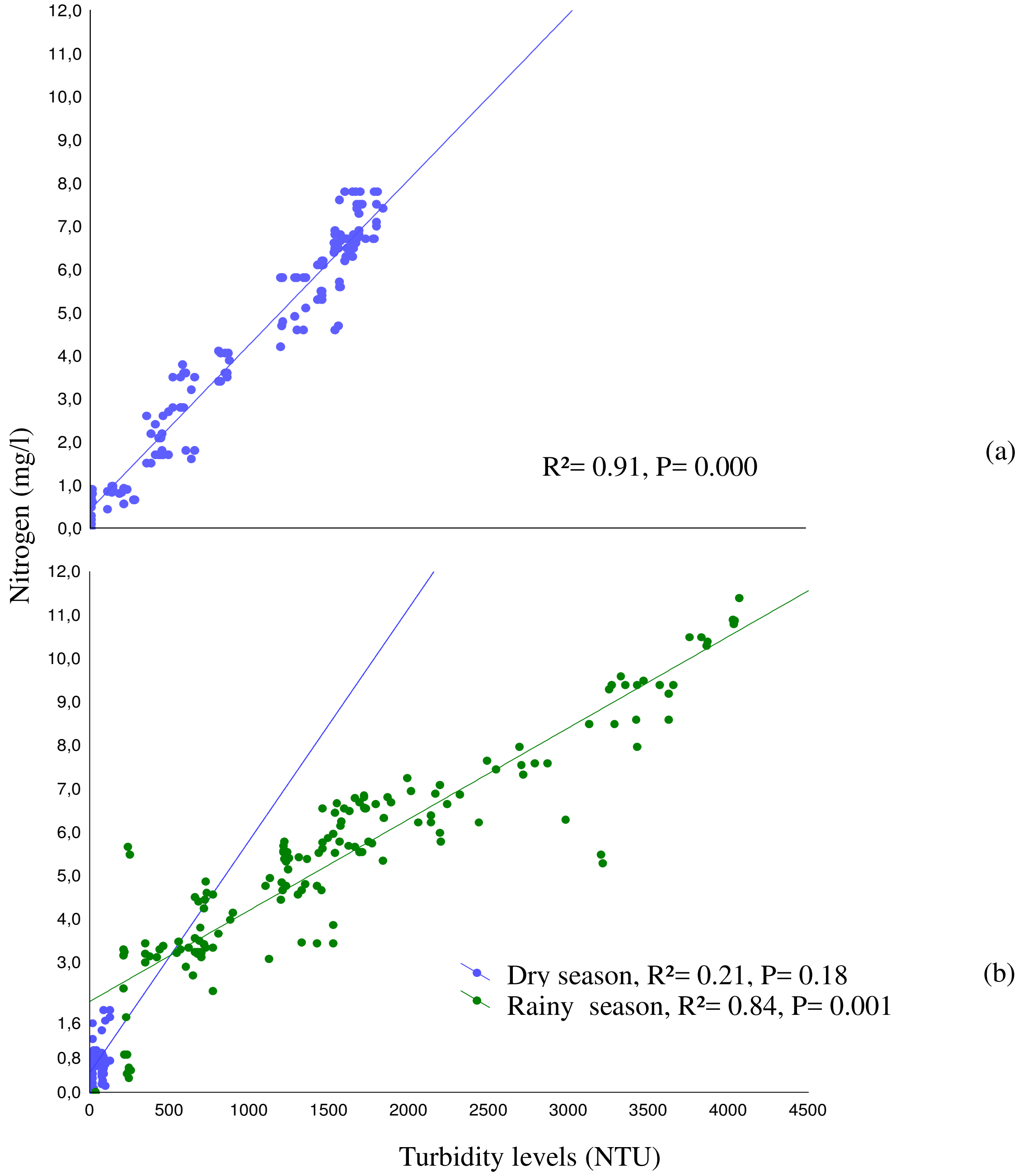


Figure 5.12: The relationship between turbidity levels and nitrogen concentration detected in (a) laboratory experiments and (b) field data from four Rwandan rivers and two lakes.

## 5.4 Discussion

### 5.4.1 The effects of water turbidity on the development of *N. eichhorniae*

This study revealed that high water turbidity (>1000 NTU) had a negative effect on the development of *N. eichhorniae* immature stages. It is clear that apart from temperature and nutrients, water turbidity is another parameter that constrains the efficacy of *Neochetina* weevils. Visalakshy and Jayanth (1996) investigated sediment and silt as the cause of low numbers of *Neochetina* weevils and low levels of feeding by weevils on water hyacinth in some invaded rivers and lakes in India. They found a low percentage (20%) of adult emergence on water hyacinth with roots covered by silt, and 70% emergence of adult weevils on the plants free of silt (Visalakshy and Jayanth, 1996). Although that study showed the effect of silt on *Neochetina* weevils' pupation, which prevented the third larval instar from reaching the pupal stage, it is not easy to compare it to the current study due to the difference in the setup of the two experiments. The study by Visalakshy and Jayanth (1996) did not indicate the level of turbidity used during the experiment, and did not indicate sample size, or looked at how different levels of silt and sediments affected pupation. The current study is therefore the second to document the detrimental effect of turbidity on the biological control agents of water hyacinth that pupate in the roots of the plant. Hence, the results are primarily compared to the results from other studies that investigated the effect of turbidity on other aquatic insects, such as mayflies, damflies and caddflies.

Studies by Lyimo *et al.* (1992), Bayoh and Harding (2000), Death (2000), Rowe *et al.* (2002), Lindsay (2003), and Ebenebe *et al.*, 2016) also found low survival of aquatic insects such as mayflies, damselflies, and caddisfliesn in water systems with a high turbidity (>1000 NTU). Results from laboratory work using three different levels of turbidity confirmed the absence of caddis flies at a high turbidity (>1000 NTU) (Armitage and Cannan, 2001; Rowe *et al.*, 2003). These findings also agree with the results in the current study, where the low dissolved oxygen content of 0.8–1.2 mg/l found in the tubs with a high turbidity levels (>1000 NTU) led to no emergence of adult *N. eichhorniae*. Wilson (2010) indicated that aquatic insects do not grow in water bodies with dissolved oxygen ranging below 2 mg/l, while between 2 mg/l to 4 mg/l insects struggle to develop. However, in dissolved oxygen above 5mg/l, or an oxygen saturation of >30%, aquatic insects grow in a normal way (Wilson, 2010). The current study found that low dissolved oxygen levels measured in the laboratory experiment and field survey were 0.8–2 mg/l and 0.1–2 mg/l, respectively) at the high turbidity level (2000NTU and above). At these dissolved oxygen levels, no *N. eichhorniae* adults emerged. On other hand, the dissolved oxygen (from 3–5 mg/l and 5–16mg/l) found in the medium, and low turbidity levels allowed the emergence of adults. This is supported by the results of probit analysis that showed that lethal turbidity ($LT_{50}$) of *N. eichhorniae* is 439.8 NTU. Therefore, *Neochetina* could establish in the Rwandan lakes (Figure 5.14) even in the wet season, as the highest turbidity recorded in the lakes is below 439.8 NTU. This result refutes the hypothesis that turbidity alone could be the reason behind the failure of *Neochetina* weevils released into the Rwandan lakes such as Lake Mihindi and Lake Ihema. Turbidity levels in the aforementioned lakes were lower than the lethal turbidity calculated in this study. Additionally, water turbidity in Rwandan lakes was also less than 150 NTU in 2002 (Nile Basin Initiative, 2005); and therefore, turbidity levels in the lakes should not affect the establishment of *Neochetina* weevils or their performance on water hyacinth. The failure of establishment was probably caused by the low numbers of *Neochetina* weevils released into each lake. Only 25 weevils were released per lake or river (Moorhouse *et al*., 2001). However, in the Nyabarongo River and the Akagera River, *Neochetina* weevils failed to control water hyacinth since they were not able to compensate their life cyle due to high turbidity that affected their pupation stage.

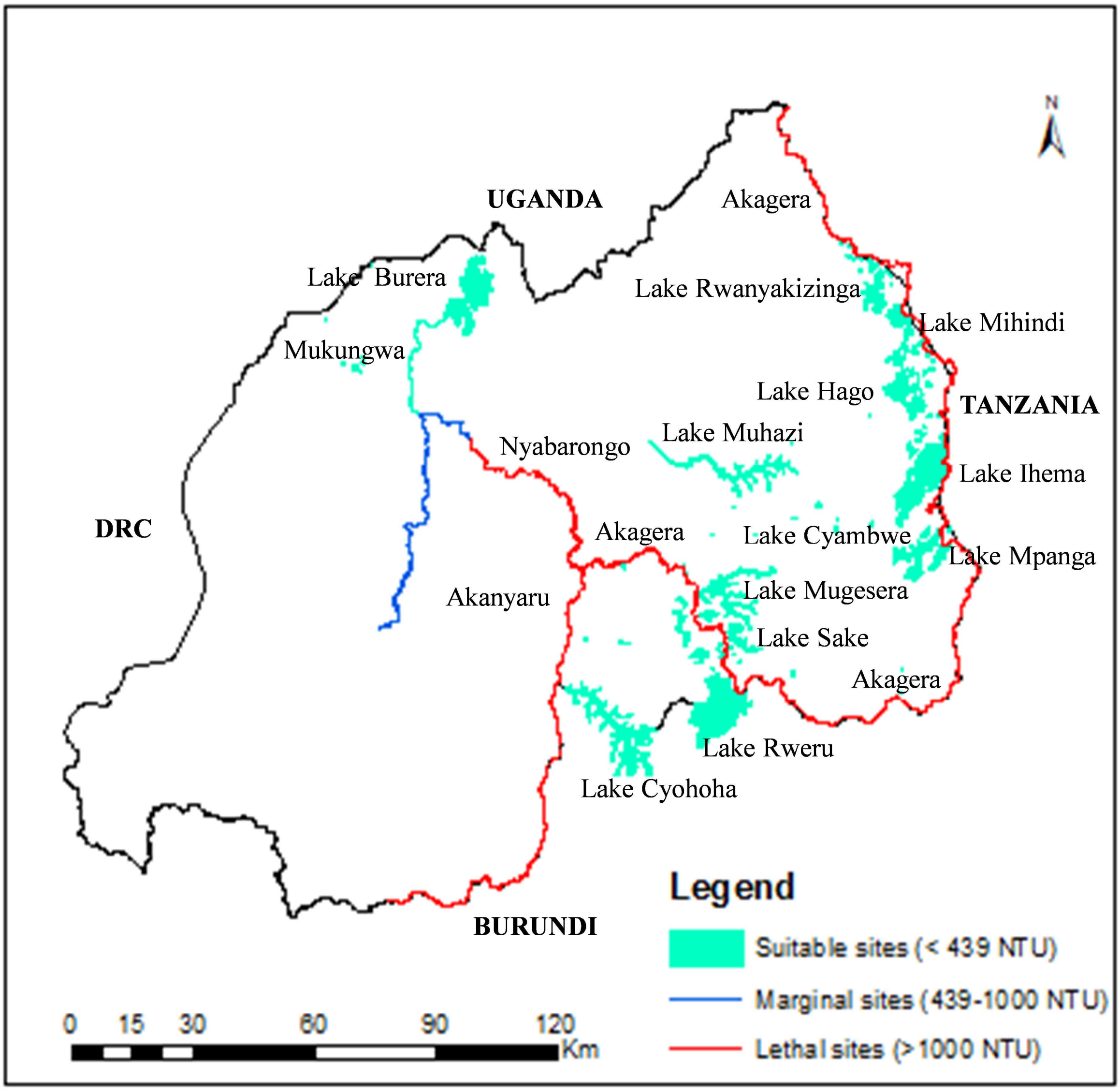


Figure 5.13: Rwandan water bodies' suitability for establishment of *Neochetina* weevils, based on measured turbidity levels.

### 5.4.2 The effect of turbidity on *N. eichhorniae* feeding on water hyacinth growth

In the biological control of invasive plants, the level of insect feeding on the target weed is an important measure of the efficacy of the biocontrol agents. The effect of feeding of *N. eichhorniae* on water hyacinth as measured by changes in plant weight, petiole length, and leaf number was high on the plants grown in the clear water, followed by plants in the low and medium turbidity treatments which all lost biomass. Plants in very turbid water, however, showed a gain in both biomass and number of leaves. *Neochetina* weevils consume less at high nutrient levels compared to medium and low nutrient levels (Mukarugwiro *et al*., 2018), and water hyacinth can easily compensate for the herbivore's feeding, faster than insect's ability to inflict sufficient damage that will suppress the plants' population (Bownes *et al*., 2013). Although the focus of this study was on water turbidity, the nitrogen and phosphorus content of the water from laboratory and field surveys showed a strong positive correlation with turbidity levels. This shows that water hyacinth plants in the high water turbidity were able to compensate for the insect damage and continue to grow, while the plants in the medium and low turbidity levels as well as in the clear water treatments could not compensate the feeding damage caused by *N. eichhorniae*.

Aside from nutrients, temperature has a great effect on the establishment of *Neochetina* weevils (King, 2012; Bokotomba, 2017). The fact that *Neochetina* weevils are able to develop and feed on water hyacinth grown at temperatures ranging from 15 ˚C to 30˚C (Bokotombo, 2017), it means that Rwandan temperatures would not be detrimental to *Neochetina* weevils (This was investigated in more detail in chapter 7).

Because turbidity increases during the wet season, bio-control practitioners, working with the Rwandan government should consider the role of the seasons in future releases of *Neochetin*a weevils. During the months of the dry season, *Neochetina* weevils should establish and perform well on water hyacinth. However, at low nutrient levels, the weevils take longer to develop, about 56 days from larvae to pupae (Mukarugwiro *et al.,* 2018) and 120 days from larvae to adult (Hamadina *et al*., 2015). Because the weevils will not be able to complete development before the end of the dry season, there is a high chance of them being affected by turbidity levels that often increase during the wet season from mid-September to end of December. Thus, *Neochetina* weevils should be released towards the end of wet seasons.

Although turbidity in water bodies has not received adequate attention in the area of biocontrol of aquatic invasive weeds, unlike other water parameters such as temperature and nutrients, this study has produced information on how water turbidity can constrain the efficacy of *Neochetina* weevils as biocontrol agents of water hyacinth. Water turbidity also directly or indirectly influences other water parameter that affects the insect's life cycle. Thus, considering the level of water turbidity before the introduction of any aquatic biocontrol agent, particularly those which partly or completely conduct and complete their life cycle below the water surface, is crucial. The results of this study can assist biological control practitioners in making decisions on the suitability of any potential biocontrol agents based on turbidity levels of the target water systems

**Conclusions**

Water turbidity affects abundance, survival, and diversity of aquatic living organisms. Turbidity has a detrimental effect on other abiotic factors, especially dissolved oxygen and temperature, which may also affect biocontrol agents and other aquatic organisms. This study showed that high turbidity levels (>1000 NTU) negatively affect *N. eichhorniae* development and establishment. It reduces weevils'feeding on water hyacinth and ability to control hyacinth infestations. The fact that the lethal turbidity (LT 50) is 439.5NTU, there is a high chance of *Neochetina* weevils' establishment in the Rwandan lakes but that they are unlikely establish in Rwandan rivers such as the Nyabarongo, Akanyaru and Akagera Rivers, with turbidity above 600 NTU.

For the Rwandan government, this study suggests that efforts in reducing agricultural runoff should be increased by emphasizing better farming practices, using terraces, contour ploughing and buffer zones around the rivers where riparian vegetation is preserved. To biocontrol practitioners, the study suggests (i) to consider Integrated Pest Management to control water hyacinth, particularly in main the rivers infested by water hyacinth. If this is not possible, biocontrol agents with all their developmental life-cycle stages occurring in the aerial parts of water hyacinth above the water surface such as *Megamelus scutellaris*, and *Cornops aquaticum* should be used. (ii) It is important to measure water turbidity levels before the release of any biocontrol agent.

# CHAPTER 6:

# THE EFFECTS OF WATER NUTRIENT LEVELS ON THE BIOLOGICAL CONTROL OF WATER HYACINTH

***This chapter was prepared to be submitted to the Journal of Biological Sciences***

**ABSTRACT**
Pollution of water bodies by nitrates and phosphates from agricultural and industrial activities facilitates the rapid growth of water hyacinth worldwide, and Rwanda is no expetion. The weed apparently benefited from the nutrient rich water systems in Rwanda and as a result became a serious challenge to the country. Although biological control of water hyacinth is sustainable, cost effective and no hazardous to the environment, it can be hampered by excessive nutrients in water bodies. This study investigated whether Rwandan water nutrient levels might hamper the efficacy of biocontrol of water hyacinth, prior to the inception of a new water hyacinth biological control programme for the country. Field surveys were carried out, measuring nitrogen and phosphorus levels in four main rivers and two lakes in Rwanda. This was followed by a meta-analysis of theses and published papers that investigated the combined effect of water nutrient levels on the efficacy of biological control of water hyacinth. The results show that three main rivers such as the Nyabarongo, Akanyaru and Akagera Rivers, are eutrophic and the Mukungwa River is not. Lake Rweru and Lake Hago surveyed in this study are oligotrophic and become mesotrophic during the wet season. Extrapolation of the Rwandan nutrient levels to the meta-analysis results revealed that nitrogen and phosphorus concentrations may not negatively affect biological control of water hyacinth. Nevertheless, water nutrients should always be monitored. A reduction of factors contributing to soil runoff into the rivers and limiting water pollution will contribute to the the improved efficacy of biocontrol agents.

**Key words**: biocontrol agents, extrapolation, meta-analysis, Nutrients, Rwanda

## 6.1 Introduction

Nutrient enrichment has long been known to be a threat to the health of freshwater systems, leading to many problems, including eutrophication (Bootsma and Hecky, 1993; Walmsley, 2000). This promotes rapid development of aquatic organisms and rapid decay of biological material in certain water systems (Walmsley, 2000; Van Ginkel, 2011). Very few countries have escaped the issues associated with increasing nutrients in their water bodies, and Rwanda is no exception (Organization for Economic Co-operation and Development, 1982; Thornton and Harding, 2005). Erosion, domestic sewage, agricultural activities, pasture operations, and urbanization all contribute to the pollution of water bodies and are key factors causing water eutrophication in Rwanda (Usanzineza *et al.*, 2011). Eutrophication is accelerated by the nutrient input from anthropogenic activities into water systems and is determined by measuring nitrogen and phosphorus concentrations in water (Khan and Ansari, 2005). Based on water nutrient levels, water bodies are categorized into four trophic groups, namely oligotrophic, mesotrophic, eutrophic and hypertrophic (Khan and Ansari, 2005). Oligotrophic water has a nitrogen concentration of 0.25 to 0.6 mg/l and a phosphorus concentration of <0.005–0.01 mg/l; mesotrophic water has a nitrogen range of 0.5–1.1mg/l and a phosphorus range of 0.01 – 0.03 mg/l, while anything above this is called eutrophic and hypertrophic (Khan and Ansari, 2005). These trophic groups are available in the South African Water Quality Guidelines (Table 6.1) (Byrne *et al.*, 2010).

Table 6.1: Average concentrations of nitrogen and phosphorus recorded in South African water systems (Byrne *et al.*, 2010).

| Status of water | Phosphorus concentration (mg/l) | Nitrogen concentration (mg/l) |
|---|---|---|
| Oligotrophic | <0.005 | <0.5 |
| Mesotrophic | 0.005–0.025 | 0.5–2.5 |
| Eutrophic | 0.025–0.25 | 2.5–10 |
| Hypertrophic | >0.25 | >10 |

Although, water nutrient levels from Rwandan water bodies have not yet been categorized into trophic groups, Rwandan water bodies are facing the challenge of eutrophication (Usanzineza *et al.*, 2011; RNRA, 2012). The Rwandan Natural Resource Authority reported that that average of concentration is 3.2mg/l for nitrogen and 0.56 mg/l of phosphorus. These nutrient levels may increase in the absence of effective intervention measures of management (Usanzineza *et al.*, 2011). Aquatic organisms, including plants, respond strongly to eutrophication (Khan and Ansari, 2005). For instance, the aquatic macrophyte water hyacinth grows exponentially with an increasi of nitrogen and phosphorus levels, spreading rapidly by displacing other co-existing aquatic plants (Hill, 2014), and its invasion is often considered as an indicator of eutrophication problems (Coetzee and Hill, 2012; Hill, 2014).

### 6.1.1 Water hyacinth and nutrients

The growth and multiplication of water hyacinth (*Eichhornia crassipes*) depends on water nutrient concentrations, particularly nitrogen and phosphorus (Reddy *et al.*, 1989; 1990; Gopal, 1987; Heard and Winterton, 2000; Xie *et al.*, 2004; Ripley *et al.*, 2006; Coetzee *et al.*, 2007; Stanley et al. 2007; Marlin *et al.*, 2013; Mukarugwiro *et al.*, 2018). Water hyacinth multiplies rapidly by producing daughter plants (ramets), adventitious stolons that form dense mat and cover the water surface (Reddy *et al.*, 1989; 1990). Water hyacinth takes up nutrients from water (Hill, 2014) and stores them in the petioles for later use during photosynthesis (Reply *et al.*, 2006). Thus, there is a relationship between the level of nitrogen and phosphorus in the tissues of water hyacinth and their concentration in the water in which the weed is growing (Heard and Winterton, 2000; Coetzee and Hill, 2012).

Among the methods used to control water hyacinth, biological control is often considered the most sustainable and promising method. It involves the introduction of natural enemies (biological agents) that only feed and grow on their specific target (the invasive alien plant species). So far, nine water hyacinth biological control agents have been released in South Africa (Coetzee *et al.*, 2011; Winston *et al.*, 2014). Like other living organisms, these biocontrol agents need sufficient nutrients for growth, development and multiplication, which they obtain from feeding on their host plant (Heard and Winterton, 2002; Karley *et al.*, 2008; Bownes *et al.*,2013, Mukarugwiro *et al.*, 2018).

### 6.1.2 Insects and nutrients

Both nitrogen and phosphorus contribute to insect growth and reproduction along with carbohydrates (Mattson, 1980). The more nitrogen and phosphorus available in the plant host, the better the insect grows and develops (Mattson, 1980; Huberty and Denno, 2006). Sterner and Elser (2002) revealed that sufficient nitrogen and phosphorus in a host plant enhances insect survival, development and reproduction. A decrease in phosphorus causes cellular dysfunction that may lead to the insect's death (Sterner and Elser, 2002). The mealybug, *Planococcus citri* Risso (Homoptera: Pseudococcidae) did not survive on *Solenostemon scutellarioides* L. Codd at low nutrient levels (0.25 mg/l nitrogen) (Hogendorp *et al.*, 2006). However, when nutrients were increased by adding fertilizers with high nitrogen (400 mg/l), insect body biomass growth and development were enhanced (Hogendorp *et al* 2006). High nitrogen and phosphorus levels in the host plant *Holcus lanatus* L. (*Poaceae*) increased survival rate of *Agromyza nigripes* Meigen (Diptera: Agromyzidae) and the biomass of *Agromyza nigripes* females (Ohmart *et al.*, 1985; Honek, 1993; De Bruyn *et al* 2002).

Biocontrol agents of water hyacinth benefit from nitrogen and phosphorus concentrations (Deloach and Cordo 1976; Wilson *et al.*, 2006). Coetzee *et al.* (2007) found an increase in the body size of the mirid *Eccritotarsus catarinensis* as nitrogen and phosphorus levels in the water were increased.

Although high nutrient levels enhance the development and survival of biocontrol agents, the impacts of biocontrol agents under such high nutrient conditions are often found to be low (Hill and Cilliers 1999; Heard and Winterton 2000; Coetzee *et al.*, 2007; Bownes 2009; Mukarugwiro *et al.*, 2018). This is because high nutrients allow the growth of water hyacinth to exceed the growth and development rates of its biocontrol agents and to compensate for any insect damage (Coetzee *et al.*, 2007; Bownes, 2009; Bownes *et al.*, 2013). Conversely low host plant nutrients will allow the biocontrol agents to damage the plant material faster than the plants' ability to compensate for the damage (Bownes 2009; Mukarugwiro *et al.*, 2018).

Despite the success of water hyacinth biocontrol agents in African countries such as Benin, Kenya, Uganda and Tanzania (Albright *et al.*, 2004; Mwende and Njoka, 2005; Wilson *et al.*, 2007) and some areas of South Africa (Hill and Coetzee, 2017), the method has not yet been fully considered for use in Rwanda. Biological control of water hyacinth in Rwanda was attempted once in 2000. However, the method failed to control the weed invasion and understanding the reasons behind this remains a knowledge gap to be investigated in Rwanda. Several studies have already shown the impact of high eutrophication on the efficacy of water hyacinth biocontrol agents (Coetzee and Hill, 2012). Thus, it is possible that the eutrophication problems in the Rwandan water systems have contributed to the failure of the water hyacinth weevils, although it has not been proven yet. Hence, the addition of new biocontrol agents, particularly those with capabilities for rapid population increase such as *Cornops aquaticum* Brüner (Orthoptera: Acrididae) and *Megamelus scutellaris* Berg (Hemiptera: Delphacidae) is essential. *Megamelus scutellaris* is a phloem-feeding bug originally from Brazil, Argentina, Peru and Uruguay in South America (Sosa *et al.*, 2007). It is able to adversely affect water hyacinth growth rates by causing substantial tissue damage (Tipping *et al.*, 2011). *M. scutellaris* has been shown to reduce water hyacinth growth at high nutrient levels since it facilitates plant infection by fungal and other pathogens which further aggravate plant damage (Sutton *et al.*, 2016). *C. aquaticum* is the most recent promising biocontrol agent of water hyacinth (Adis *et al.*, 2007, Bownes *et al.*, 2011). Pre-release studies showed a strong synergy between *C. aquaticum* and *Neochetina* weevils on water hyacinth even at high nutrient levels (Bownes *et al.*, 2011). It is therefore thought that *M scutellaris* and *C aquaticum* can be additional biocontrol agents to *Neochetina* weevils in controling the water hyacinth invasion in Rwanda.

The study aimed to investigate the effects of Rwandan water nutrient levels on *Neochetina* weevils, which were released in 2000 and later reported as a failure. It also investigated if Rwandan water nutrient levels could adversely affect the future success of *C aquaticum* and *M. scutellaris*

The following research questions are addressed in this study:

- Are Rwandan fresh surface water systems eutrophic?
- Were high nutrient levels in Rwandan water bodies one of the causes of *Neochetina* weevils' failure, when released in 2000?
- Will Rwandan nutrient levels affect either the establishment or performance of *C. aquaticum* and *M. scutellaris*?

## 6.2 Methods and materials

The study involved fieldwork to collect water nutrient data and a meta-analysis that reviewed previous studies which investigated the effects of nutrients on *Neochetina* weevils, *Cornops aquaticum* and *Megamelus scutellaris* with the purpose of extrapolating review findings to the likelihood of the establishment and performance of these biocontrol agents in Rwandan conditions.

### 6.2.1 Sampling sites and data collection

Data collection was conducted twice a month from July to December in 2016. The field sites were on the four main rivers of Rwanda, namely the Mukungwa, Nyabarongo, Akagera and Akanyaru Rivers, and Lakes Rweru and Hago (Figure 6.1). This selection was based on the extent and distribution of water hyacinth in these water bodies as shown in Chapter 2 of this thesis.

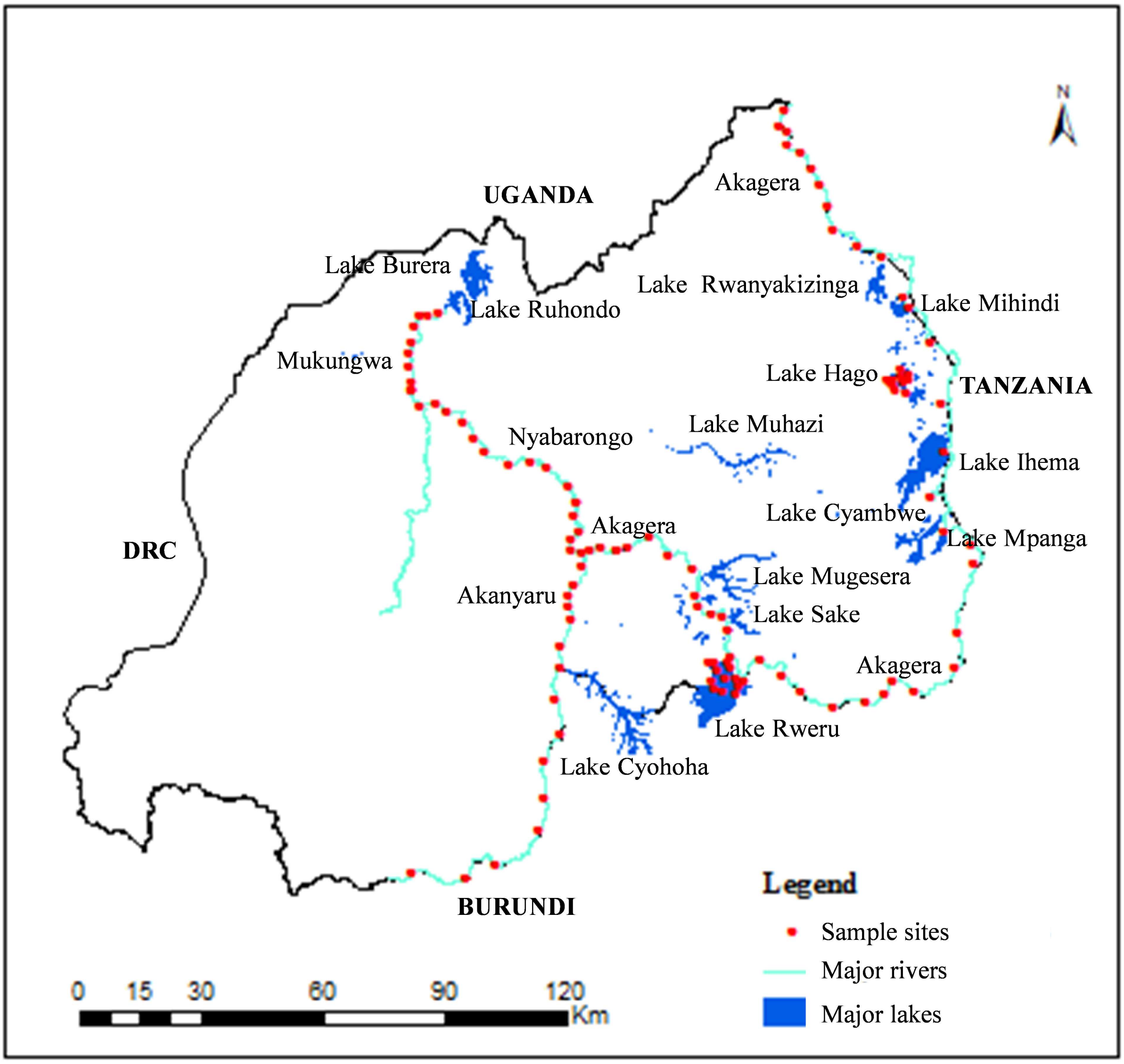


Figure 6.1: Rwandan map showing rivers and lakes from which water and plant samples were collected. The red dots indicate the specific sampling sites in each river or lake

The number of sampling sites on each of the rivers was different based on its size and length. Nine sampling locations were chosen randomly for the Mukungwa River (the shortest river), 15 for each of the Nyabarongo and the Akanyaru Rivers, and 30 for the Akagera River (the longest river in Rwanda). Ten sampling sites were chosen randomly for each of Lake Rweru and Lake Hago. Water samples were collected at 0.5m depth from the water surface, and nitrogen and phosphorus concentrations were measured directly using a Hach colorimeter (DR/870). The latitude and longitude coordinates for each site were recorded using the Global Positioning

System (GPS) to allow mapping of the sampling points and the repetition of sampling at the same point. In addition, water hyacinth leaves were collected at each site from 10 water hyacinth plants obtained from a randomly thrown quadrat of 0.5 x 0.5m ($0.25m^2$). This was to examine plant nutrient content at the different sampling points. The leaf specimens were collected from leaf number three, since it is considered fully developed and contains the highest concentration of nitrogen and phosphorus (Coetzee and Hill, 2012; Burke *et al.*, 2014). The leaf samples were rinsed in deionized water, dried at 60º C and brought to South Africa for plant nutrient analysis that aimed to determine plant nitrogen and phosphorus concentrations of collected water hyacinth in invaded Rwandan water bodies.

### 6.2.2 Meta-analysis of published papers and theses

The major role played by nutrient levels on both water hyacinth and its biocontrol agents, have been extensively studied in laboratory and field sites elsewhere, but not in Rwanda. Therefore, it was not necessary to repeat these experiments using Rwandan water nutrient levels. The meta-analysis was used to understand the role and contribution of water nutrients to the global success or failure of water hyacinth biological control. The focus of the review was only on the *Neochetina* weevils, *C. aquaticum* and *M. scutellaris*. *Neochetina* weevils were the only biocontrol agents released in 2000 in Rwanda; however, they had no effect on water hyacinth. *Cornops aquaticum* and *Megamellus scutellaris* were chosen because they are identified as promising biocontrol agents of water hyacinth and suitable for both low and high water nutrient levels (Bownes 2009; Sutton *et al.*, 2016). Moreover, *C. aquaticum* and *M. scutellaris* are not affected by turbidity as they do not have submerged life-cycle stage (Sosa *et al.*, 2005; Capello *et al.*, 2011).

***Literature survey and inclusion criteria***

The online search was conducted using the following websites: ISI Web of Knowledge (http://apps.webofknowledge.com), Scopus (www.corpus.com) and the Centre for Agriculture and Biosciences International (CABI) websites. The search was based on the effects of biological control agents on water hyacinth grown under different nutrient regimes. The keywords used for the online search were: nutrient levels, water hyacinth, biological control agents, nutrients, and impact of nutrients. The website http://scholar.google.com was used with the search sentence "effect of nutrients on *Neochetina* weevils, on *C. aquaticum* or *M. scutellaris*" to obtain literature published before 2000 and after. Nutrient levels, duration of the studies, conditions in which the studies were conducted (greenhouse or field), were considered. Studies that looked at plant growth parameters such as plant weight or plant biomass (wet or dry) and number of leaves per plant were considered. Furthermore, studies that looked at the effects of nutrients on insect growth parameters such larval development, days taken to reach maturity stages and from immature stages to adult, and survival rate for both immature and adults were also included.

***Data extraction***

Through the online search, a total of 38 studies concerning the effects of nutrients on the biological control of water hyacinth (using *Neochetina* weevils, *C. aquaticum* or *M. scutellaris*) were obtained. However, only 16 studies were eligible for meta-analysis, as they had all inclusion criteria. Among those 16 studies, 10 studies investigated the impact of nutrients on *Neochetina* weevils, three looked at the impact of nutrients on *C. aquaticum*, and the remaining three focused on *M. scutellaris* (Table 6.2). The University of Texas, San Antonio, Texas (UTHSCSA) image tool was used to extract data such as the mean values, standard deviation and measurement of variances for the results presented in graphs. For studies that used dry weight, the dry plant weight was converted to wet plant weight using the following formula: $X1 = \frac{Y - 1.219 - 0.317.X2}{0.074}$. Where X1 stands for wet weight; Y for dry weight; and X2 is the length of longest petiole as described by Van der Meer and Rice (1980).

Table 6.2: Previous studies that examined the impact of water or plant nutrients on the performance and establishment of biocontrol agents on water hyacinth. “no” denotes the study that did not provide the measurements of the indicated parameters; “yes” indicates that the study did provide the measurements on indicated parameters.

| Studies | Year | Biocontrol agents | Water nutrient levels | | | | Presence of plant biomass and leaves | Insect data |
|---|---|---|---|---|---|---|---|---|
| | | | N (mg/l) | | P (mg/l) | | | Insect developmental time (days) and survival (%) |
| | | | High | Low | High | Low | | |
| Mukarugwiro *et al.* | 2018 | *N. eichhorniae* | 6 | 2.8 | 0.65 | 0.001 | yes | yes |
| Firehun *et al.* | 2015 | *Neochetina* weevils | 50 | 10 | 2.56 | 0.56 | yes | yes |
| Raghu *et al.* | 2013 | *N. eichhorniae* | 1.86 | 1.57 | 0.37 | 0.15 | yes | no |
| Center & Dray | 2010 | *Neochetina* weevils | 8.5 | 0.5 | 0.04 | 0.001 | yes | no |
| Wilson *et al.* | 2006 | *N. eichhorniae* | 4 | 0.4 | 0.3 | 0.004 | yes | yes |
| Moran | 2005 | *Neochetina* weevils | 1.2 | 0.4 | 0.2 | 0.001 | yes | yes |
| Heard & Winterton | 2000 | Both weevils | 1.6 | 0.4 | 1 | 0.02 | yes | yes |
| Obeholzer (thesis) | 2002 | *N. eichhorniae* | 1.56 | 0.73 | 0.48 | 0.02 | yes | no |
| Chikwenhere (thesis) | 2000 | *N. bruchi* | 6 | 2 | 1.6 | 0.2 | yes | yes |
| Ongwang & Molo | 1997 | Both weevils | 10 | 3 | 0.86 | 0.0025 | no | yes |
| Bownes (thesis) | 2009 | *C. aquaticum* | 7.6 | 0.034 | 1.35 | 0.024 | yes | yes |
| Bownes *et al.* | 2013 | *C. aquaticum* | 7.6 | 0.034 | 1.37 | 0.024 | no | yes |
| Adis & Junk | 2003 | *C. aquaticum* | 6 | 0.37 | 1.2 | 0.02 | no | yes |
| Sutton *et al.* | 2016 | *M. scutellaris* | 40 | 8 | 1.55 | 0.5 | yes | yes |
| Fitzgerald & Tipping | 2013 | *M. scutellaris* | 10 | 2.5 | 2.56 | 0.37 | yes | yes |
| Patela (thesis) | 2017 | *M. scutellaris* | 50.5 | 0.5 | 2.56 | 0.05 | yes | yes |

### 6.2.3 Data analysis

#### 6.2.3.1 Data from the field

All data were checked for normal distribution using a Shapiro-Wilks test. Simple and descriptive statistics were conducted by calculating means and standard deviations using Microsoft Excel. One-way ANOVA followed by turkey HSD post-hoc tests, was utilised to compare means of nitrogen and phosphorus concentrations for all sites using Statistica (version 12.6). This was followed by post-hoc tests to indicate the specific significance for nitrogen and phosphorus in different sites. Graphs were generated to compare nutrient levels recorded during dry and rainy seasons.

#### 6.2.3.2 Data from meta-analysis of theses and published papers

Data from the literature were analyzed using Comprehensive Meta-Analysis (CMA) software. Analysis was conducted to examine the insect feeding and insect development on water hyacinth at low and high nutrient levels by calculating effect sizes in each study. The effect size known as Hedges'd (Ds) was calculated for each study. Effect size aims to quantify the size of the difference between two groups such as control and treatment groups. The effect size enhances the quantification of certain intervention's effectiveness relative to some comparison to known and normal statistical difference in a study (Huberty, 2002; Borenstein *et al.*, 2009. In this study, effect size was defined as a measure of the impacts of nutrient levels on the biological control of water hyacinth. Meta-analysis of the studies concerning impacts of nutrients on insect developmental time and survival was extracted by calculating effect size in the form of proportions. This approach synthesizes a one-dimensional binomial measure known as "weighted average proportion" (Nyaga *et al.*, 2014). The weighted average proportion is calculated using the proportions of multiple studies divided by the inverse of their sampling variances (Barendregt *et al.*, 2013). In this case, developmental time (in days) for larvae or nymphs and their survival rate (as percentages at low and high nutrient levels) were available. To better interpret the overall effect size, we classified them according to Cohen (1988). It is essential to note that the analysis models used in this study were random-effects models because of heterogeneity across all selected studies. Random analysis models are only appropriate for studies that have variation in effect sizes, while fixed models are only used when there is homogeneity of effect size or when the implication of the results from the studies is limited (Hedges and Vevea, 1998).

## 6.3 Results

### 6.3.1 Field measures of nutrients

#### 6.3.1.1 Analysis of water samples

Rwandan main rivers are rich in nitrogen and phosphorus regardless of the season (Figure 6.2). However, the Mukungwa River had the lowest nutrient levels across both seasons. For the lakes, Lake Hago had low nitrogen and phosphorus concentrations compared to Lake Rweru. There were significant differences in water nitrogen and phosphorus concentrations recorded: N (mg/l): $F_{10, 842} = 104.31$, $P = 0.0023$; P (mg/l): $F_{10, 842} = 98.55$ $P = 0.0035$ for the dry season; and N (mg/l): $F_{10, 842} = 165.68$, $P = 0.0025$, P (mg/l): $F_{10, 842} = 132.28$, $P = 0.001$ for the wet season.

By classifying the recorded concentrations of nitrogen and phosphorus into their respective trophic groups, it was found that all nutrient levels recorded during the dry season fall into the oligotrophic and mesotrophic categories, except for the Akagera River where the nitrogen concentration was 3.33 mg/l and phosphorus was 0.17 mg/l (Figure 6.2). However, the results from data collected during the wet season showed that only two sites, Mukungwa River and Lake Hago, were categorized as mesotrophic, while the remaining sites were found to be eutrophic with nitrogen ranging between 2.61 mg/l and 8.7 mg/l (Figure 6.2).

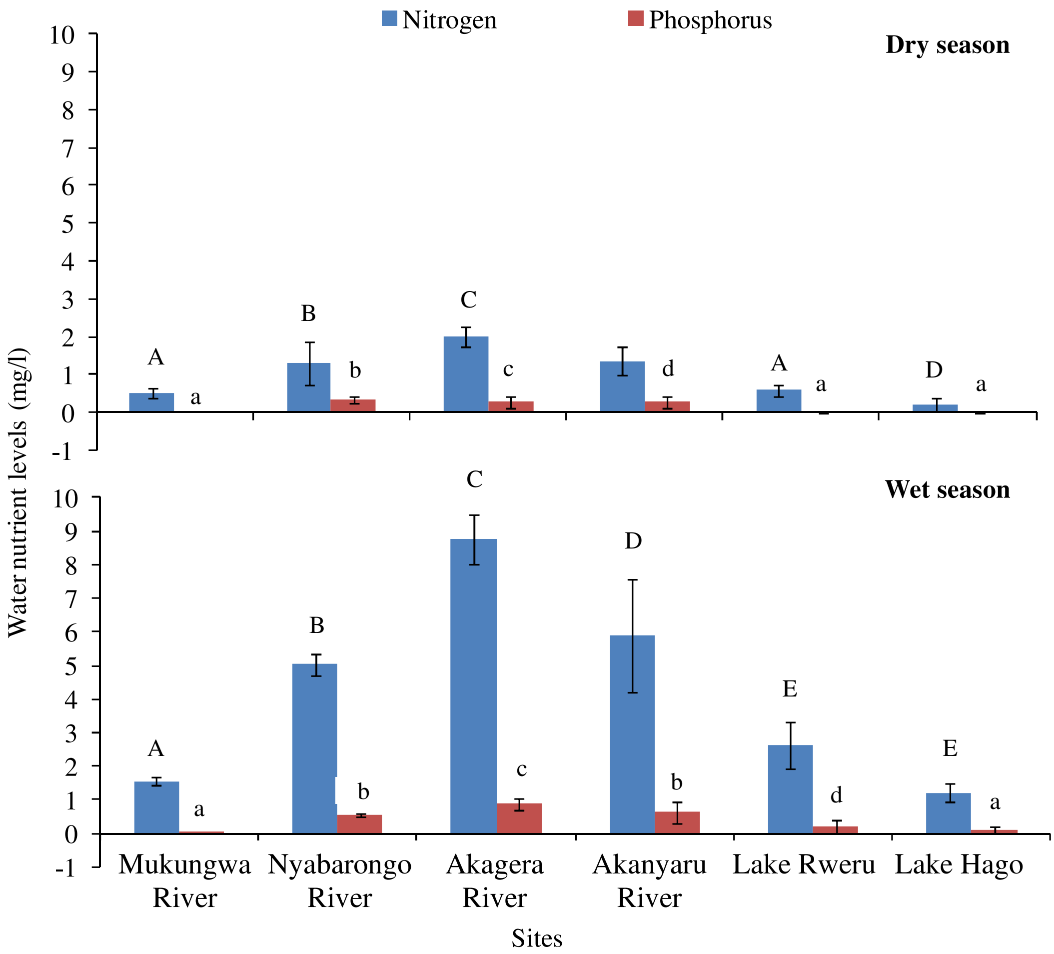


Figure 6.2: Nitrogen and phosphorus recorded in the four main rivers and two lakes identified to have a large extent of water hyacinth. Data were collected during the dry and wet seasons. One-way ANOVA followed by Turkey HSD post-hoc tests was used to determine the statistical significance between the different water bodies at p <0.05. Means with same capital letters indicate no statistical significance for nitrogen; the lower case letters indicate no statistical significance for phosphorus.

#### 6.3.1.2 Analysis of plant nutrients

Nitrogen and phosphorus (%) obtained from water hyacinth leaves were significantly different in all the sites: N (mg/l): $F_{6, 25} = 0.549$, $P < 0.01$, P (mg/l); $F_{6, 25} = 21.224$, $P < 0.01$ for the dry season and N (mg/l): $F_{6, 25} = 0.298$, $P < 0.01$, P (mg/l): $F_{6, 25} = 12.454$, $P < 0.01$ for the wet season (Figure 6.3).

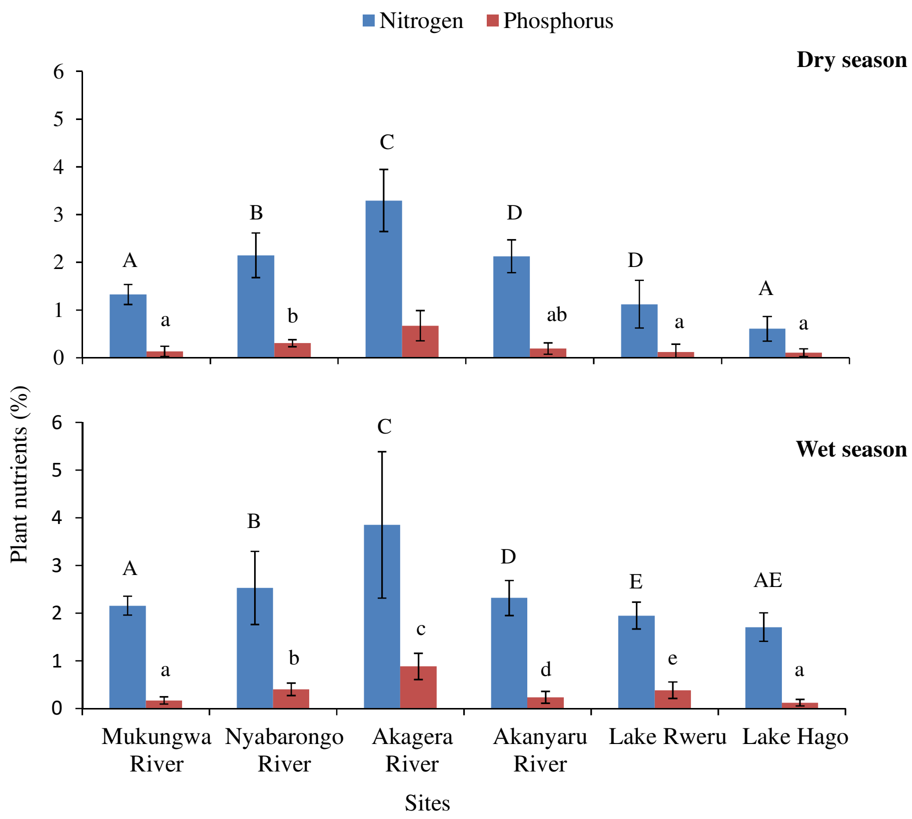


Figure 6.3: Concentrations (%) of nitrogen and phosphorus obtained from water hyacinth leaves collected from the four main Rwandan rivers and two lakes during the dry and wet seasons. One-way ANOVA followed by Turkey HSD post-hoc tests was used to check the statistical significance at $p < 0.05$. Means with same capital letter indicate no statistical significance difference for nitrogen, and the lower case letters letters indicate no statistical significant for phosphorus.

Interestingly, the relationship between nutrient levels in water and water hyacinth leaves recorded during the dry season was weak with $R^2$ of 0.35 while the relationship between nutrient levels in water and water hyacinth leaves recorded in the wet season was strong with $R^2$ 0.94 of (Figures 6.4 and 6.5).

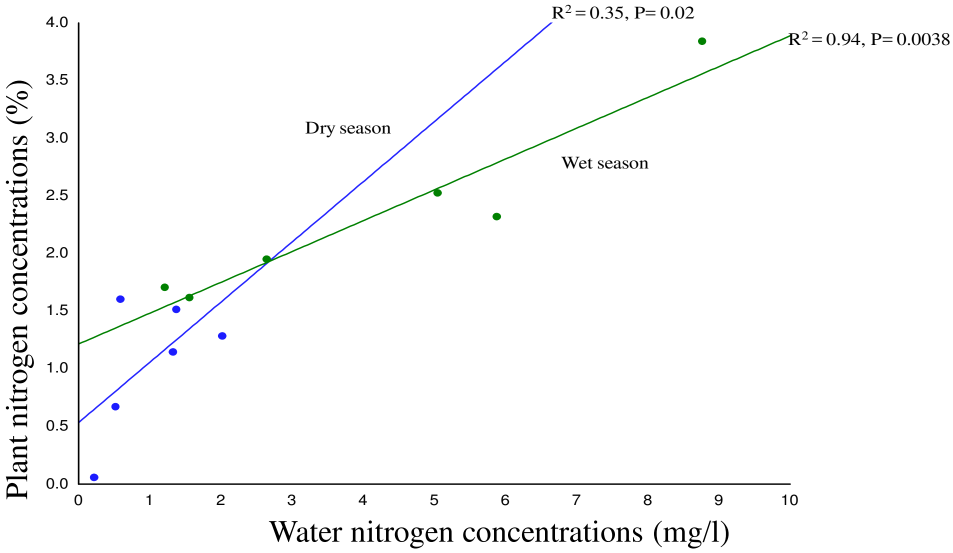


Figure 6.4: Relationship between plant and water nitrogen concentrations measured during the dry and wet seasons of Rwanda.

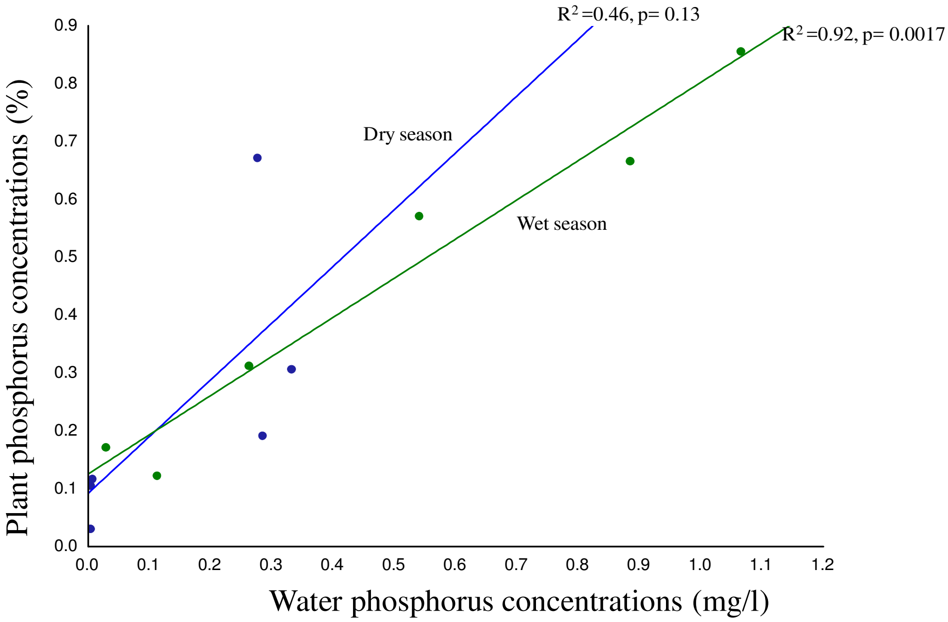


Figure 6.5: Relationship between plant and water phosphorus concentrations collected during the dry and wet seasons.

### 6.3.2 Meta-analysis outcome

All examined studies in the meta-analysis showed the value of the biological control of water hyacinth. The overall effect sizes of biocontrol agents on water hyacinth growth parameters (biomass and leaves) were smaller at high nutrient levels and higher at low nutrient levels (Figure 6.6 and 6.7). At high nutrient levels there was less loss of plant biomass and plant leaves caused by insects‘feeding, while at low nutrient levels, water hyacinth lost a lot of biomass and leaves.

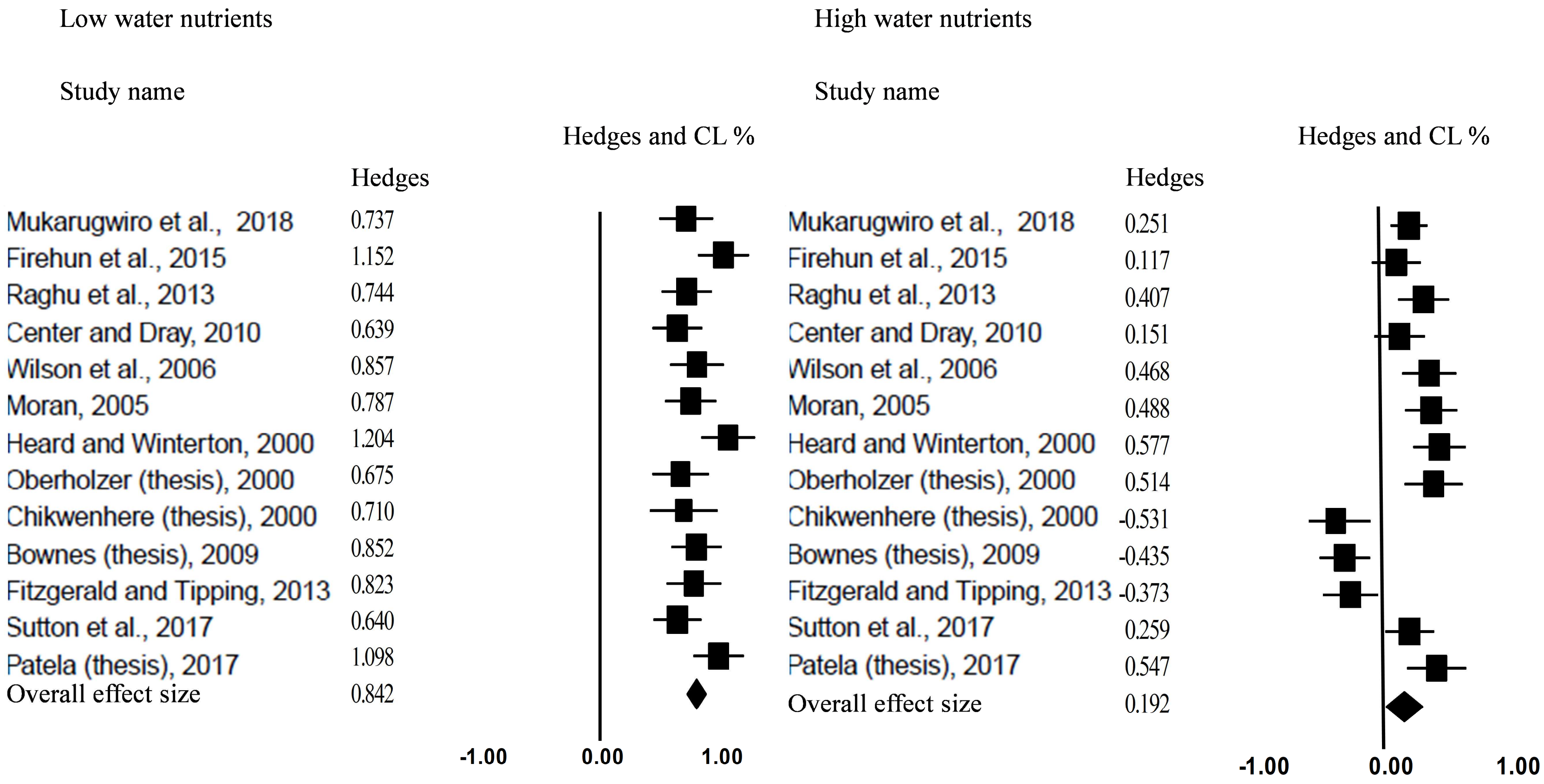


Figure 6.6: Effect sizes of herbivory on water hyacinth plant biomass reduction at low and high water nutrient levels. The effect sizes were calculated using the 13 listed studies that investigated the impact of nutrients on water hyacinth biological control. The first nine studies looked at *Neochetina* weevils, the following study looked at the effect of nutrients on *C. aquaticum*, and the last three studies investigated the effect of nutrients on *M. scutellaris*.

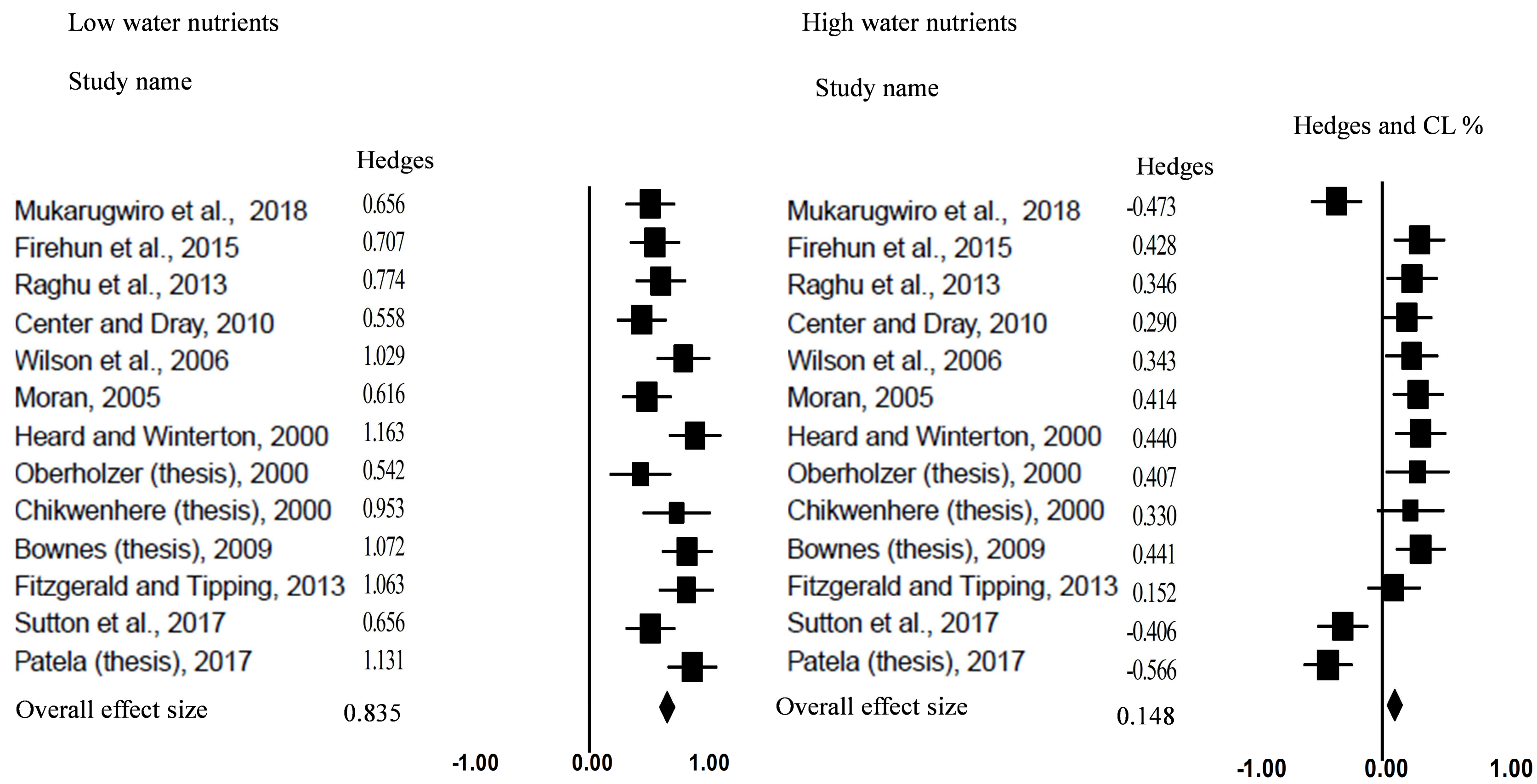


Figure 6.7: Effect sizes of herbivory on reduction in number of water hyacinth plant leaves at low and high waternutrient levels. The effect sizes were calculated using the 13 listed studies that investigated the impact of nutrients on water hyacinth biological control. The first nine studies looked at *Neochetina* weevils, the following study looked at effect of nutrients on *C. aquaticum*, and the last three studies investigated the effect of nutrients on *M. scutellaris*.

The results of the meta-analysis provided evidence of the contribution of nutrients in water hyacinth on the development and survival of its biocontrol agents. The larger effect sizes were found at high nutrient levels, while at low nutrient levels the effect sizes were smaller (Figure 6.8 and 6.9).

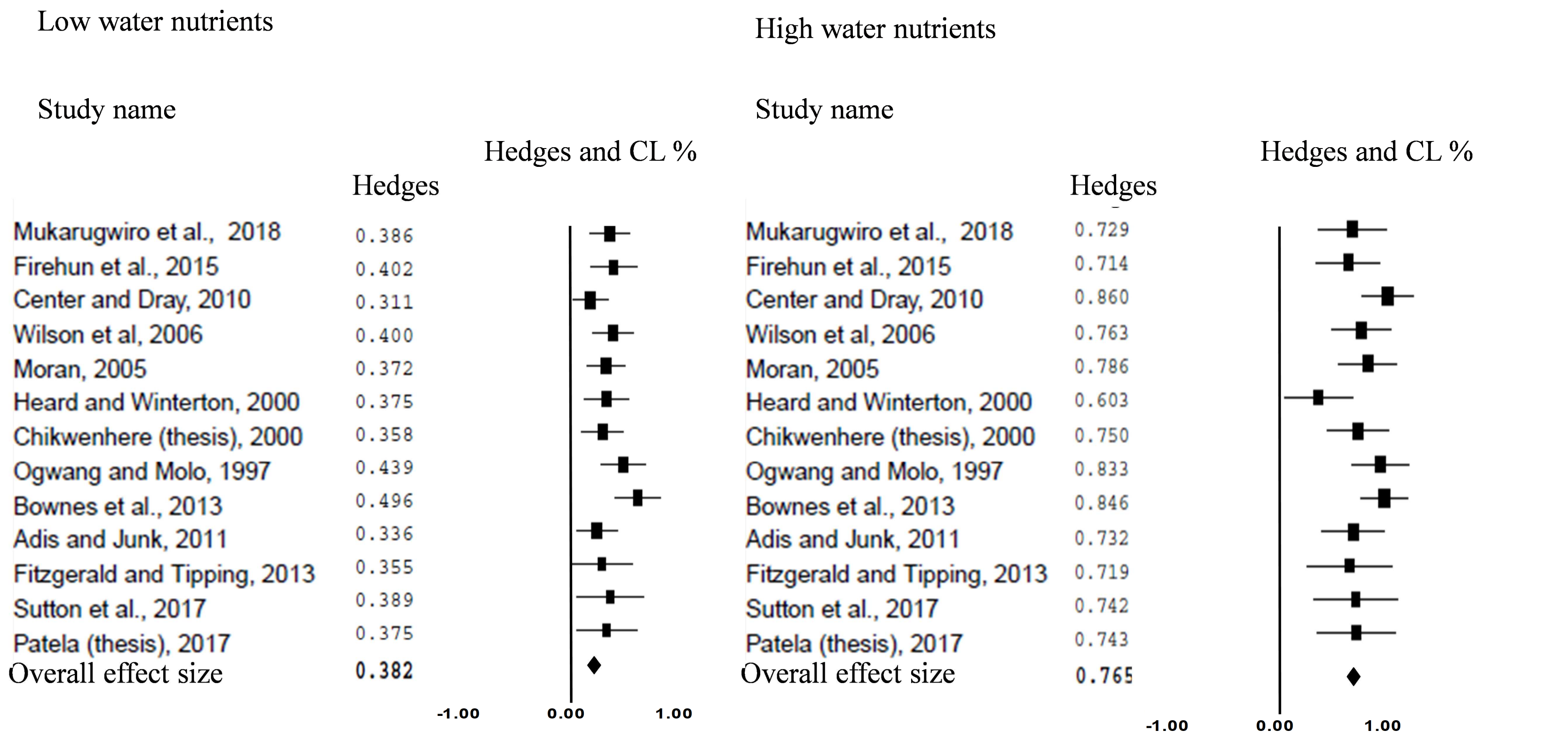


Figure 6.8: Effect sizes of water nutrient levels on the developmental time of water hyacinth herbivores used as biocontrol agents. The effect sizes were calculated using the 13 listed studies that investigated the impact of nutrients on water hyacinth biological control. The first eight studies investigated the impact of nutrients on the development of *Neochetina* weevils; the following two studies investigated *C. aquaticum*; while the last three studies investigated the impact of nutrients on developmental time of *M. scutellaris*

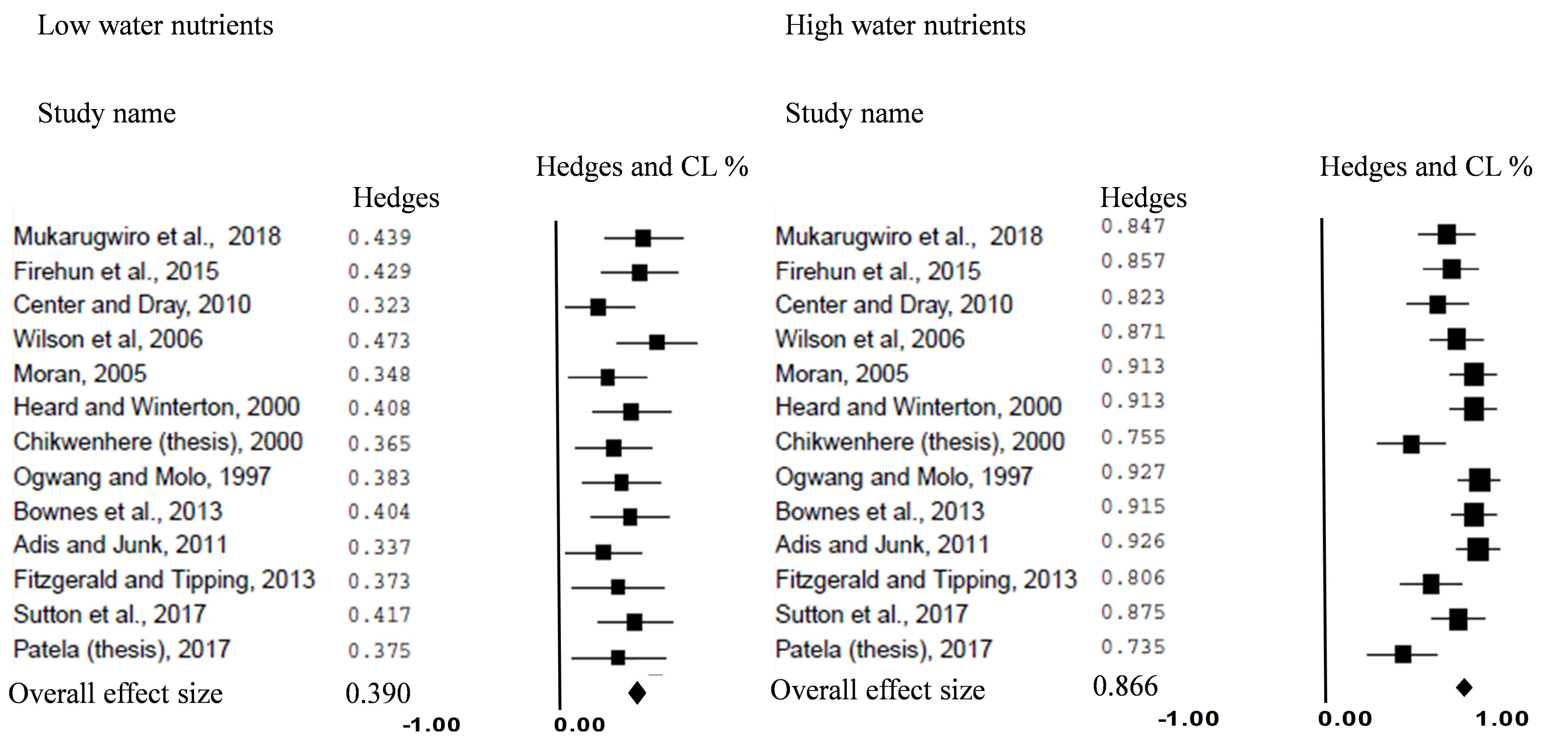


Figure 6.9: Effect sizes of water nutrient levels on the survival of water hyacinth herbivores used as biocontrol agents. The effect sizes were calculated using the 13 listed studies that investigated the impact of nutrients on water hyacinth biological control. The first eight studies investigated the impact of nutrients on the development of *Neochetina* weevils; the following two studies investigated *C. aquaticum*; while the last three studies investigated the impact of nutrients on developmental time of *M. scutellaris*.

The extrapolation of Rwandan nutrient levels from the meta-analysis outcome indicated that Rwandan nutrient levels fall within the range of nutrients levels used in different studies (Table 6.3). The nitrogen and phosphorus concentrations recorded in the Rwandan water bodies, are sufficiently high to support the development, survival and feeding of the water hyacinth biocontrol agents (*Neochetina* weevils, *C. aquaticum* and *M. scutellaris*). However, high nitrogen and phosphorus concentrations recorded in rivers which are classified as hypertrophic, would allow water hyacinth compensation for biocontrol agent damage (Table 6.3). Compared to other nutrient levels used in previous studies, the Rwandan high nutrient levels of nitrogen (2.8–8 mg/l) will have a medium effect size on the decrease of plant biomass as well as number of the leaves. Nitrogen levels (<2.8 mg/l) and phosphorus levels (<0.2 mg/l) will allow a high effect size on both plant growth parameters.

Table 6.3: Comparison between effect sizes calculated using different studies that investigated the impact of nutrient levels on the biological control of water hyacinth, and nutrient levels (nitrogen and phosphorus concentrations) (mg/l) recorded in four main Rwandan rivers and two lakes.

| Nutrient groups | Nutrient levels from studies | | Nutrient levels from Rwandan water bodies | | | Effect sizes | | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | P | Number of water bodies | N | P | Plant growth parameters | | Insect growth parameters | |
| | | | | | | Biomass loss | Leaf loss | Developmental time (days) | Survival (%) |
| Low | 0.034–0.4 | 0.001–0.004 | 5 | 0.14–0.17 | 0.001–0.002 | 0.826 | 0.794 | 0.345 | 0.325 |
| Medium | 0.721–2.5 | 0.02–0.056 | 5 | 0.57–2.09 | 0.006–0.025 | 0.563 | 0.608 | 0.532 | 0.632 |
| High | 2.8–10 | 0.055–0.2 | 4 | 2.8–8 | 0.04–0.145 | 0.322 | 0.324 | 0.798 | 0.728 |
| Hyper | 21–50.5 | 0.3–2.56 | 1 | 10–11.9 | 0.52–0.71 | -0.245 | -0.234 | 0.867 | 0.831 |

## 6.4 Discussion

### 6.4.1 Rwandan nutrient levels

The nutrient levels in Rwandan rivers and lakes investigated in this study exceeded the nitrogen and phosphorus concentrations recommended by the Organization for Economic Co-operation and Development (OECD). According to the OECD water quality guidelines, nitrogen and phosphorus concentrations should not exceed 0.6 mg/l and 0.02 mg/l, respectively (OECD, 1982). Unfortunately, the nutrient levels found in the Rwandan water bodies were far above this benchmark and fall under the eutrophic category, except for those recorded in the Mukungwa River, Lake Hago and Lake Rweru during the dry season. The problem of eutrophication is exacerbated during the wet season and increased by surface runoff that carries soil sediment, municipal and industrial wastes, as well as leached agricultural herbicides and fertilizers into the surface water system in the country (Karamage *et al.*, 2016). The Akagera River had higher nitrogen and phosphorus concentrations compared to other water systems examined. Other studies on water quality in Rwanda showed that the Akagera River is the most eutrophic river in the country (Wali *et al.*, 2011; RNRA, 2012). The Akagera River is the longest river in Rwanda, and it has many small tributaries that flow into it at different locations (Wali *et al.*, 2011). These tributaries that originate from urban regions carry excessive dissolved organic materials, wastes from industries, as well as soil sediments (Karamage *et al.*, 2016). An example of this is the Muvumba River that contributes to eutrophication in the middle- and downstream regions of the Akagera River (Dusabe *et al.,* 2019). Domestic sewage and industrial wastes from Nyagatare city is considered the source of the nutrients carried by the Muvumba River into the Akagera River (Wali *et al.*, 2011; Dusabe *et al.,* 2019). In addition to this, modern agricultural practices around the downstream part of the Akagera River may also contribute to high nitrogen and phosphorus in the river (pers. observation).

High levels of nitrogen and phosphorus concentrations generally signify low water quality. Eutrophication in water bodies is considered the main cause for the proliferation of aquatic invasive species such as water hyacinth (Coetzee and Hill, 2012). The Akagera River was found to be the most eutrophic river in the country, and this matches the vast extent of water hyacinth reported in this thesis compared to the other rivers (refer to Chapter 2 and 3). Surprisingly, Lake Hago was found to have a high coverage of water hyacinth compared to Lake Rweru, even though the latter was classified as eutrophic. Although Lake Hago has low nitrogen (oligotrophic), it has high levels of phosphorus (between 0.025 and 0.25 mg/l), which may contribute to water hyacinth proliferation. Thus, knowing the status of water and plant nutrient levels in Rwanda helps to prioritize and allocate resources to curb eutrophication problems, but also facilitates the implementation of suitable and effective biocontrol agents to control the spread of water hyacinth in Rwanda.

### 6.4.2 Understanding the meta-analysis outcome

The meta-analysis of previous studies demonstrated a significant role played by water or plant nutrients on the feeding and development of biological control agents, which are determinants of the efficacy and success of different biocontrol agents of water hyacinth. The meta-analysis showed that like other insect herbivores, the growth and development of the biocontrol agents depend on the plant nutrient levels. At high nutrient levels, the insects grow faster but they can not inflict enough damage on the plant's tissues to stunt its growth, because their nutrient needs are easily met when feeding on nutrient rich tissues (Ripley *et al.*, 2006). This has been confirmed by all the studies considered in the meta-analysis. At high nutrient levels, the insect damage to water hyacinth was low (plants lost less biomass and leaves) compared to plants with low nutrient levels. On other hand, the rapid development and high survival of biocontrol agents of water hyacinth were seen at high nutrient levels. Although, the overall effect size for insect feeding (loss of plant biomass and leaves) was positive (0.1 to 0.2) at high nutrient levels, it falls into the small category, which indicates that the effect of nutrients on herbivores' feeding on water hyacinth was low. The small decrease in plant biomass and number of leaves observed in most of the selected studies suggests that the plant undergoes equal compensation for the insect herbivore damage. Equal compensation occurs when the productivity of a plant exposed to insect herbivores is equal to the productivity of plants not exposed to the herbivores (Maschinski and Whitham, 1989). This equal compensation was shown by Bownes (2009) and Mukarugwiro *et al.* (2018), even though the experiments were conducted on different herbivores. The significance of the findings from meta-analysis is that potential biocontrol agents (*Neochetina* weevils, *Cornops aquaticum* and *Megamelus scutellaris*) can contribute to water hyacinth control and can be successful when feeding on water hyacinth plants in oligotrophic and mesotrophic water systems. However, in water bodies with high nutrients, water hyacinth plants can undergo equal compensation and so lose less biomass, leaves and other plant growth parameters.

Integrated pest management may be the best option to control water hyacinth invasions under such circumstances (Jadhav *et al.*, 2008; Byrne *et al.,* 2010, Katembo *et al.*, 2013).

### 6.4.3 Extrapolation of Rwandan nutrient levels from meta-analysis outcomes

Given the Rwandan water nutrient levels and findings from the meta-analysis, it is possible to predict that the water hyacinth biocontrol agents (*Neochetina* weevils, *Cornops aquaticum* and *Megamellus scutellaris*) selected for this study could establish and perform well in Rwanda, considering other abiotic factors such as turbidity and temperature are not limiting. The Rwandan nutrient levels fall within the range indicated in many other such studies. The Rwandan water nutrients will not constrain the efficiency of the proposed water hyacinth biocontrol agents in the country except in the Akagera River. The nutrient levels in the Akagera River can reach up to 11.9 mg/l of nitrogen and 1.5 mg/l of phosphorus (classified as hypertrophic group), and are comparable to the highest nitrogen and phosphorus levels used in the selected studies for meta-analysis, namely 50.5mg/l N, and 2.56 mg/l P (Firehun *et al.*, 2015; Patela, 2017), and 40 mg/l N; 1.55 mg/l P (Sutton *et al.*, 2016). The fact that high nutrients cause low damage by biocontrol agents to water hyacinth, there is high probability that high nutrient levels in the Akagera River will also affect the biocontrol agents of water hyacinth. On other hand, the nutrient levels from other sites should allow the insect herbivores to establish and perform well against the water hyacinth. These findings refuted the study's hypothesis stated that "Water nutrient levels caused the failure of *Neochetina* weevils released in Rwandan lakes to control water hyacinth".

When compared to nutrient levels where *Neochetina* weevils were successful, it is clear that the Rwandan nutrient levels, particularly those recorded in the lakes, will not limit the success of the weevils. For instance, *Neochetina* weevils successfully controlled water hyacinth in the New Year's Dam in South Africa (Hill and Coetzee, 2017) where the average nitrogen and phosphorus content of water was 2mg/l and 0.1 mg/l respectively (Byrne *et al.*, 2010), comparable to those recorded in some Rwandan lakes (0.001–0.21 ml/l and 0.6–2.6mg/l N). Similar success against water hyacinth was achieved in Lake Victoria (Albright *et al.*, 2004, Mwende and Njoka, 2006). Lake Victoria has nutrient levels of 0.3 to1.3 mg/l of nitrogen and 0.1 to0.001 mg/l of phosphorus (Gikuma-Njuru *et al.*, 2013), which are lower than those reported for Rwandan water bodies, except for the Akagera River. Apart from the lakes and rivers selected for this this study, the nutrient levels of lake Muhazi, one of the other lakes infested by water hyacinth (Chapters 2 and 3), were 0.26mg/l N and 0.09 mg/l P (Usanzineza *et al.*,2011), and these concentrations fall in the same range as that where biocontrol has been successful. This suggests that *Neochetina* weevils can also control water hyacinth in Lake Muhazi.

Despite the predicted success of the weevils in water bodies with oligotrophic and mesotrophic status, high turbidity, which increases during the wet season, specifically in the Rwandan rivers, except the Mukungwa River, was found to constrain the establishment of *Neochetina* weevils by negatively affecting its pupation (Chapter 5). Thus, this chapter looked at whether the nutrient levels in Rwandan water bodies can affect *C. aquaticum* and *M. scutellaris,* biocontrol agents which do not pupate in the roots of water hyacinth. By comparing studies that investigated the impact of nutrient levels on *C. aquaticum* and *M. scutellaris*, the current study showed that Rwandan nutrient levels fall within the range of nutrient levels used in those studies. Since they were successful in nutrient conditions similar and even higher to those of Rwandan water bodies, there is high chance of their establishment and thriving in Rwandan water bodies under the current nutrient conditions found in this study.

***Cornops aquaticum and water/plant nutrients from literature versus Rwandan nutrient levels***

Nymphs and adults of *C. aquaticum* inflict severe damage on plant leaves and petioles. Adults create large holes in the leaves, while the early instar nymphs create scars by destroying leaf tissues resulting in more defoliation (Bownes *et al.*, 2010). Using 6 mg/l of N and 1.2 mg/l of P, Adis and Junk (2003) showed that *C. aquaticum* developed quickly, the body biomass of female adults was high, enhancing fecundity and the number of eggs laid, leading to a large population. Bownes (2009), Bownes *et al.* (2011) and Bownes *et al.* (2013) found the same results as those in Adis and Junk (2003), using three different nutrient regimes: high (7.6 mg/l N, 1.37 mg/l P); medium (2.52 mg/l N, 0.36 mg/l P); and low (0.032 mg/l N, 0.020 mg/l P). Although at the low nutrients level, the development and growth rates were not the same as at the high nutrient level, *C. aquaticum* were still able to develop and grow. Rwandan water nutrient levels fall in the range used by Adis and Junk, (2003), Bownes (2009), Bownes *et al.* (2011), and Bownes *et al.* (2013). Therefore, *C. aquaticum* can be considered as a potential biocontrol agent of water hyacinth in Rwanda, especially in the lakes and rivers, except possibly for the Akagera River since this river has high nutrient level (>7.6mg/l N, 1.37 P) particularly during wet season.

***Megamelus scutellaris* and water/plant nutrients from the literature versus Rwandan nutrients levels**

*Megamellus scutellaris* is a biocontrol agent of water hyacinth capable of multiplying quickly to reach densities that damage and weaken water hyacinth plants, leading to complete destruction (Tipping and Center, 2010). Few studies have investigated the impacts of water nutrients on the efficacy of *M. scutellaris*. Sutton *et al*., (2016) found a shorter period (12–15 days) of insect development and growth when reared at high nutrient levels and a longer period (15–22 days) when grown at low nutrient levels. Using 40 mg/l N, 1.55mg/l P and 8mg/l N, 0.5 mg/l P as high and low nutrient regimes respectively, Sutton *et al*., (2016) showed that *M. scutellaris* decreased plant biomass and number of leaves at all nutrient levels. Patela (2017) also investigated the impacts of nutrients on the efficacy on *M. scutellaris,* and revealed that *M. scutellaris* inflicted more damage to water hyacinth at both low and high nutrient levels, than *N. eichhorniae*. Patela (2017) suggested that *M. scutellaris* is a promising biocontrol agent capable of reducing water hyacinth growth at both low and high nutrient levels because of its rapid growth. The nutrients used in the above studies are far higher than the Rwandan nutrient levels. Therefore, *M. scutellaris* should establish and perform well in Rwanda as a biological control agent of water hyacinth weeds.

**Conclusions**

This chapter investigated the impact of Rwandan water nutrient levels on the establishment and performance of *Neochetina* weevils, *M. scutellaris* and *C. aquaticum.* To achieve the objectives of this chapter, a meta-analysis of selected studies from related literature and extrapolation of water nutrient levels recorded in the four main rivers and two lakes in Rwanda to the findings of the meta-analysis were involved. The study revealed that Rwandan water bodies are oligotrophic, and mesotrophic and that eutrophication increases during the wet season, particularly in the Akagera River. The meta-analysis helped to understand the role played by water or plant nutrients for different biocontrol agents of water hyacinth. Although there was no laboratory or field experiments conducted using Rwandan nutrient levels on the biocontrol agents of water hyacinth, *M. scutellaris*, *C. aquaticum* and *Neochetina* weevils should cope with Rwandan nutrient levels and should control water hyacinth. Given the causes of the prevailing nutrient levels, this study suggests putting more effort into controlling factors that contribute to their increase in the Rwandan water systems. It is a pre-requisite for biocontrol practitioners to consider the nutrient levels as well as other water abiotic factors such temperature in water bodies prior any introduction of a biological control agent. The next chapter, therefore, investigated whether the Rwandan temperatures are suitable for the establishment and performance of the water hyacinth biocontrol agents such as *M. scutellaris*, *C. aquaticum* and *Neochetina* weevils.

# CHAPTER 7:

# THE EFFECT OF LOCAL TEMPERATURES ON POTENTIAL BIOCONTROL AGENTS FOR WATER HYACINTH IN RWANDA

***This chapter was prepared to be submitted to the Journal of Biological Control***

**ABSTRACT**

The water hyacinth invasion in Rwanda has caused socio-economic problems. While biological control is the only sustainable method envisaged to manage the scourge of water hyacinth, the success of released biocontrol agents depends on a number of abiotic factors, among which is temperature. Hence, it is crucial to understand the thermal boundaries of biocontrol agents before they are released. The aim of this study was to determine if Rwandan temperatures were the reason behind the historical failure of *Neochetina* weevils released in Rwanda in 2000 and to predict the suitability of *Cornops aquaticum* and *Megamelus scutellaris* as potential biocontrol agents of water hyacinth in Rwanda. The results revealed that *Neochetina eichhorniae* and *N. bruchi* had a lower CTmin (2.4 ºC, 2.6 ºC) than *M. scutellaris* (4.7 ºC) and *C. aquaticum* (6.2 ºC). CLIMEX eco-climatic modelling predicted the suitability of the climate in Rwanda for the *Neochetina* weevils and *C. aquaticum*. *M. scutellaris* appears to be unsuitable for release in the Northern region of Rwanda but it should establish in othe regions of the countrye. The implications of this study are that the low and high temperatures in Rwanda were not the cause of the historical failure of the *Neochetina* weevils in 2000.



**Key words**: Biocontrol agents, CLIMEX, critical temperature, lethal temperature, thermal limits

## 7.1 Introduction

Temperature is one of environmental factors that affects all aspects of living organisms, such as behaviour, physiology, nutrition, growth, development as well as the organism's distribution in the environment (Clark, 2014). Temperature affects survival, fecundity, fertility and the whole life span of an insect (Yang *et al.*, 1994; Zheng *et al.*, 2008). Hence, it has a strong and profound impact on insect abundance, distribution, and establishment in native or non-native environments (Bryant *et al.*, 2002; Hoffman *et al.*, 2003; Yadav and Chang, 2013).

Biocontrol agents of invasive alien plant species, such as insects, also depend on the environmental temperature (Morin *et al.*, 2009). Biocontrol agents are expected to grow, develop, and reproduce to reach sufficient population levels to reduce the population growth of their specific target weeds (Barton, 2004). However, such agents are ectothermic organisms that do not always establish because of unfavourable temperatures, consequently, their feeding damage on a weed may be trivial (Dennill and Gordon, 1990; McEvoy and Coombs, 2000; Byrne *et al.*, 2002; Goolsby *et al.*, 2005; McClay and Hughes, 2007).

### 7.1.1 Climate incompatibility and biocontrol agents

Climate incompatibility constrains species' distributions, reduces agent multiplication and ultimately their survival (Byrne *et al.*, 2004). Studies by Andow *et al.* (1997) and McEvoy and Combs (2000) showed that 44% of biocontrol agents fail to establish due to poor climate compatibility. The distribution of biocontrol agents and their target weeds are supposed to have similar climatic conditions (Sheppard, 2003; Hinz and Schwarzlander, 2004); however, this is not always the case, as weeds can adapt more quickly to new environments than their biocontrol agents (Mooney and Cleland, 2001; Turner *et al.*, 2015). This may be due to adaptation via phenotypic plasticity of the invasive species (Broennimann *et al.*, 2007). An example of this is a biocontrol agent *Gratiana spadicea* (Klug) (Coleoptera: Chrysomelidae) (tortoise beetle) from South America that was released in South Africa in 1994 to control *Solanum sisymbriifolium* Lamarck (Solanaceae), a species native to South America (Hill and Hulley, 1995). Although this plant rapidly adapted to the climate of the Mpumalanga Highveld, the insects failed to control the weed, being unable to cope with the new climatic conditions of the site (Byrne *et al.*, 2002). *Anthonomus santacruzi*, originally from the warm and humid temperatures in North-eastern regions of Argentina, failed to establish in the Highveld regions of South Africa because of incompatibility in climate conditions (Cowie *et al.*, 2016). Thus, understanding the thermal tolerance or thermal boundaries of biocontrol agents helps to decrease the failure of biocontrol agents because of climatic mismatch (Byrne *et al.*, 2004, May and Coetzee, 2013).

### 7.1.2 Parameters used to determine thermal boundaries

Studies on thermal boundaries in the area of biological control received more attention after noticing that biocontrol agents sometimes fail, despite the host specificity tests having shown good performance on the weed (Chown *et al.*, 2009; Hughes *et al.*, 2011; Hakizimana, 2011). Thermal boundaries are assessed using either static or dynamic methods (Hoffmann *et al.*, 2003). Static methods assess insect survival at a certain point of time after exposure to a stressful temperature. In contrast, the dynamic method determines the tolerance of an organism by changing the temperature at a constant rate for a certain period. This determines the temperature at which individual organisms become weak and eventually reach the knockdown stage (Terblanche *et al.* 2007). (1) One dynamic technique that has been widely used to resolve extreme temperature thresholds is Critical Thermal limits (CTLs) (Chown and Nicolson, 2004; Terblanche *et al.*, 2007; Rezende *et al.*, 2011). These are the temperatures that specify the point at which an organism loses its locomotory function and can either be highest or lowest temperatures. Low temperatures lead to a chill coma (Hazell and Bale, 2011). Critical temperatures also provide an insight into how quickly and to what extent the organism can undergo an acclimatization process (Terblanche *et al.*, 2007). They are well thought-out ecologically and relevant because of the activity range for an organism under severe conditions exposure (Somero, 2005).

One static technique is lethal limits (LTs). Lethal limits are temperatures beyond which organisms cannot recover (Mitchell *et al.*, 1993). It is a temperature at which 50% of the population cannot survive (Chown *et al.*, 2004; Overgaard *et al.*, 2011). Lower or upper limits of lethal temperatures ($LT_{50}$) are an ecologically relevant measure of insect thermal tolerance (Terblanche *et al.*, 2011). Lethal temperature is used to describe an insect's survival under stress or extreme temperatures that are common within the insect's natural thermal habitat. It is can facilitate the understanding of insects' thermal physiology (Andersen *et al.*, 2015) and provide information on their geographical distribution (Terblanche *et al.*, 2005). Chanthy *et al.* (2012) found that the average of upper lethal temperature of *Nezara viridula* (L) (Heteroptera:

Pentatomidae) in the Breeza and Grafton regions in New South Wales, Australia, was 40.2 ºC, and 40.4 ºC, respectively, while the lower lethal temperature was −8ºC in both regions. This shows that this insect can survive in tropical, subtropical and temperate regions and that they are tolerant of extreme low and high temperatures. Thus, to increase the success and cost-effectiveness of a biological control programme, the distribution, establishment and efficacy of biocontrol agents should be predicted and modelled before their release into new areas (Byrne *et al.*, 2002; Denoth *et al.*, 2002; Byrne *et al.*, 2004,; Palmer *et al.*, 2007; May and Coetzee, 2013; Allen *et al.*, 2012; Suckling and Sforza, 2014). However, there are many countries in which biocontrol agents have been released without prior establishment of the suitability of the climatic conditions to the agents. A typical example is the release of the *Neochetina* weevils against water hyacinth in Rwanda in 2000 (Moorhouse *et al.*, 2001), without any prior assessment of the agents' thermal limits or sensitivity to turbidity. The weevils failed to establish and thus they could have not any impact on weed's invasion. Therefore, the current study investigated the thermal limits of *Neochetina* weevils, *Cornops aquaticum* and *Megamelus scutellaris*. The two latter biocontrol agents are thought to be promising for water hyacinth control in Rwanda. The knowledge of these thermal limits will help to ascertain if the temperate climate of Rwanda was the cause of *Neochetina*'s failure in the country. It will also help to predict if *Cornops aquaticum* and *Megamelus scutellaris* have the potential to establish in Rwanda.

## 7.2 Methods and materials

### 7.2.1 Description of the Rwandan climate

Rwanda is a land-locked country, located at the latitudes of 1 to 3 ºS and longitudes of 28 to 31 ºE. It is bordered to north by Uganda, to the East by Tanzania, to the South by Burundi and to the West by the Democratic Republic of Congo (Figure 2.1). The country is characterized by a complex topography that includes high hills, mountains, and valleys, ranging in altitude from 4507m 950m (Ntwali *et al.*, 2016). This variation in altitude gives the country a moderate climate (Ntwali *et al.*, 2016; Siebert *et al.*, 2019). The weather is temperate and moderate, with average maximum and minimum temperatures of 22.9 ºC and 14 ºC respectively (Muhire *et al.*, 2015). Low temperatures are observed in the high altitude regions where the average annual temperature is 15.9°C (Nshimiyimana *et al.*, 2010). However, this can go down to 8°C for some days in April and May (Haggag *et al.*, 2016). Moderate temperatures are found in areas with intermediate altitude (1350–1550 m) and vary between 19 C and 21°C. In the lowlands (east and southwest with an altitude of 900m) average temperatures vary between 21 °C and 22.9 ºC (Muhire *et al.*, 2015) (Figure 7.1). The extreme high temperature in these regions can reach 35 ºC in July and August for some days (Safari, 2012; Haggag *et al.*, 2016). However, the effects of these warm temperatures on water hyacinth proliferation as well as the establishment and performance of its biocontrol agents are still unknown in Rwanda. Knowing the temperature range within which biocontrol agents can survive and reproduce allows making predictions about where the agents will thrive (Byrne *et al.*, 2004; Byrne *et al.*, 2010, King, 2012; Allen *et al.*, 2012; May and Coetzee, 2013).

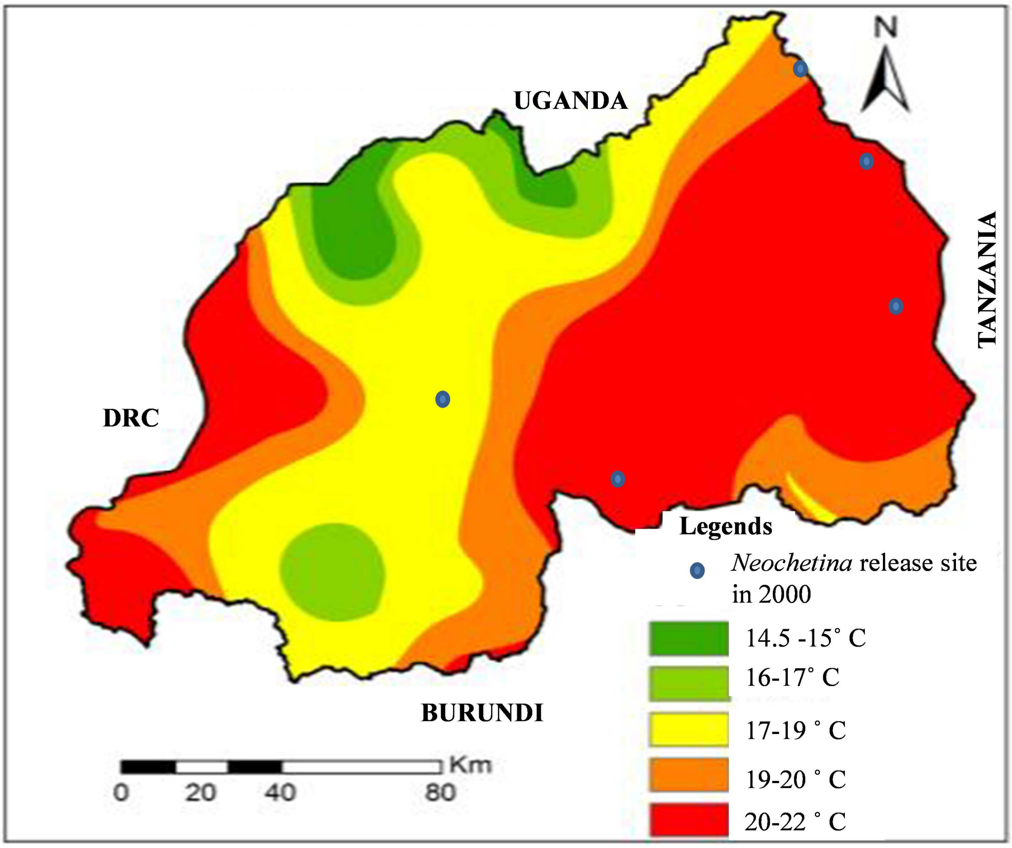


Figure 7.1: Spatial distribution of air temperatures in different regions of Rwanda (Adopted from Muhire *et al*. 2015).

This study aimed to determine the likely effects of Rwanda's moderate climate on the success of biocontrol agents of water hyacinth. The study involved laboratory experiments that aimed to determine the thermal limits (critical thermal and lethal temperature) of biocontrol agents in Rwanda, and the use of CLIMEX modelling to predict the establishment of selected biocontrol agents in different regions of the country.

### 7.2.2 Critical Thermal and Lethal Temperature of *Neochetina* Weevils

The Critical Thermal maximum (CTmax) and Critical Thermal minimum (CTmin) for adult *Neochetina* weevils were assessed using a programmable water bath (Julabo F32-ME, Seelbach, Germany) connected to a Labcon circulator (CPE50). Twelve insects were placed individually into 20 ml glass vials and sealed with moist cotton wool to prevent evaporative cooling of the insects. Vials were then placed into a water bath set at 25°C. The water cooling or heating was done at a rate of 0.5°C per minute until critical thermal temperature (the temperature at which individual *Neochetina* weevils lost the ability to move) was reached. The CTmax and CTmin were recorded when *Neochetina* weevils lost their coordination.

Lower lethal temperature experiments were carried out on adult weevils using a Labcon low temperature water bath (LTB 12/30) with a Labcon circulator (CPE50). Only the lower lethal temperature was investigated as it was found that low temperatures restrict the survival and establishment of biocontrol agents (Cowie *et al.*, 2016), and low temperatures from the high-altitude region (4800 km) in the northern region of Rwanda can reach 5°C during the rainy season (Haggag *et al.*, 2016). Ten weevils were placed separately into 20 ml vials. Thereafter, the vials were placed into a water bath and subjected to target temperatures. After one hour of exposure time, the vials containing the weevils were removed from the water bath. The experiment was repeated with different individuals at the following degrees of temperatures: 2, 1, 0, -1, -2, -3, -4, -5, -6, -7 °C. The temperature at which 50% of 10 *Neochetina eichhorniae* or 10 *Neochetina bruchii* were alive or dead was recorded. Weevils from the water bath were placed into petri dishes for 24 hours to recover.

### 7.2.3 Use of CLIMEX modelling

CLIMEX is a softaware used to develop eco-climatic models that can provide information on the geographical distribution, establishment and distribution of species (Sutherst *et al.*, 1999;

Sutherst *et al.*, 2004; Kriticos *et al.*, 2015). CLIMEX uses meteorological data and climatic responses to predict the probable distribution and relative abundance of ectothermic organisms, including insects, using existing climate data (Kriticos *et al.*, 2015). Given its ability to include over 2000 different locations (meteorological stations) worldwide, the predictions from CLIMEX are more biologically meaningful than the predictions produced by other modelling systems such as ANUCLIM or BIOCLIM (Zalucki and Van Klinken, 2006). CLIMEX has been used in biological control programmes and can be successful in predicting the distribution and establishment of biocontrol agents in newly introduced regions with the purpose of controlling invasive species (Byrne *et al.*, 2002; Byrne *et al.*, 2004; Hoddle, 2004; McConnachie, 2004; Kriticos *et al.*, 2005; Palmer *et al.*, 2007; Cowie *et al.*, 2016). Thus, CLIMEX can help to know the areas that are the best climatic match with potential biocontrol agents of water hyacinth in Rwanda. CLIMEX model for Windows Version 2 (Sutherst *et al.*, 2004) was used to predict the suitability of *Neochetina* weevils*, Cornops aquaticum* and *Megamelus scutellaris*. This was done by matching the Rwandan climate with climates of origin of the biocontrol agents, collection sites located in Benin and the rearing locations in South Africa (Table 7.1). Climate data of four Rwandan stations were used: The Ruhengeri station, that reflects the northern regions' climate data and the release site at the Mukungwa River and upper middle parts of the Nyabarongo River; the Gitega station that reflects the central region climate data and lower part of the Nyabarongo River; the Nyamata station for the Bugesera district and part of the eastern region; and the Rusumo station that captures the climates of the other parts of the eastern region where the Akagera National Park is located.

Table 7.1: Origin and rearing sites of biocontrol agents investigated in this study matched with Rwandan climate.

| Biocontrol agents | Matched sites from different countries |
|---|---|
| *Neochetina* weevils | 1) Argentina (original site of weevils' collection)<br>2) Ouemé and Zou Rivers in the region of Tevedji (collection sites) in Benin<br>3) South African Sugarcane Research Institute, rearing site located KwaZulu-Natal, South Africa |
| *Cornops aquaticum* | 1) Manaus, in Brazil (original site)<br>2) Rietondale, Pretoria, South Africa |
| *Megamelus scutellaris* | 1) Corrientes regions of Argentina<br>2) Waainek Research Facility from Rhodes University Grahamstown, South Africa |

### 7.2.4 Data analysis

Descriptive statistics such as mean and standard deviation were used to provide a summary about CTmax, CTmi, LTmin measures of biocontrol agents tested in this chapter. Lethal temperature ($LT_{50}$), at which 50% of *Neochetina* weevils were predicted to die, was obtained using probit analyses as described by Mitchell *et al*. (1993). A repeated measures ANOVA followed by turkey HSD post-hoc test was used to compare means of maximum and minimum temperature data from the intended Rwandan release sites to those of the biocontrol agents' origin, collection or rearing sites. The match climates attribute in CLIMEX software was used to predict the climatic suitability between the Rwandan climate and the climates of the regions of origin of the biocontrol agents using composite match indices

## 7.3 RESULTS

### 7.3.1 Thermal Limits

The biocontrol agents selected for use in Rwanda all show a broad range of tolerance to high and low temperatures, which would allow them to establish in Rwanda (Table 7.5).

Table 7.2: Thermal limits for the biological control agents *N. eichhorniae* and *N. bruchi,* released against water hyacinth in Rwandan water bodies in 2002, and *Cornops aquaticum* (Venturi unpublished data) and *Megamellus scutellaris* (Coetzee unpublished data), intended biocontrol agents to be released in Rwandan.

| Insects | CTmax | CTmin | LT min |
|---|---|---|---|
| *Neochetina eichhorniae* | 47.3 ± 1.1 | 2.4 ± 0.81 | -3.7±0.36 |
| *Neochetina bruchii* | 48.1 ± 0.97 | 2.61 ± 1.07 | -3.7±0.36 |
| *Cornops aquaticum* | 47.9 ± 0.53 | 6.15 ± 0.09 | No data |
| *Megamelus scutellaris* | 39.14±0.42 | 4.7±0.37 | -3.2 ± 0.46 |

### 7.3.2 Comparison of different climatic conditions

Generally, the results from climatic matching showed a good match between the Rwandan and the native range climate conditions (Table 7.2, 7.3 and 7.4). In most Rwandan release sites, *Neochetina* weevils had matches over 50% when compared to Argentinean native areas, collection sites in Benin, and rearing sites in South Africa (Table 7.2). A high match in minimum and maximum temperatures, above 50%, was obtained between Rwandan, Argentinean and South African climatic conditions, but not with that of Benin (Table 7.2).

The potential release sites for *Cornops aquaticum* in Rwanda displayed a total index match above 50% when compared to the site of origin of *C. aquaticum* (Table 7.3). Good matches were found when comparing the Rwandan climate to the rearing site of *C. aquaticum* in Pretoria, South Africa (Table 7.3). Moreover, climatic matching indicated the suitability of *M. scutellaris* from the Corrientes region in Argentina being introduced into Rwandan sites with an overall match above 60% (Table 7.4). However, it was observed a low match, below 50%, in the minimum and maximum temperature between when compring Rwandan sites and the rearing sites of *M. scutellaris* in South Africa (Table 7.4).

Table 7.3: CLIMEX comparison between Rwandan release sites of *Neochetina* weevils and their sites of origin in Argentina, collection sites (Tevedji and Lihu) in Benin where weevils were collectedfrom and transported to Eastern Africa countries, and the rearing sites of *Neochetina* weevils at KwaZulu-Natal, South Africa.

| Rwandan weather stations | CLIMEX match index (%) for Rwandan proposed sites for biocontrol release and Argentinean native areas, collection sites in Benin, and rearing sites in South Africa | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Buenos Aires sites | | | Beninese sites | | | KZN, South Africa | | |
| | Total Index | Max Temp | Min Temp | Total Index | Max Temp | Min Temp | Total Index | Max Temp | Min Temp |
| Rusumo | 68 | 56 | 50 | 63 | 69 | 52 | 76 | 61 | 62 |
| Ruhengeri | 76 | 53 | 58 | 72 | 54 | 58 | 58 | 56 | 54 |
| Gitega | 63 | 51 | 64 | 63 | 53 | 55 | 66 | 54 | 56 |
| Nyamata | 71 | 63 | 58 | 68 | 52 | 61 | 64 | 55 | 52 |

Table 7.4: Comparison of Rwandan sites proposed for release of *Cornops aquaticum*, with the sites origin of *C. aquaticum* in Brazil and their rearing site in Pretoria, South Africa.

| Rwandan Weather Stations | CLIMEX match index of intended Rwandan release sites and origin sites and rearing sites of *C. aquaticum* | | | | | |
|---|---|---|---|---|---|---|
| | Manaus, Brazil | | | Pretoria, South Africa | | |
| | Total Index | Max temp | Min temp | Total Index | Max temp | Min temp |
| Rusumo | 58 | 54 | 49 | 64 | 62 | 58 |
| Ruhengeri | 53 | 63 | 53 | 68 | 54 | 56 |
| Gitega | 65 | 62 | 56 | 74 | 66 | 79 |
| Nyamata | 78 | 64 | 80 | 72 | 65 | 86 |

Table 7.5: Comparison of Rwandan proposed release sites for *Megamellus scutellaris* and their sites of origin and the rearing site at the Waainek research facility, Grahamstown, South Africa.

| Rwanda weather stations | CLIMEX match index (%) of Rwandan intended release site and origin sites of *Megamellus scutellaris* from Corrientes region of Argentina and its rearing site in Grahamstown, South Africa | | | | | |
|---|---|---|---|---|---|---|
| | Corrientes region of Argentina | | | Grahamstown, South Africa | | |
| | Total index | Max temp | Min temp | Total index | Max temp | Min temp |
| Rusumo | 717 | 61 | 62 | 59 | 50 | 52 |
| Ruhengeri | 42 | 31 | 27 | 46 | 35 | 21 |
| Gitega | 65 | 58 | 62 | 42 | 39 | 28 |
| Nyamata | 70 | 610 | 55 | 42 | 32 | 22 |

Compared to the Rwandan climate, mean maximum temperatures from Argentina, were statistically different ($F_{4, 5} = 42.2$; $P < 0.01$) (Figure 7. 2). The Argentinean mean minimum temperatures were also significantly lower compared to Rwandan low temperatures ($F_{4, 5}$ =

52.562; P < 0.01). The mean maximum temperatures of Benin and Brazil were higher than the Rwandan maximum temperatures but not statistically significant ($F_{4,5} = 12.45$; $P > 0.05$; $F_{4,5} = 18.215$; $P > 0.05$) (Figure 7.2). The mean minimum temperatures of Benin and Brazil were significantly higher than the mean minimum temperatures of the Rwandan proposed sites for release ($F_{4,5} = 27.84$; $P < 0.01$; $F_{4,5} = 37.142$; $P < 0.01$ respectively (Figure 7.3).
7.3).

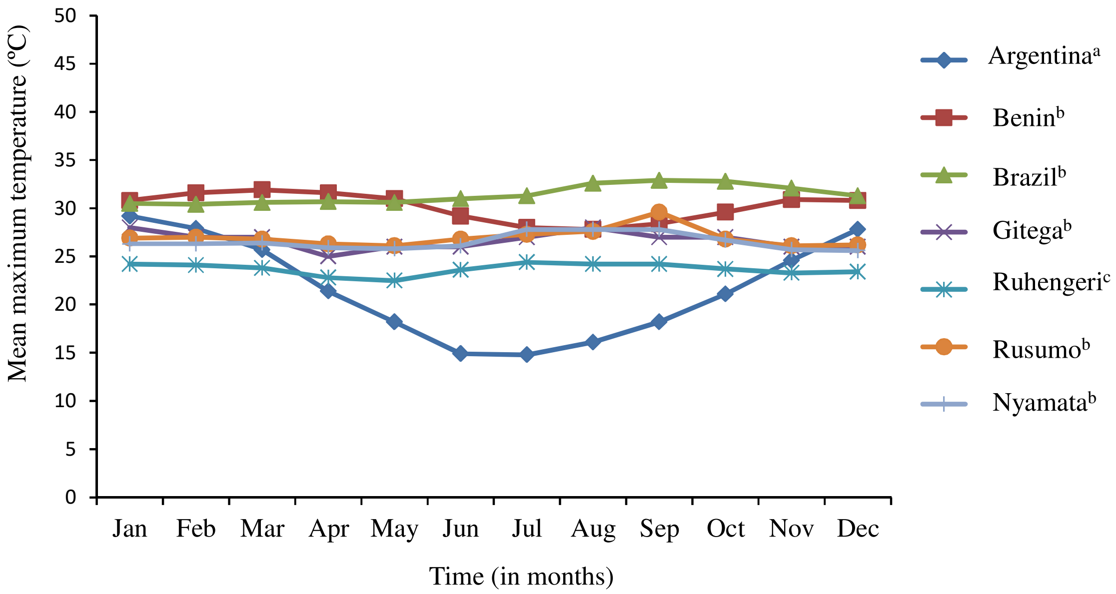


Figure 7.2: Monthly maximum temperatures for Argentinean, Beninese and Brazilian biocontrol agent's collection sites and Rwandan proposed sites for release of *Neochetina* weevils, *C. aquaticum* and *M. scutellaris*. Climatic data were produced using CLIMEX. A repeated measure ANOVA followed by Turkey HSD post-hoc test, was used to determine the statistical significance of differences in maximum temperatures between the different sites at p <0.05. The same lower case letters indicate no statistically significant in maximum temperature between sites.

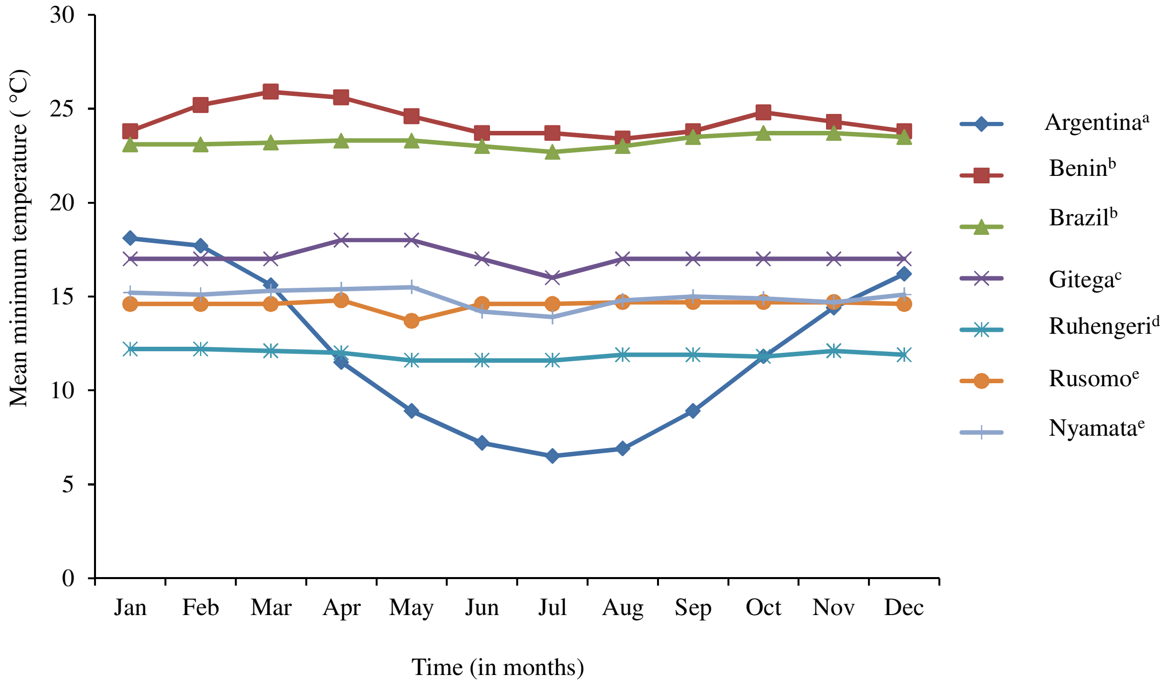


Figure 7.3: Monthly minimum temperatures for Argentinean, Beninese and Brazilian biocontrol agent's collection sites and Rwandan proposed release sites for *Neochetina* weevils, *C. aquaticum* and *M. scutellaris*. Climatic data were produced using CLIMEX. A repeated measure ANOVA followed by Turkey HSD post-hoc test, was used to determine the statistical significance of differences in minimum temperature between the different sites at $p < 0.05$. The same lower case letters indicate no statistically significant in minimum temperaturebetween sites.

### 7.4 Discussion

The establishment and performance of biocontrol agents of water hyacinth are constrained by extreme temperatures (Hill and Olckers 2001). The results from this study showed that Rwandan temperatures are not a threat to biological control agents selected for this study, confirming that the four biocontrol agents *Neochetina eichhorniae*, *Neochetina bruchi*, *Cornops aquaticum* and *Megamelus scutellaris* are likely to establish and perform well in controlling water hyacinth in Rwandan water systems.

***Neochetina* weevils**

*Neochetina* weevils can establish in many cold areas but will have unsignificant impact on water hyacinth (Byrne *et al.*, 2010; King, 2012). The hypothesis of the current study was that *Neochetina* weevils cannot control water hyacinth in Rwanda because of low temperatures in the northern regions and high temperatures in eastern regions. However, the study revealed that the weevils can survive at both high (22 to 33 ºC) and low temperatures (12 ºC to 8ºC). The CTmin (2.42 ºC for *N. eichhorniae* and 2.6 ºC for *Neochetina bruchii*) and lower lethal temperature (-3.7 ºC) suggest that both species of weevils will not be affected by the Rwandan low temperatures. Normally cold stress affects insects at temperatures below their CTmin and lower LT (Chown and Nicolson, 2004). This, however, will not be an issue for *Neochetina* weevils since the low temperature in the northern region varies between 12 ºC to 8 ºC. The study by Reddy *et al.* (2018) also found that weevils from Australia will establish better in the Delta River, Northern California compared to the *Neochetina* weevils from South Africa and Uruguay since their CTmin (1.9 ºC) are below the low average temperature (3.9 ºC) of the Northern California regions.

In addition, the evidence from climate matching confirmed the suitability of *Neochetina* weevils for use in Rwanda, even if the level of matching varies across regions. An example is the low total index (58%) obtained when matching climates for the central region of the country and climates of Benin. This suggests that there will be a low establishment of *Neochetina* weevils from Beninese regions introduced to the central regions of the Rwanda. On other hand, a high matching index (above 60%) between the climate of the northern and eastern regions and climates of Beninese regions indicates the good establishment of *Neochetina* weevils from Benin. The study suggests that the Rwandan climate is suitable to *Neochetina* weevils from all sites considered in this study (Argentinean sites, Beninese sites and the rearing sites in South Africa). The study by Firehun *et al.* (2015) revealed that *Neochetina* weevils are the best biocontrol agents that can permanently populate the Western and Eastern regions of Africa. Warm and temperate climates that characterize the Western and Eastern regions of Africa, including Rwanda, are the most suitable for *Neochetina* weevils. The climate matching method provides an insight into the potential distribution, establishment and performance of *Neochetina* weevils on water hyacinth in the aforementioned regions of Africa (Firehun *et al.*, 2015). Based on the results of this chapter and the preceding chapters, it is evident that water nutrients and temperatures were not the causes of the non- establishment of *Neochetina* weevils and not having any impact on water hyacinth invasion in Rwanda.

*Neochetina* weevils released in Rwandan lakes such as Lake Mihindi and Lake Ihema probably failed to establish because of the low number released into each lake (Moorhouse *et al*., 2001). On the other hand, *Neochetina* weevils released in the Nyabarongo River and the Akagera River probably failed because of the high turbidity in those rivers (Chapter 5). Non establishment of *Neochetina* weevils in Rwandan water bodies was also confirmed by the absence of *Neochetina* weevils observed during field surveys conducted in 2016, visiting the above mentioned rivers and lakes in which weevils had been released. Non establishment of *Neochetina* weevils was probably due to low number of weevils (25 agents per sites) Rwandan water bodies (Moorhouse *et al*., 2001).

***Cornops aquaticum***

A critical thermal minimum (CTmin of 6.15 ºC) suggests that *Cornops aquaticum* can establish in Rwanda. The low temperature in Rwanda may go down to 8 ºC for some days in April and May (Meteological data, 2018; *Siebert et al*., 2019, and this "extreme" temperature will not prevent *C. aquaticum* from establishing since it is higher than its CTmin. This is not, however, the same in other countries that experience low temperatures and frost. One such example is the cold temperature recorded at Breede River and Crocodile River in South Africa, where the low minimum temperatures are lower than CTmin of *C. aquaticum* reaching 1 ºC. In areas that experience low temperatures and frost, biocontrol agents may experience a "chill coma" and stay there, approximately 3 to 4 hours during winter (Byrne *et al*., 2010). This hinders insect population establishment (Bale *et al*., 2002; Weisser and Siemann, 2013) and leaves individuals vulnerable to predation. However, this will not happen in Rwanda, since there are no such extreme low temperatures. In addition, the winter season in Rwanda is not characterized by frost as in the other countries where *C. aquaticum* failed to establish (Adis *et al*., 2007). The Rwandan winter is characterised by rain (Hagg *et al*., 2016) which should not be a constraint to the establishment of *C. aquaticum*. Given the high match index of 58% and above between the Rwandan, Brazilian, and South African climates, the temperate climate in Rwanda is likely to be favourable for the establishment of *C. aquaticum* in all the sites proposed for release of the agent in Rwanda.

***Megamelus scutellaris***

*Megamelus scutellaris* has been selected as the best biocontrol agent of water hyacinth in the cooler, high-altitude regions of South Africa due to its origin in high-altitude regions of Argentina and Peru (Tipping *et al*., 2008). However, the current study showed that *M. scutellaris* should also control water hyacinth in both warm and temperate climates. Both its CTmax and CTmin indicate that Rwandan temperatures are suitable for *M. scutellaris,* since low temperatures in Rwanda are higher than the CTmin (4.7 ºC) and the lower lethal temperature of *M. scutellaris* (-3.2 ºC). However, the CLIMEX results suggest the establishment of *M. scutellaris* from Argentina in all proposed Rwandan release sites except in the northern regions. This is because this region is characterised by low temperatures (12–8 ºC), especially in April and May. Although there is no frost incidences in winter (Muhire *et al*., 2015), *M. scutellaris* cannot grow in an environment with low temperatures (<15ºC) (Grodowitz *et al*., 2017).

**Conclusions**

The biocontrol agents for water hyacinth released in Rwanda in the past failed to establish and control the weed and no post-release investigations or any other efforts were undertaken to determine the reasons behind this failure and explore new biocontrol options. This study highlighted the importance of prior knowledge on the suitability of potential biocontrol agents to proposed sites of release. All biocontrol agents tested in this study were compatible with the Rwandan climatic conditions and they should perform well at Rwandan temperatures. Such investigations are needed to predict the success and efficacy of biological agents before their release and to monitor population sizes after being released. Overall, the best biocontrol agents among those tested here are *Neochetina* weevils and *C. aquaticum* as they can establish in all potential sites for release. However, the *Neochetina* weevils will be affected by seasonal high turbidity in some Rwandan rivers (refer to Chapter 5). Hence this study suggests that *Cornops aquaticum* will establish in all proposed release sites. *Megamellus scutellaris* shoul be also considered since they will establish in all proposed Rwandan sites, except sites from Northern region of the country.

# CHAPTER 8:

# WATER HYACINTH IN RWANDAN WATER SYSTEMS: A SYNTHESIS

## 8.1 Introduction

Water hyacinth remains a threat to freshwater bodies in tropical, subtropical and warmer temperate regions (Hill, 2003). Its spread in freshwater ecosystems leads to a marked disruption of aquatic ecosystems by reducing dissolved oxygen and sunlight penetration necessary for aquatic life. Its impacts, however, are not only restricted to aquatic life forms: Water hyacinth invasions also affects the socio-economic activities of the nearby communities by impeding boat navigation, recreational activities, fishing, irrigation channels, reducing water quality and blocking turbines for power generation (Shekede *et al.*, 2008; Theel *et al.*, 2008; Villamagna and Murphy, 2010; Schultz and Dibble, 2012). Since its first declaration as an invasive weed in Rwanda, the government and other stakeholders have been trying to find a suitable and effective method to control its invasion. Following the failure of the biological control attempted in 2000, the country resorted to campaigns of intensive manual removal of water hyacinth. However, the weed invasion has persisted and continued to spread and flourish further in many Rwandan water bodies (REMA, 2016). Thus, aims of the study were to: (1) to provide detailed information on water hyacinth's distribution in Rwanda on its extent in each invaded water body, documenting the changes over time, as well as to provide information on abiotic factors that contribute to water hyacinth's proliferation and distribution in the water systems (rivers, lakes and wetlands) using remote sensing techniques.(2) To investigate and identify the possible reasons behind the failure of attempted biological control in 2000. (3) To analyse the feasibility of biological control of water hyacinth in Rwanda.

This chapter aims to synthesise major findings of the work and to draw final conclusions and recommendations for Rwandan government, policy makers, and stakeholders involved in the management of Rwandan water bodies, also biocontrol practitioners of water hyacinth who are keen to help Rwanda to combat the weed invasion.

## 8.2 Mapping water hyacinth using remote sensing techniques

Prior to any management intervention for water hyacinth control, identifying and mapping the extent and distribution of the weed effectively is paramount for prioritizing resource allocation and sustainably curbing the weed population. The common practice for such data acquisition is, the traditional field survey method used around the world (Ballatore *et al.*, 2014). The growing advancement in remote sensing has, however made the effective mapping of plant invasion (Thamaga and Dube, 2018). Remote sensing can timely and accurately map floating-leaved plants as mats that move from one place to another in open water bodies (Shekede *et al.*, 2008). Since water hyacinth was recognized by the Rwandan law as an invasive plant in 1999, there have been two attempts to map its invasion in the country using field-based techniques (REMA, 2009; 2016). However, neither of those reports was able to determine the spatial distribution of water hyacinth or to quantify its extent. The current study employed Landsat 8 to detect and quantify the occurence and extent of water hyacinth in Rwandan water bodies (chapter 2). This revealed water hyacinth coverage (%) in each identified invaded water body. Furthermore, the study revealed that the wetlands, such as the Gashora, Akanyaru and Akagera Wetlands, through which invaded main rivers pass, are also invaded by the water hyacinth (chapter 2); while the previous reports did not mention its presence in any wetlands. Besides being spatially constrained, field surveys are unable to detect new invasions of weeds, and thus, cannot provide continuous information without the expense of a new survey (Ritchie *et al.*, 2003). The availability of archival and real-time Landsat data dating back to the early 1970s provided any opportunity for spatio-temporal observations of water hyacinth over 28 years (1989–2017) (Chapter 3). Continual coverage data of Landsat data aid in identifying and assessing efficacy of measures and management practices currently in place (Shekede *et al.*, 2008; Penatti *et al.*, 2015). Using Landsat data (Landsat 5, 7 and 8), the current study confirmed that water hyacinth was already present in Rwandan water bodies long time ago since in 1989 water hyacinth coverage was above >10%. Although manual removal has been intensified since 2002, water hyacinth continues to spread in most Rwandan water systems including small lakes (chapter 3). These results confirm the drawbacks of manual removal, including reinvasion of the weed once removal is stopped. An example of this is Lake Cyohoha, where intensive manual removal was carried out from 2009 to 2014 (REMA, 2016); However, the lake is now reinfested by the weed with coverage above 22% (chapter 3). This problem of the persistence of water hyacinth after intense manual removal was also noticed in the Zhu River of Guangdong Province, China (Lu *et al.*, 2007).

Although remote sensing is not yet being used to monitor water hyacinth in Rwanda, the current study found that it is a useful approach that can help get continuous data on the water hyacinth infestation in Rwanda. With remote sensing it is easy to get monthly or annual data without conducting field surveys all the time. It will be easy to measure the annually rate of water hyacinth growth in each invaded water body, which will help to track the success or failure of water hyacinth control measures in the country.

### 8.3 Mapping water abiotic factors contributing to water hyacinth proliferation

Besides identifying water hyacinth distribution and quantifying its extent in Rwandan water systems, it is crucial to understand the status of abiotic factors that contribute to water hyacinth growth and spread (Hill and Olckers 2001). Among these, are nitrogen, phosphorus (Reddy *et a*l., 1989; 1990) and temperature (*Shu et al.*, 2014). Kenfack Voukeng (2016) revealed that salinity and pH influence water hyacinth growth. In addition to this, the current study revealed that turbidity also enhances water hyacinth growth (chapter 5). It is therefore imperative that these water parameters be appropriately investigated and assessed prior to any management intervention. This will help to determine the type of control necessary, the time required to achieve successful control, and finally, the level of control that is likely to be achieved. Field-based methods have been used to quantify the levels of abiotic and biotic factors. However, it is costly and time consuming and cannot provide both spatial and temporal information on the levels of water abiotic factors across a wide area (Gholizadeh *et a*l., 2016). Remote sensing techniques can deliver such information. In this regard, the current study used Landsat 8 to determine spatial information on turbidity, nitrogen, phosphorus and temperature in the dry and wet seasons. Landsat 8 revealed high levels of these parameters in rivers compared to lakes and that these levels increased during the rainy season (Chapter 4). Turbidity, temperature, nitrogen and phosphorus are considered as indicators of water quality and key influencers on the health of aquatic ecosystems in general (Ndugu, 2014). Water bodies with high levels of those parameters are those with high water hyacinth coverage, which means that turbidity, nitrogen, phosphorus and temperature influence water hyacinth growth in the Rwandan water systems. This is confirmed by a strong correlation between the turbidity levels, nutrient levels and temperature in rivers and water hyacinth coverage in the same rivers, such as the Akagera, Nyabarongo and Akanyaru Rivers (Chapter 4). In addition to this, high turbidity was found to enhance water hyacinth growth (Chapter 5). Thus, the spatial and temporal status of such factors in water systems is crucial to manage natural water resources in the country, as well as the management of water hyacinth in Rwandan water systems.

### 8.4 Feasibility of biological control of water hyacinth in Rwanda

The increasing invasion of water hyacinth needs a sustainable, long-term solution and the integration of numerous techniques in which biological control is an essential component. Experience gained in biological control of water hyacinth in different regions worldwide suggests that biological control offers a potentially excellent, long-term solution to problems caused by invasive alien plant species. However, the impact of that biological control agents offer may vary from one region to another, since environmental factors that influence both invasive species and its biocontrol agents are different from one region to another. Thus it is imperative to understand the impact of local abiotic factors on those biocontrol agents prior to introducing biological control agents in new environments (Morin *et a*l., 2009). This knowledge provides insight into the biocontrol agents that are most likely to be effective (Van Klinken and Raghu, 2006). Among the environmental abiotic factors that may hamper the effectiveness of biological control of water hyacinth are nutrient levels and climatic conditions (Hill and Olkers, 2001; Broughton and Pemberton, 2008). Field surveys, laboratory studies and modelling studies on abiotic factors affecting biological control of water hyacinth have been conducted in other countries to predict their effectiveness or failure (Hauptfleisch, 2015). However, such studies have never been attempted for Rwanda, which had a bad impression of biocontrol after its failure. Therefore, authorities have remained unaware of its potential. This study found that biological control of water hyacinth is feasible in Rwanda. High nutrient levels (nitrogen and phosphorus concentrations) in Rwandan rivers, especially in the Akagera River, may limit the effectiveness of all potential biocontrol agents, especially during the wet season. However, medium and low nutrients in the Rwandan lakes and other rivers such as the Mukungwa and Akanyaru Rivers will allow both the establishment of biocontrol agents and their performance on water hyacinth (Chapter 6). Bownes (2009) showed that water hyacinth continues to grow and compensate for biocontrol agent’s damage at high nutrient levels. On the other hand, Mukarugwiro *et a*l. (2018) found that in oligotrophic and mesotrophic waters, biocontrol agents take time to develop but their damage to water hyacinth is high.

The warm Rwandan climate was found to be suitable to all the potential biocontrol agents except *Megamelus scutellaris*, which would be affected by the low temperatures of the Northern Province. However, this agent is a potential use to control water hyacinth in other regions of the country where its establishment should be high (Chapter 7).

Although the nutrient levels and temperature conditions in Rwanda are favourable for *Neochetina* weevils, high turbidity in the rivers, which increases during the wet season, would hamper the establishment of weevils (Chapter 5). Turbidity is one of the water parameters able to influence other parameters such as dissolved oxygen, water nutrients and water temperature (Kale, 2016). High turbidity causes a decrease in dissolved oxygen (Chapter 5), which leads to reduced adult emergence because pupae die by asphyxia. Turbidity has received little attention in the biological control of aquatic invasive species, but it affects not only dissolved oxygen but also water temperature (Kale, 2016). High turbidity can raise surface water temperatures above normal by facilitating the absorption of heat from sunlight (Kale, 2016) and may impede the establishment of biocontrol agents such as *M. scutellaris*, which is affected by temperatures above 30 ºC and temperatures below 15 ºC (Grodowitz *et al.,* 2017). However, Rwandan water surface temperature do not currently go above 30 ºC and *Cornops aquaticum* and *Megamelus scutellaris* are agents that do not pupate in the roots of water hyacinth; therefore, Rwandan water turbidity and temperature will not affect them (Chapters 6 and 7). Thus they should be released in both lakes and rivers, specifically in the rivers where *Neochetina* weevils cannot establish.

**Conclusions and recommendations**

This study has highlighted the value of remote sensing techniques in detecting and mapping water hyacinth invasions and at the same time providing spatial and temporal information on the abiotic factors that enhance the proliferation of the weed in the Rwandan water systems. This study also revealed that biological control is feasible in Rwanda and could be successful. However, this method would need to be coupled with other integrated management strategies, especially in the sites where biocontrol agents will be limited by high levels of water nutrients and turbidity.

**a) Recommendations to biocontrol practitioners**

Although *Cornops aquaticum* and *Megamelus scutellaris* should cope with relevant environmental factors in Rwanda, the following the step that are suggested before their release into Rwandan water bodies to ensure their success once the decision to use them in Rwanda is made:

1. Investigating other thermal limits such as the degree day and the developmental rate of *C. aquaticum* and *M. scutellaris* using low Rwandan temperatures to determine if the daily low temperatures will affect these biocontrol agents.
2. Host specificity test of *C. aquaticum* and *M. scutellaris* to determine if these two insects will attack non-target species in Rwanda.
3. Studies on the ecological and socio-economic impacts of water hyacinth in Rwanda should be conducted prior to implementing a biological control programme in the country.

**b) Recommendations to the Rwandan government and policy makers**

1. The long-term monitoring and seasonal mapping of water hyacinth in all affected water bodies is needed in Rwanda to successfully control water hyacinth. For this to be achieved, remote sensing techniques should be used instead of only using field surveys.

2. It is important to consider and learn from what has been done to combat water hyacinth invasions in other African countries such as Kenya, Tanzania, Uganda, Benin, South Africa, Ghana, Zambia and Sudan, which have put into practice a number of national and regional biological control strategies. The success story of the control of water hyacinth in Lake Victoria through biological control is a good example that the Rwandan government should consider. The integrated management programmes that are used in South Africa should be also example for the Rwandan government, policy makers and other stakeholders involved in the management of water resources.

3. The Rwandan government should collaborate with international organizations and research centres that can provide technical support and regular advice on how to control water hyacinth. Some of these include the International Center of Insect Physiology and Ecology (ICIPE), Centre for Agriculture and Biosciences International (CABI), Center for Biological

Control (CBC) at Rhodes University Sout Africa, the Commonwealth Scientific and Industrial Organization (CSIRO), International Institute of Biological Control (IIBC), the Food and Agricultural Organization of the United Nations (FAO) etc.

**c) Proposed pilot study for biological control programme in Rwanda**

Biological control of water hyacinth is feasible and is the only sustainable method to combat the weed invasion in Rwandan water bodies. However, before rolling out biological control program into all water bodies, a pilot study should be carried out in one of infested lakes for example Lake Rweru, which is located in the Bugesera district, Eastern Province. This lake has warm temperature, low and medium nutrients and low turbidity (<439 NTU) (Chapter 4). All these water parameters can allow biocontrol agents to establish and perform well on water hyacinth in Lake Rweru (Chapter 5). The proposed pilot study would involve release of *Neochetina* weevils and *Cornops aquaticum* into the Lake Rweru. The Rwandan Agricultural Board (RAB) station of the Bugesera district will provide a space for insect rearing stations. The first release of biocontrol agents can be done at the beginning of the dry season (start from mid-June). During this trial of biological control in Lake Rweru, , both remote sensing and field surveys techniques can be used to evaluate the impact of both proposed biocontrol agents on water hyacinth growth. This evaluation can be done monthly over a period of one year.

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