

IMPACT AND CONTROL OF WATERWEEDS IN THE SOUTHERN MOZAMBIQUE BASIN RIVERS

A thesis submitted in fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

of

RHODES UNIVERSITY

by

Sílvia da Fátima Langa

2013

Frontispiece



Mats of aquatic weeds (water hyacinth, water lettuce and red water fern) in the Incomati River.



Barrier used to control aquatic weeds in Xinavave (Incomati River).



Eichhornia crassipes mat negatively affecting domestic water use at Umbeluzi River.



Eichhornia crassipes hampering navigation at Incomati River.

Abstract

In Mozambique, establishment of aquatic weeds has been enhanced through the increased enrichment of water bodies by nutrient runoffs from human and agricultural wastes that lead to an increase in nitrate and phosphate in the water. The aquatic weeds, water hyacinth (*Eichhornia crassipes*), red water fern (*Azolla microphylla*), water lettuce (*Pistia stratiotes*) and salvinia (*Salvinia molesta*) were found in most watercourses in Mozambique and are becoming aggressive in some watercourses, especially in the Umbeluzi and Incomati rivers. Farmers and people living along the rivers are aware of the negative impact of the water weeds because the large mats of weeds cause loss of shoreline and navigability along the rivers. Other commonly perceived effects of aquatic invasive plants in Mozambique rivers include: reduced navigable surface area; difficulties for fishermen, which reduces income; increased prevalence of insects and insect-borne disease, and decreased aesthetic value. The methods currently used for the control and management of the aquatic weeds are mechanical and manual control. Both methods are costly, time consuming, and only provide a short-term solution to the problem. The study found that the weevils *Neochetina eichhorniae* and *N. bruchi* were effective biological control agents in the study area but their impact is too gradual compared to the aggressive proliferation of water hyacinth. The one year lab-experiment clearly demonstrated that the water lettuce weed had a significant impact on the recruitment of macro-invertebrates to the artificial substrates, and water lettuce contributed to the reduction of oxygen in the water and consequent reduction of macro-invertebrate abundance and diversity. The biodiversity recovered at the same time in the pools containing water lettuce controlled by *N. affinis* and water lettuce controlled by herbicide, but richness and diversity of macro-invertebrates was higher in the water lettuce controlled by *N. affinis* during the first sampling occasion compared to the water lettuce in pools controlled by herbicide, where macro-invertebrates increased only when DO levels recovered after water lettuce mat decay. The number of taxa recorded in this study is an indication of the significance of macro-invertebrates in an aquatic environment. This therefore emphasizes the need for more research efforts into macrophyte and macro-invertebrate associations in the aquatic system to better understand the implications of habitat modification arising from human activities. It will also enable us to be better equipped with a more appropriate ecological understanding for aquatic resources management.

Table of Contents	Page
Frontispiece	1
Abstract	3
Table of contents	4
Contents	4
List of Figures	11
List of Tables	17
Acknowledgements	20

Contents

Chapter 1	22
General Introduction	22
1.1 Introduction.....	22
1.2 Invasive aquatic plants and their distribution.....	22
1.3 Mechanism of invasion by aquatic plants	23
1.3.1 Modes of introduction.....	24
1.3.2 Vacant niche hypothesis	24
1.3.3 Enemy release hypothesis.....	25
1.3.4 Disturbance hypothesis	25
1.4 Impacts of invasive aquatic plant species	26
1.5 Invasive aquatic plants problems around the world.....	27

1.6	The most important aquatic weeds in Mozambique.....	29
1.6.1	<i>Eichhornia crassipes</i>	31
1.6.1.1	Origin and distribution of <i>Eichhornia crassipes</i>	31
1.6.1.2	Methods of controlling water hyacinth	32
1.6.1.3	Uses of water hyacinth	35
1.6.2	<i>Pistia stratiotes</i>	36
1.6.2.1	Origin and distribution of <i>Pistia stratiotes</i>	36
1.6.2.2	Methods of controlling water lettuce	36
1.6.2.3	Uses of <i>Pistia stratiotes</i>	37
1.6.3	<i>Salvinia molesta</i>	38
1.6.3.1	Origin and distribution of <i>Salvinia molesta</i>	38
1.6.3.2	Methods of controlling <i>Salvinia molesta</i>	39
1.6.3.3	Uses of <i>Salvinia molesta</i>	40
1.6.4	Red water Fern (<i>Azolla</i> spp.)	40
1.6.4.1	Origin and distribution of <i>Azolla filiculoides</i>	40
1.6.4.2	Methods of controlling <i>Azolla</i> spp.	41
1.6.4.3	Uses of <i>Azolla filiculoides</i>	42
1.7	Thesis outline	43
Chapter 2.	.....	47
Distribution of aquatic invasive weeds in southern Mozambique rivers.....		47
2.1	Introduction	47
2.2	Specific objectives.....	47
2.3	Material and methods	47
2.3.1	Sampling procedures.....	47
2.3.2	Characteristics of the sites sampled	48
2.3.3	Survey of the occurrence, diversity and abundance of aquatic invasive alien plants.....	51

2.3.4	Survey on the abundance of aquatic invasive plants	52
2.3.5	Percentage cover of the aquatic macrophytes.....	52
2.3.6	Mapping.....	52
2.3.7	Data analysis	53
2.4	Results	54
2.4.1	Relative density of aquatic plants along the southern Mozambique Basin rivers ..	54
2.4.2	Percentage covers of aquatic macrophytes	57
2.4.3	Distribution of different aquatic weeds.....	60
2.4.3.1	Distribution of the water hyacinth, <i>Eichhornia crassipes</i> along southern Mozambique rivers	60
2.4.3.2	Distribution of <i>Salvinia molesta</i> along the southern Mozambique rivers.....	64
2.4.3.3	Distribution of red water fern <i>Azolla microphylla</i> along southern Mozambique rivers.....	65
2.4.3.4	Distribution of the water lettuce, <i>Pistia stratiotes</i> along southern Mozambique rivers.....	69
2.5	Discussion	71
2.6	Conclusion.....	74
Chapter 3.	.....	76
Socio-economic impact of water weeds in the Incomati River in Mozambique.....		76
3.1	Introduction	76
3.2	Specific objectives.....	79
3.3	The study area	79
3.4	Material and methods.....	80
3.4.1	Sampling procedures.....	80
3.4.2	Data analyses	81
3.5	Results	82
3.5.1	Characteristics of the respondents	82
3.5.2	Activities performed along the Incomati River Basin by local population	84
3.5.3	Weed distribution and coverage in three regions in the Incomati River.....	85

3.5.4	Local perceptions of aquatic weeds along the Incomati Basin River	86
3.5.5	Impact of the aquatic weeds on the local population along the Incomati River Basin.....	88
3.5.6	Estimation of annual income from the main activities during 2010 in the Incomati River.....	93
3.5.7	Control of aquatic weeds in Incomati River	98
3.6	Discussion	100
3.6.1	Major threats to the Incomati River.....	100
3.6.2	Management of aquatic weeds.....	103
3.7	Conclusion.....	103
Chapter 4.	.....	104
Status of aquatic weeds associated with biological control agents in the southern Mozambique rivers	.....	104
4.1	Introduction	104
4.2	Specific objectives.....	104
4.3	Material and methods	105
4.3.1	Description of the study area	105
4.3.1.1	Govuro, Inharrime and Save reference sites	105
4.3.1.2	Maputo and Limpopo rivers.....	106
4.3.1.3	Umbeluzi and Incomati rivers.....	106
4.3.2	Sampling procedures for assessment of weevils, <i>Cyrtobagous salviniae</i> , <i>Neohydronomus affinis</i> and <i>Stenopelmus rufinasus</i>	106
4.3.3	Sampling procedure for assessment of weevils <i>Neochetina eichhorniae</i> and <i>N. bruchi</i>	106
4.3.4	Statistical analyses	108
4.4	Results	108
4.4.1	Estimation of weevils <i>Neohydronomus affinis</i> , <i>Stenopelmus rufinasus</i> and <i>Cyrtobagous salviniae</i> , on their host plants along the southern Mozambique rivers	108
4.4.2	Characteristics of water hyacinth plants in the southern Mozambique rivers	110

4.4.3	Effect of the weevil <i>Neochetina eicchorniae</i> , <i>N. bruchi</i> , mite and pathogens on the water hyacinth plants along the southern basin rivers	118
4.5	Discussion	124
4.5.1	Biological control of <i>Azolla microphylla</i>	124
4.5.2	Biological control of <i>Pistia stratiotes</i>	124
4.5.3	Biological control of <i>Salvinia molesta</i>	125
4.5.4	Water hyacinth growth in the southern Mozambique rivers.....	125
4.5.4.1	Growth variation of water hyacinth between the studied rivers.....	125
4.5.4.2	Biological control agents recorded on water hyacinth plants in Mozambique .	126
4.6	Conclusion.....	128
Chapter 5.	.....	129
Studies on biodiversity recovery following management of the invasive aquatic weed <i>Pistia stratiotes</i> L. (Araceae) in pools	.....	129
5.1	Introduction	129
5.2	Materials and Methods	131
5.2.1	Weed control treatments	132
5.2.2	Herbicide treatments and water chemistry.....	132
5.2.3	Experimental design.....	133
5.3	Statistical analyses.....	135
5.3.1	Biodiversity indices	135
5.3.2	South African Scoring System version 5 (SASS5).....	136
5.3.3	Determination of accumulation curve.....	136
5.3.4	Community analyses.....	136
5.3.5	Canonical correspondence analysis (CCA)	137
5.4	Results	138
5.4.1	Macro-invertebrates recruitment in 12 open water pools (O) in the 1 st sampling occasion (Step 1).....	138
5.4.2	Macro-invertebrate recruitment in three open water pools (O) and nine pools with <i>Pistia stratiotes</i> (W) in the 2 nd sampling occasion (Step 2).....	139

5.4.3	Effect of biological control and herbicide application on percentage cover (% cover) of water lettuce mats during the study period (Step 3).....	140
5.4.4	Effect of water lettuce mats in dissolved oxygen (DO) level in different treatments during the study period (Step 3).....	142
5.4.5	Nitrate, phosphate, and temperature measurement during the study period in the water lettuce mats in water lettuce pools (W), water lettuce controlled by <i>Neohydronommus affinis</i> (N), water lettuce mats controlled by herbicide (H) and in open pools (O) on three sampling occasions (Step 3).....	143
5.4.6	Comparison of number of families between water lettuce mats (W), water lettuce mats controlled by biological control weevils <i>Neohydronommus affinis</i> (N), water lettuce mats controlled by herbicide (H) and open water (O) sites during six sampling occasions (Step 3).....	144
5.4.7	Duration of study and accumulation curves.....	154
5.4.8	Community analyses.....	159
5.4.9	Analysis of similarity and dissimilarity in macro-invertebrate abundance and composition between sampling sites.....	162
5.4.10	Relationship between macro-invertebrate communities and water quality	165
5.4.11	Sensitivity to water quality of the taxa sampled	167
5.5	Discussion	170
5.5	Conclusion.....	175
Chapter 6.	.....	176
General Discussion	.....	176
6.1	Introduction	176
6.1.1	Evaluation of biological control programme	177
6.1.2	Identification and knowledge of invasive species with the greatest impact on biodiversity	178
6.1.3	Recommendations for long-term management of the invasive aquatic plants in Mozambique	180
6.1.4	Importance of Aquatic ecosystem in Mozambique	182

Chapter 7. 184
References 184

List of Figures

Figure 1.1 World-wide distribution of <i>Eichhornia crassipes</i>	32
Figure 2.1 The southern part of Mozambique showing the rivers basins studied and the sampling sites on those rivers.....	51
Figure 2.2 Comparison between the mean number of invasive and indigenous plants per quadrat in each river. Mann-Whitney U test shows the differences between mean number of invasive and indigenous aquatic plants per quadrat in Incomati, Limpopo, Inharrime and Govuro rivers ($p < 0.05$). Box: represents Mean \pm SE and Whisker represents Mean \pm 2*SD.....	58
Figure 2.3 A. B. C. D. E and F Distribution of water hyacinth, <i>Eichhornia crassipes</i> in the southern Mozambique rivers in 2008. The following letters represent: A (Maputo Basin), B (Umbeluzi Basin), C (Incomati Basin), D (Limpopo Basin), E (Inharrime Basin) and F (Govuro Basin).....	63
Figure 2.4 A and B Distribution of <i>Salvinia molesta</i> in the southern Mozambique Basin Rivers in 2008. The following letters represent: A (Umbeluzi River) and B (Incomati River).....	65
Figure 2.5 A. B. C. D and E Distribution of <i>Azolla microphylla</i> in the southern Mozambique Rivers in 2008. The following letters represent: A (Maputo River), B (Umbeluzi River), C (Incomati River), D (Limpopo River) and E (Save River).....	68
Figure 2.6 A. B and C Distribution of <i>Pistia stratiotes</i> in the southern Mozambique rivers in 2008. The following letters represent: A (Umbeluzi River), B (Incomati River) and C (Govuro River).....	70
Figure 3.1 The three sampling sites (upper, middle and lower region) in the Incomati River Basin.....	80

Figure 3.2 A and B Water usages in the Incomati River by the riverine population. A: activities performed by male respondents; B: activities performed by female respondents.....85

Figure 3.3 Distribution patterns of aquatic weeds in the upper middle and lower Incomati River. The plants density varies from no occurrence, rare, less common, common, abundant to very abundant.....86

Figure 3.4 A. B. C and D Distribution of malaria and diarrhea disease at Moamba and Marracuene districts during 2010. Data represent only the number of malaria and diarrhea cases confirmed by laboratory test in the hospitals.....92

Figure 3.5 A. B and C Monthly incomes of different activities performed in the upper, middle and lower Incomati River. (A): irrigation; (B): transport; (C): other activities.....95

Figure 3.6 The percentage presented refers to the number of people that were needed to control the weeds' impact in the Incomati River at the peak of weeds.....99

Figure 4.1 Mean numbers of *Neohydronomus affinis* per 100 sampled water lettuce plants along the Incomati and Umbeluzi Rivers. Each bar represents mean \pm Standart Deviation of each sampling time. Means marked with letters within each sampling time are significantly different at $P < 0.05$109

Figure 4.2 Mean number of weevils, *Stenopelmus rufinasus*, per 100 sampled *A. microphylla* along the southern Mozambique rivers. Each bar represents mean \pm Standard Deviation of each sampling time.110

Figure 4.3 Mean water hyacinth plant longest leaf length per plant in dry season (June) and wet season (November) sampling 10 plants at each of six sampling sites. There were significant differences in the length of longest leaf between dry and wet seasons at Govuro ($F=1.13$; $df=18$; $p < 0.005$); Inharrime ($F=1.29$; $df=18$; $p < 0.0003$); Umbeluzi river ($F=1.52$; $df=18$; $p < 0.0002$) and Incomati ($F=4.19$; $df=18$; $p < 0.004$) sampling sites. (* denotes significant differences)....112

Figure 4.4 Mean water hyacinth plant length of longest root per plant in dry season (June) and wet season (November), sampling 10 plants each six sampling sites. There were no significant differences in the mean of root length on water hyacinth plants between dry and wet seasons ($p>0.05$).....	113
Figure 4.5 A and B Comparison of mean number of ramets (A) and number of flowers (B) on water hyacinth plant communities during June 2009 (dry season) and November 2009 (wet season) at the different sampling sites. (* denotes significant differences).....	115
Figure 4.6 Mean water hyacinth leaves per plant in dry season (June) and wet season (November) sampling 10 plants each at six sampling sites. There were no significant differences in the mean of leaves on water hyacinth plant between dry and wet seasons ($p>0.05$).....	116
Figure 4.7 Mean water hyacinth fresh weight per plant in dry season (June) and wet season (November) sampling 10 plants at six sampling sites. Significant difference in fresh weight between dry and wet seasons fresh weight of the plant in Govuro, Inharrime and Umbeluzi rivers ($p< 0.05$).....	117
Figure 4.8 Plots of leaf scarring by water hyacinth weevils against fresh weight based on the impact of weevil feedings. Each plot represents the average from 10 plants; $n= 40$ samples from two sampling times (June 2009 and November 2009).....	118
Figure 4.9 Adult feeding damage by <i>Neochetina spp.</i> and mite, <i>Orthogalumna terebrantis</i> on the leaves of <i>Eichhornia crassipes</i> in Umbeluzi River (Mozambique).....	121
Figure 4.10 Scars of <i>Acremonium zonatum</i> on water hyacinth plants in Incomati River (Mozambique).....	121

Figure 4.11 Scars of <i>Alternaria eichhorniae</i> on water hyacinth leaves in Incomati River (Mozambique).....	122
Figure 5.1 Flow chart of the experimental design for the experiment. Step 1, 2, and 3. The O, W, N and H refers to: open water pools (O), water lettuce pools, without control (W), water lettuce pools controlled by weevils (<i>Neohydronomus affinis</i>) (N) water lettuce pools controlled by the herbicide glyphosate (H).....	134
Figure 5.2 Percentage of the macro-invertebrates sampled in 12 open pools (O) after six weeks in the first step of the experiment.....	138
Figure 5.3 Percentage of the macro-invertebrates sampled in three open pools (O) after six weeks in the second step of the experiment.....	139
Figure 5.4 A, B and C Mean percentage cover of water lettuce mats in water lettuce pools (W); water lettuce controlled by <i>Neohydronomus affinis</i> (N) and water lettuce mats controlled by herbicide (H) during the six sampling occasions.....	141
Figure 5.5 Measurement of the dissolved oxygen in the water lettuce mats in water lettuce pools (W), water lettuce controlled by <i>Neohydronomus affinis</i> (N), water lettuce mats controlled by herbicide (H) and in open pools (O) on three sampling occasions.....	142
Figure 5.6 Measurement of water temperature in the water lettuce mats in water lettuce pools (W), water lettuce controlled by <i>Neohydronomus affinis</i> (N), water lettuce controlled by herbicide (H) and in open pools (O) on three sampling occasions.....	143
Figure 5.7 A and B Distribution of mean number of individuals (A) and mean number taxa (B) during study period in the artificial substrates under water lettuce mats (W), in water lettuce mats controlled by <i>Neohydronomus affinis</i> (N), in water lettuce mats controlled by herbicide (H) and open water (O).....	146

Figure 5.8 A, B, C and D Comparison in number of individuals collected in water lettuce mats in water lettuce pools (A), water lettuce controlled by *Neohydronomus affinis* (B), water lettuce mats controlled by herbicide (C) and in open pools (D) on six sampling occasions.....149

Figure 5.9 Comparison of total number of taxa collected from water lettuce mats (W), water lettuce mats controlled by biological control weevils *Neohydronomus affinis* (N), water lettuce mats controlled by herbicide (H) and open water (O) sites on six sampling occasions.....150

Figure 5.10 Comparison richness (d) of samples from water lettuce mats (W), water lettuce mats controlled by biological control weevils, *Neohydronomus affinis* (N), water lettuce mats controlled by herbicide (H), and open water (O) sites on six sampling occasions.....152

Figure 5.11 Comparison of degree of evenness and abundance, using Shannon-Weiner (H) index, of samples from water lettuce mats (W), water lettuce mats controlled by biological control weevils *Neohydronomus affinis* (N), water lettuce mats controlled by herbicide (H) and open water (O) sites on six sampling occasions.....153

Figure 5.12 Comparison of evenness of samples from water lettuce mats (W), water lettuce mats controlled by biological control weevils *Neohydronomus affinis* (N), water lettuce mats controlled by herbicide (H) and open water (O) sites on six sampling occasions.....154

Figure 5.13 A, B, C and D Accumulation curves of taxa sampled in water lettuce mats (W), water lettuce controlled by *Neohydronomus affinis* (N), water lettuce controlled by herbicide (H) and open water (O).....156

Figure 5.14 A, B, C and D Individual-based rarefaction curves indicating observed number of species (S_{obs} Mao Tao), Michaelis-Menten Mean (MMM_{Mean}) richness estimator and incidence-based estimator coverage (ICE) of macro-invertebrates collected from water lettuce mats (A), water lettuce controlled by *Neohydronomus affinis* (B), water lettuce controlled by herbicide (C) and in the open water (D).....158

Figure 5.15 Cluster Plot indicating percentage similarity of total samples. Each branch represents sample event (number) and site (W=water lettuce, N=water lettuce mats controlled by *Neohydronomus affinis*, H=water lettuce controlled by herbicide, O=open water).....160

Figure 5.16 Multi-dimensional scaling (MDS) ordination of macro-invertebrate community composition. In the analysis indicating a stress of 0.1, with Cluster Plot overlay, showing four distinct communities and sample event is indicated by number followed by site (W=water lettuce, N=water lettuce mats controlled by *Neohydronomus affinis*, H=water lettuce controlled by herbicide, O=open water).....161

Figure 5.17 CCA ordination tri-plot for macro-invertebrate taxa and water quality variables at the four study sites. Abbreviations: Sample event is indicated by number followed by site (W=water lettuce, N=water lettuce mats controlled by *Neohydronomus affinis*, H=water lettuce controlled by herbicide, O=open water); DO= dissolved oxygen.....166

List of Tables

Table 1.1 Important aquatic weeds (data modified from Charudattan 2001a).....	27
Table 1.2 The natural enemy species established on water hyacinth in Africa (data modified from Harley, 1990; Julien 2001, Cilliers <i>et al.</i> , 2003).....	34
Table 2.1 Phytosociological analyses of macrophytes along the southern Mozambique rivers. Species marked by * represent invasive aquatic plants; %Freq.=%Frequency; RF Relative frequency; Dens.=Density; RD=Relative density; Abund.=Abundance; IV=Importance Value; <i>H'</i> =Shannon-Wiener diversity; <i>E</i> =Evenness.....	56
Table 2.2 Macrophyte diversity in the different Mozambican basin rivers expressed in an ACFOR scale, based on overall dominance according to Den Hartog and Segal (1964).	58
Table 3.1 A and B Biographical characteristics of the population living by the Incomati River A: the ages of respondents at different localities, and B: the educational level of the riverine population.....	83
Table 3.2 Weeds mentioned by the local population in the upper (a); middle (b) and lower (c) Incomati River. The abbreviations (RF, WH, WL and S) refers to red water fern; water hyacinth; water lettuce and salvinia, respectively	87
Table 3.3 Economic problems associated with aquatic weeds in the upper, middle and lower Incomati River	89
Table 3.4 Social problems associated with aquatic weeds in the upper, middle and lower Incomati River.....	90

Table 3.5 Total number of malaria and diarrhea cases in three hospitals located in the Incomati River Basin. These scores would probably be doubled if cases without a confirmed laboratory test were added.....	92
Table 3.6 The monthly income from different activities along the Incomati River during 2010 (Mt. means Meticaís, currency used in Mozambique).....	93
Table 3.7 Estimated costs of mechanical control of weeds according to the data obtained data from Maragra sugar cane farm. Mt= Meticaís (Mozambican currency).....	96
Table 3.8 Influence of aquatic weeds on income from fish and trade activities in September, October, November 2009, and March–August 2010. The time before the peak of weeds is October and November. 2009 and March, April, May 2010 and the peak of weeds was observed only during four months namely June–July and August–September 2010.....	97
Table 3.9 Different strategies used by male and female respondents to reduce the aquatic weeds in the upper, middle and lower Incomati River.....	98
Table 3.10 Estimated cost of manual control of water weeds during July 2010.....	100
Table 4.1 Water hyacinth plant and biological agent parameters measured in the study area...	107
Table 4.2 Assessment of water hyacinth condition in previsions of mean number of weevils, larvae, pupae, mines and percentage of feeding scars and mites on the water hyacinth leaf found in southern Mozambique rivers.....	119
Table 4.3 Mean weevil numbers per 10 plants in different locations in southern Mozambique rivers during dry and wet seasons. (The Formula used to calculate number of adults on water hyacinth plant was $\{0.0336 \times (\text{Average number of feeding scars})^{0.775}\}$ (Wright and Center, 1984).....	120

Table 4.4 Water quality parameters during the dry season (June 2009) and wet season (November 2009) in the southern Mozambique rivers. (n=number of sampling sites on each river).....123

Table 5.1 Results for one-way ANOSIM comparison of macro-invertebrate species similarity of each group during the study period. Av. Abund. (average abundance); Av. Sim.(average similarity); Sim/SD (measure of variation in contribution to similarity); Contrib. % (percentage contributed to the overall Bray-Curtis similarity between communities at sites from four groups); Cum.%(cumulative percentage).....163

Table 5.2 Results of ANOSIM and SIMPER analysis for macro-invertebrate abundance, and comparison between identified groups (Not significant at P>5% and Significant at P<5%).....164

Table 5.3 Properties of the Canonical Correlation Analysis ordination tri-plot.....167

Table 5.4 A. B. C and D Sensitivity indication of invertebrates sampled using SASS5 scoring system on the water lettuce (A), water lettuce controlled by weevils *Neohydronomus affinis* (B), water lettuce controlled by herbicide (C) and in the open water without water lettuce (D).....168

Acknowledgements

First and foremost, I wish to express my unalloyed and unreserved gratitude to my Supervisor, Professor Martin Hill. Despite his very busy schedule, he found the time to provide very sound, logical and constructive criticism that made this project see the light of the day. I deeply appreciate his guidance and mentorship.

My thanks too, to Dr. Julie Coetzee, Mr. Oghenekaro Odume (Rhodes University) and Dr. Almeida Guissamulo (Eduardo Mondlane University) for their patience and guidance with the statistical analyses of this study. It brought all the fieldwork to an understandable conclusion and helped me to understand science from a different perspective.

I sincerely thank my English teacher, Mrs. Helen Holleman, who painstakingly proofread my thesis and provided vital feedback; and also Mr. Armindo da Silva, who spent hours with me creating maps of my study area. God bless you all!

My immeasurable appreciation goes to the staff of the Department of Zoology and Entomology at Rhodes University for their assistance and to Mrs. Kate Benyon for assisting with the arrangements for my trips to Grahamstown. I extend my gratitude to the staff from the Albany Museum who provided me with invaluable literature on insect identification and helped by identifying the macro-invertebrates. To all staff and students at Rhodes University (Entomology and Zoology Department), I appreciate your company and I say “thank you” for always being there for me. I wish specially to thank Puja, Philip, Grant, and Jackie.

I am eternally grateful to SIDA/SAREC for the opportunity given to perform this work through the project: Strengthening of the Biological and Oceanographic Research Capacity at Department of Biological Sciences, Faculty of Science at Eduardo Mondlane University.

I also extend my gratitude to the Eduardo Mondlane University for all the arrangements provided for me during my studies, Dr. Amalia Uamusse (Director of Science Faculty) Dr. Almeida Guissamulo and Prof. Lars Hernroth (SAREC coordinators), Dr. Adriano Macia (Director of

Masters course), Dr. Aídate Mussagy and Dr. Bandeira (Heads of Biology Department) for all their attention and help related to field trips, necessary equipment, books, and all financial help.

I am grateful to Mr. Jotamo Gabriel, my field assistant and driver who spent hours with me during field surveys under the burning sun or in the rain. You really encouraged me not to stop the work when we encountered snakes and other dangerous animals during the field trips.

I appreciate the support, prayers and words of Pastor Debbie (River of Life Church, Grahamstown) and Pastor Camilo Manhice and his wife, Pastor Joshua and his wife, and Ms. Pastor Augusta Gemo from Mozambique. I am also deeply grateful for the support of my friends and colleagues, Elsa Salvador, Noor Gulamussene, Sandra Silva, Eunice Ribeiro, Perpetua Scarlet, Angelina Martins, Alice Massinga, Mizeque Mafambissa, Narciso Macuacua, Natércia Mabunda, Diamantina Mbanze and Linda Botina.

To my father, Ernesto Tiago, my mother, Joana Langa (who passed away during the writing phase of this thesis) my daughter, Melanie Petracicla, and her fiancé, Leo Netzband, who egged me on in my “ripe old age” to do something useful for my country, my sincere thanks.

Above all, I say a big “thank you” to Almighty God for His infinite mercy, favour and protection over my life, and who has seen me through this journey, despite all odds.

General Introduction

1.1 Introduction

Invasive alien aquatic plant species have invaded freshwater lakes, dams and rivers throughout Africa. In their introduced range, invasive alien aquatic species can grow to densities where they cover water bodies with a thick mat of vegetation. This has negative effects on the environment, human health, and economic development. These aquatic weeds impact all aspects of natural resource utilization and degrade aquatic biodiversity. This thesis investigates the impacts of some known problematic aquatic weeds in Mozambique and offers solutions.

1.2 Invasive aquatic plants and their distribution

Invasive plants have the ability to spread naturally, but humans can introduce them to otherwise inaccessible places (Mitchell and Power, 2003; Keane and Crawley, 2002). The species introduced by man to new areas are called non-indigenous species or alien species (Richardson *et al.*, 2000). Introduction of invasive aquatic plants into foreign ecosystems can be intentional for economic or aesthetic reasons, or it can be accidental, as when species are transported by ballast water (Martin and Coetzee, 2011; Padilla and Williams, 2004). Non-indigenous species that manage to reproduce rapidly often become problematic and can totally dominate a habitat, even if they do not do so in their native range.

Invasive aquatic plants occur in both permanently and seasonally wet environments and they include a diverse group of macrophytes, including angiosperms and some freshwater macroalgae. While the focus of this thesis is on free-floating hydrophytes, Kariba weed (*Salvinia molesta* D. S. Mitchell (Salviniaceae)), red water fern (*Azolla microphylla* Kaulf (Azollaceae)), water lettuce (*Pistia stratiotes* Linnaeus (Araceae)), and water hyacinth (*Eichhornia crassipes* (Martius) Solms-Laubach (Pontederiaceae)), invasive aquatic plants may be assembled into four groups, (Cronk and Fennessy, 2001):

- Emergent species, which are rooted in the substrate but extend above the water surface. This group includes species of giant sedge (*Cyperus dives* Del. (Cyperaceae)), bulrush (*Typha*

capensis Rohrb (Typhaceae)), rushes (*Juncus effuses* Rush (Junceae)), sawgrasses (*Cladium mariscus* L. (Poaceae)) and cattails (*Typha latifolia* L. (Typhaceae)).

- Floating-leaved hydrophytes which are rooted in the substrate but usually have leaves floating on the water surface. They may be prominent in low-visibility water, and include species of lotus (*Nelumbo nucifer* Komarovii (Nelumbonaceae)) and water lily (*Nymphaea mexicana* Zucc. (Nymphaeaceae)).
- Submerged hydrophytes, which are normally fully submerged in the water but which have free-floating foliage. This group includes species of water-milfoil (*Myriophyllum spicatum* L. (Haloragaceae)), pondweed (*Potamogeton schweinfurthii* A. Benn. (Potamogetonaceae)), elodea (*Elodea canadensis* Michx.) (Hydrocharitaceae)), wild celery (*Vallisneria americana* Michx. (Hydrocharitaceae)) and frog-bit (*Hydrocharis morsus-ranae* L. (Hydrocharitaceae)).
- Free-floating hydrophytes, which float on the water surface and do not have roots fixed in sediment; they moved freely with wind and water currents. This group includes species of water-lettuce (*Pistia stratiotes*), mosquito-fern (*Azolla filiculoides* Lam. (Azollaceae)), water hyacinth (*Eichhornia crassipes*), duckweed (*Spirodela polyrrhiza* L. Schleiden (Lemnaceae)) and watermeal (*Wolffia columbiana* H. Karst (Lemnaceae)).

Aquatic plant species are richer in diversity in temperate regions than in tropical regions (Crow, 1993). However, some tropical and subtropical regions have higher aquatic plant endemism than others (Sculthorpe, 1967). For example, southern Africa (Botswana, Lesotho, Namibia, Swaziland and South Africa) supports about 600 species of wetland plants, including 114 endemic taxa but few free-floating species (Cook, 2004).

1.3 Mechanism of invasion by aquatic plants

Several hypothesis have been put forward to explain why non-indigenous aquatic plant species become invasive. Although these are dealt with individually below, it is most likely a combination of these factors that drives invasion.

1.3.1 Modes of introduction

Introduction of aquatic invasive plants in freshwater systems can be intentional or unintentional. Intentional reasons include economic or aesthetic reasons. For example, *Azolla filiculoides* was introduced as an ornamental fish-pond plant in 1948 (Oosthuizen and Walters, 1961); once established, water fowl spread it throughout South Africa. The unintentional reasons include instances when species are transported in ballast water; or introduced to new areas accidentally by man (Martin and Coetzee, 2011); or by mislabeling; or by retailers using species names inconsistently which can lead to the accidental purchase of invasive aquatic species (Maki and Galatowitsch, 2004); or by improperly disposing of unwanted species into storm sewers, ditches or local waters which can result in the establishment of invasive aquatic plants in the local natural environment (Cal-IPC, 2007).

Weeds are dispersed in different ways: water-dispersed species, which include species like *Ludwigia peploides* Kenth (Onagraceae) (easily detached, floating stems) and *Eichhornia crassipes* (free-floating plants) which share the common attribute of hydrological connectivity; wind-dispersed species which include *Typha latifolia* L. (Typhaceae) and *Phragmites communis* Trin. (Poaceae), have aerodynamic seeds; and finally, those species dispersed by animals, which include *Lemna minor* L. (Lemnaceae) and *Wolffia punctata* Griseb. (Lemnaceae). These are tiny plants that are readily carried on fur or feathers.

1.3.2 Vacant niche hypothesis

Introduced plants can become invasive when they are presented with niche opportunities in their new habitats. This depends on there being a relatively empty niche for them to exploit (Corbin and D' Antonio, 2004; Uveges *et al.*, 2002). For example, southern Africa has very few indigenous floating aquatic macrophytes (Cook, 2004) and this has made the aquatic ecosystem in this region prone to invasion by floating weeds. However, the region also has a high diversity of submerged aquatic macrophytes (Cook, 2004) which has made these systems relatively immune to invasion by submerged invaders.

1.3.3 Enemy release hypothesis

Invasive alien species have escaped from their natural enemies and therefore have a greater competitive advantage over the native species (Clay, 2003; Torchin *et al.*, 2003; Keane and Crawley, 2002; Mack *et al.*, 2000). Alien invasive species typically have few or no natural enemies in the invaded region (Mack *et al.*, 2000). Without natural enemies, invaders allocate more of their resources to growth, to acquiring water and nutrients, and to reproduction, and are thus able to compete with indigenous species for space, nutrients and sunlight. In contrast, native plants must continue battling their natural enemies, plus compete with new weed neighbours (Lake and Leishman, 2004; Keane and Crawley, 2002). For example, purple loosestrife (*Lythrum salicaria* L.) (Lythraceae) is a highly invasive competitor in wetlands in North America, although its success may be reduced if controlling herbivores are introduced from its native habitat (Houlahan and Findlay, 2004; Smith and Smith, 2001) and this is further evidenced by the highly successful biological control programmes using a root-mining weevil, *Hylobius transversovittatus*, two leaf-eating beetles, *Galerucella californiensis* and *Galerucella pusilla*, and a flower-feeding weevil *Nanophyes marmoratus* (Lindgren *et al.*, 2002). The enemy release hypothesis is further supported through the biological control of some invasive plants such as *Salvinia molesta* (Tipping *et al.*, 2008), *Eichhornia crassipes* (Hill and Coetzee, 2008; Cilliers *et al.*, 2003; Center *et al.*, 2002), *Pistia stratiotes* (Neuenschwander, *et al.*, 2009; Hill, 2003; Dray *et al.*, 1993,) and *Azolla filiculoides* (Hill, 2003; Mc Connachie *et al.*, 2003).

1.3.4 Disturbance hypothesis

Invasive aquatic weeds tend to become problematic in habitats that are disposed to ecological disturbance and often thrive in habitats that are in a constant state of disturbance. Disturbance may play a role in enabling invasive species to penetrate relatively mature communities (Nagasaka *et al.*, 2002; Lugo, 1994). After a disturbance, if the new environmental conditions fit the niche requirement of the exotic species, the plant may colonize and spread successfully (Façon *et al.*, 2006), so that the introduced species that are pre-adapted to their new habitat will probably succeed (Façon *et al.*, 2006). According to Havel *et al.* (2005), disturbances open environments to invasion because they may break down natural barriers. This means that the success of an introduced species will also depend on other characteristics such as species traits,

abiotic conditions of the habitat and propagule pressures (Jacobs and Macisaac, 2009; Chadwell and Engelhardt, 2008).

Disturbance is one of the main drivers of aquatic weed invasion as plants are able to adapt and tolerate a broad range of environmental conditions (like high nutrients) that native species cannot tolerate. In some cases, the ability of invaders to tolerate specific environmental conditions has been important, for example, a tolerance of shading or of low levels of inorganic carbon or oxygen (Bowes *et al.*, 2002; James *et al.*, 1999; Middelboe and Markager, 1997; Madsen and Maberly, 1991). As invasive aquatic plants increase rapidly, they increase environmental problems such as pollution (Palumbi, 2001; Kolar and Lodge, 2000; Pimentel *et al.*, 2000).

1.4 Impacts of invasive aquatic plant species

Aquatic invasive plants have three main impacts: economic, environmental and social. Economic impacts, which directly affect humans, typically leading to monetary losses; environmental impacts, which affect ecosystem structure and function, often leading to loss of biodiversity or unique habitats, and social impacts which focus predominantly on human health and safety, but can also cover quality of life, recreational opportunities, cultural inheritance, and other aspects of social structure (Ricciardi and Cohen, 2007; IUCN, 2000). For example, mats of aquatic invasive plants can colonize many different types of aquatic ecosystems such as lakes, reservoirs, wetlands, streams, rivers and ponds. Thomaz and Cunha (2010) stated that primary production of these aquatic invasive plants can surpass other aquatic primary producers. Thick mats of aquatic invasive plants can affect nutrient cycling through transference of chemical elements from sediment to water by active and passive processes (Camargo *et al.*, 2003). Aquatic plants can release nutrients, such as phosphates and nitrates into the water, which are used by micro- and macro-organisms. These micro-organisms (micro-algae and bacteria) and macro-organisms can live freely in the water or attach themselves to the aquatic plant surfaces and their detritus (Stets and Cotner, 2008; Anésio *et al.*, 2003).

Hill (2003) and Masifwa *et al.* (2001) state that invasive aquatic plants reduce the quality and quantity of water for urban, agricultural and industrial use; increase siltation of rivers, dams and wetlands; reduce the water surface area for recreation; clog irrigation canals and pumps; cause

the death of livestock that were unable to differentiate between pasture land and weed-covered water bodies; contribute to the deterioration of aquatic biodiversity, and considerably reduce the aesthetic value of waterfront communities. Jafari *et al.* (2010) and Charudattan (2001a) observed that dead biomass from large weed infestations increases the rates of sedimentation and eutrophication and could reduce water depth. Moreover, invasive aquatic weeds have significant, adverse effects on human health and livelihoods, especially in the developing world, since weeds provide habitats for insect-borne human diseases (Perrings *et al.*, 2000; Navaro and Phiri, 2000). Finally, invasive aquatic plants affect hydrological patterns by obstructing water flow, increasing evapo-transpiration, and preventing proper drainage of land.

A major effect of invasive aquatic plants is the change to the composition of the invasive aquatic assemblage itself (Michelan *et al.*, 2010). These plants change the waterscape, impact other taxonomic groups in the water column, and modify the aquatic assemblage because they change the vegetation. Modification of the aquatic assemblage can alter the biotic relationships between aquatic species (Person, 2009; Bickel and Closs, 2008; Longepierre *et al.*, 2005; Strayer *et al.*, 2003) and can cause species extinctions (Clavero and García-Berthou, 2005).

1.5 Invasive aquatic plants problems around the world

In their book, “The World’s Worst Weeds”, Holm *et al.* (1991) listed ten aquatic weeds, among the most notorious: water hyacinth *Eichhornia crassipes*, water lettuce *Pistia stratiotes* Linnaeus (Araceae), *Salvinia auriculata* Aublet (Salviniaceae) (later identified as *Salvinia molesta* D.S. Mitchell (Salviniaceae)), giant salvinia (or Kariba weed). In the quarter century since this book was published, the number of problematic aquatic weeds has increased (Table.1.1).

Table 1.1: Important aquatic weeds (data modified from Charudattan 2001).

Botanical name	Common name	Family	Plant type	Native	Invaded Regions
<i>Alternanthera philoxeroides</i>	Alligator weed	Amaranthaceae	Mat-forming	East coast of South America	Australia, Asia, North America
<i>Azolla filiculoides</i>	Azolla, Red water fern	Azollaceae	Floating	Australia, Asia, Madagascar, Papua New Guinea, India, China, Japan	USA, New Zealand, South Africa, Europe

<i>Ceratophyllum demersum</i>	Coontail	Ceratophyllaceae	Submerged	North America	Burkina Faso, New Zealand, Norway
<i>Crassula helmsii</i>	Australian swamp, Stonecrop	Crassulaceae	Submerged, mat-forming	Australia, New Zealand	Florida, North Carolina, England, Germany
<i>Eichhornia crassipes</i>	Water hyacinth	Pontederiaceae	Floating	South America, Brazil	Africa, Australia, China, New Zealand
<i>Egeria</i> spp.	Egeria, Elodea	Hydrocharitaceae	Submerged	South America	South Africa, Australia, California, New Zealand
<i>Hydrilla verticillata</i>	Hydrilla	Hydrocharitaceae	Floating	India, Korea, Reunion	Australia, Africa, Asia, Europe, South America, New Zealand
<i>Ipomoea carnea</i>	Water spinach, Swamp morning-glory	Convolvulaceae	Emergent, mat-forming, wetland shrub	Tropical America, South America, Mexico, West Indies	Pan-tropical
<i>Lagarosiphon major</i>	Lagarosiphon	Hydrocharitaceae	Submerged	Botswana, Lesotho, South Africa, Zambia, Zimbabwe	Australia, New Zealand, UK
<i>Lemna minor</i>	Duckweed	Lemnaceae	Floating	Argentina, South Africa, Australia, Brazil, New Zealand, Zimbabwe, India, China, Madagascar	USA
<i>Ludwigia stolonifera</i>	Water primrose, Primrose willow	Onagraceae	Emergent	Trinidad and Tobago, Argentina, Republic of Haiti, Brazil, Costa Rica, Jamaica	Puerto Rico, Australia, Dominican Republic, USA, India, Indonesia
<i>Lythrum salicaria</i>	Purple loosestrife	Lythraceae	Emergent	Asia, northern Africa, Central and southern Europe	Northeastern, midwestern and western United States
<i>Melaleuca quinquenervia</i>	Melaleuca, Paper-bark	Myrtaceae	Wetland tree	Eastern Australia, New Guinea and New Caledonia	Southern Florida, Hawaii
<i>Myriophyllum aquaticum</i>	Parrot's feather	Haloragaceae	Emergent, mat-forming,	Africa and Eurasia	Canada, Swaziland, USA, South Africa
<i>Nymphaea mexicana</i>	Water lilies	Nymphaeaceae	Emergent	Mexico, Florida and southern Texas	South Africa
<i>Panicum repens</i>	Torpedo grass	Poaceae	Mat-forming, grass	Africa (Botswana, Angola, Mozambique, South Africa, Malawi, Swaziland), Asia, India, China	Australia, Cambodia, Vietnam
<i>Paspalum</i> spp.	Paspalum	Poaceae	Mat-forming, grass	USA (Georgia)	Ecuador, New Zealand, Tanzania, Senegal, Malaysia, Western Australia
<i>Phragmites</i> spp.	Reed	Poaceae	Emergent	Africa, Asia, Canada, Europe, Puerto Rico, South America	Burkina Faso, USA (England, California, Colorado, Mississippi, New Mexico, Virginia, Oklahoma)

<i>Pistia stratiotes</i>	Water lettuce	Araceae	Floating	South America	USA , Puerto Rico, Reunion, Swaziland, Burkina Faso, Africa
<i>Polygonum perfoliatum</i>	Smartweed, Knotweed	Polygonaceae	Emergent	Eastern Asia, China	Eastern United States, North America
<i>Potamogeton</i> spp.	Pondweed	Potamogetonaceae	Submerged	Africa, Asia, Australia, Europe, North America	New Zealand
<i>Sagittaria</i> spp.	Arrowhead, Duck potato	Alismataceae	Emergent	Mexico, Panama, USA	New Zealand, Australia, Georgia, South Africa
<i>Salvinia molesta</i>	Giant salvinia, Kariba weed	Salviniaceae	Floating weed	Argentina, Brazil, southeastern Brazil, Colombia, Guyana, Mexico, Trinidad and Tobago	Africa (Burkina Faso, Ghana, Kenya, Botswana, South Africa, Madagascar, Kenya), USA
<i>Spartina</i> spp.	Cord grass, Marsh grass	Poaceae	Emergent, grass	Argentina, Brazil, Suriname, Guyana, Trinidad, Uruguay	New Zealand, Australia, China, India, France, UK, USA
<i>Typha</i> spp.	Cattail	Typhaceae	Emergent	Brazil, Algeria, Argentina, China, Ethiopia, Tanzania, Uganda, UK, USA	New Zealand
<i>Utricularia</i> spp.	Bladderwort	Lentibulariaceae	Submerged	North and Central America	New Zealand

The rapid increase in the number of recorded invasive aquatic plant species is probably due to several factors: an increase in the trade in these species, an increase in the disturbance of aquatic ecosystems and an increase in public awareness of biotic invasion.

1.6 The most important aquatic weeds in Mozambique

The most dramatic impact of alien species in Mozambique, where little attention has been paid to aquatic weeds, has clearly been from subtle invaders (Cossa, 2009, interim report). However, the increase in the weeds and their socio-economic impact on the riverine population has compelled people to take notice of the invasive plants, particularly the aquatic ones. Some introduced aquatic plants have had a negative economic impact as they have blocked water channels and provided suitable breeding grounds for mosquitos and bilharzia-carrying snails (Rodolfo, 2007, interim report; Cossa, 2009, interim report). These aquatic weeds include the water hyacinth, water lettuce, the red water fern, and parrot's feather (Cugala, 2006; Chiconela *et al.*, 2002; Jacot Guillarmod, 1979). These species are dominant and, individually and collectively, they cause serious widespread problems in the country (Rodolfo, 2007-interim report; Cossa, 2009-interim

report). Nevertheless, few efforts have been made to reduce the impact or to minimize the invasion of the weeds in rivers.

The major challenge that Mozambique faces in controlling these invasive alien species is a lack of local expertise. The country's top priority in the field of invasive alien species is a policy of prevention and containment through stricter quarantine measures, backed up by a major public awareness campaign on the invasive alien species issue. Currently, there is a concerted quarantine and monitoring process at all main points of entry into Mozambique, along the country's northern border with Malawi and Zambia, and along the southern borders with Zimbabwe and South Africa (GIIBS, 2005). The importation of any plant material or plant-associated micro-organisms is subject to strict, specified conditions. The stipulated procedure ensures that enough information on the plant material or the micro-organisms is available to evaluate the pest risk of the potential invasive. Plant and animal quarantine restrictions are based on the pest-risk analysis and rely on existing scientific knowledge about the distribution and biology of the plant or micro-organism. Suitable regulations are enforced to facilitate the import and export of plant material through import permits and phyto-sanitary certificates. The Agricultural and the Environmental Ministries provide the legal authority for treatment or destruction of infested or infected plants or plant products. Import and export permits are authorized by trade policy through the Ministry of Agriculture and the Mozambican Standing Technical Committee for Imports and Exports.

In accordance with Mozambique's regime for phytosanitary inspections and control, certain plants and plant products, and the products of apiculture require a Phytosanitary Licence of Importation, which in turn requires a phytosanitary certificate issued by the country of origin. For seeds, an additional requirement is a certificate stating that the product in question is not genetically modified, as their importation is prohibited by Mozambique. Similarly, imports of insects for biological control purposes must obtain a Phytosanitary Licence of Importation, issued by the veterinary authorities.

The four most important aquatic weeds in Mozambique and the focus of this thesis are reviewed below.

1.6.1 *Eichhornia crassipes*

1.6.1.1 Origin and distribution of *Eichhornia crassipes*

Native to South America, water hyacinth, *Eichhornia crassipes*, which belongs to the pickerelweed family (Pontederiaceae) is the most troublesome aquatic weed in the world (Figure 1.1) (Lu *et al.*, 2007; Holm *et al.*, 1991). *Eichhornia crassipes* possesses physiological characteristics and reproductive strategies that allow for rapid expansion in freshwater environments enabling it to spread throughout tropical and subtropical regions (Pushpa and John, 2010) and it now occurs in lakes and slow-moving rivers in most countries of the world (Mironga, 2004; Center *et al.*, 2002).

In West Africa, water hyacinth was first observed in the late 1970s and became a major pest in the late 1980s (Cilliers *et al.*, 2003). Julien *et al.* (1999) reported its occurrence in Mali, Burkina Faso, and Niger, but the major threat is to the highly productive coastal creek and lagoon systems, from which many people derive their living, particularly in Côte d'Ivoire, Ghana, Togo, Benin, and Nigeria.

In eastern and southern Africa, it was recorded in Zimbabwe in 1937, in Ethiopia in 1956, Rwanda and Burundi in 1957, the Pangani River (Tanzania) in 1955 and Kafue River (Zambia) in the 1960s, the Shire River (Malawi) in 1968, and Lake Naivasha (Kenya) in 1989. The most recent infestations of *E. crassipes* were reported by Navarro and Phiri (2000) in lakes Kyoga in Uganda in 1987, Victoria in 1989, Malawi-Nyasa in 1996, and Tanganyika in 1997 (Cilliers *et al.*, 2003).

The water hyacinth was first recorded in South Africa after 1900 where aquarium owners and boating enthusiasts had dispersed it (Martin and Coetzee, 2011; Cilliers, 1991; Jacot Guillarmod, 1979). It is now widespread throughout South Africa and has an impact on rivers in the Western and Eastern Cape, KwaZulu-Natal, the Vaal River, Gauteng and Free State provinces (Richardson and Van Wilgen, 2004; Hill and Cilliers, 1999).

In Mozambique, the water hyacinth, *E. crassipes*, was first observed in 1946, when the weed was introduced into the Zambezi River and its tributaries (Jacot Guillarmond, 1979; Bond and Roberts, 1978). The water hyacinth, together with other aquatic weeds (*Salvinia molesta* and *Pistia stratiotes*), was recorded in the catchment of Cabora Bassa during pre-impoundment surveys (Davies *et al.*, 1975; Macedo, 1974) and they were considered potential weeds (Bond and Roberts, 1978). In southern Mozambique, the Incomati, Limpopo and Save (Sabi) rivers were at times densely lined by water hyacinth (Jacot Guillarmond, 1979), while those rivers leading into Maputo Bay all support flourishing populations of the weed (Jacot Guillarmond, 1979). During the rainy season, water hyacinth is washed down these rivers by flood waters, floats far out to sea between Maputo and Inhaca Island and leaves plant remains in the Bay, where some of it starts flowering (Jacot Guillarmond, 1979). Currently, water hyacinth has been recorded in the Umbeluzi, Incomati, Limpopo and Zambezi rivers (DNA, 2011; GISP, 2003).

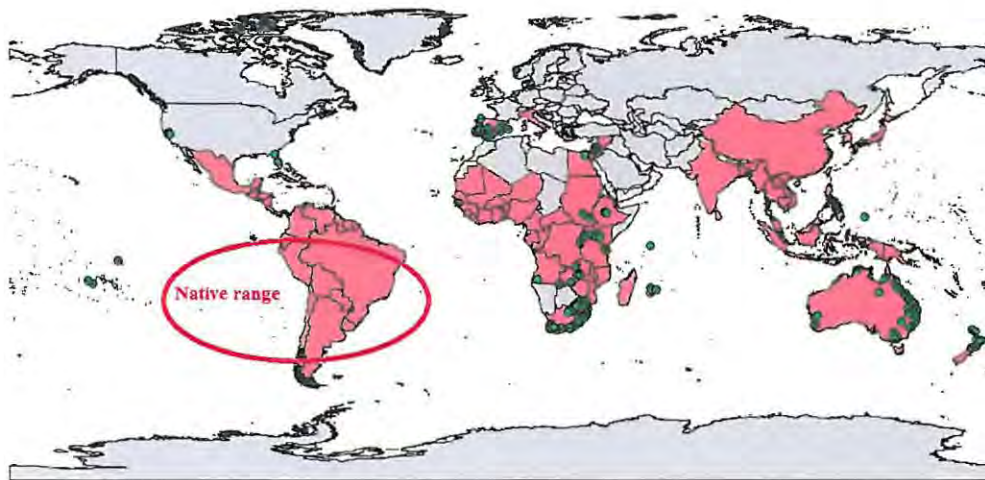


Figure 1.1 World-wide distribution of *Eichhornia crassipes*.

1.6.1.2 Methods of controlling water hyacinth

In most cases, the first control option for controlling water hyacinth is manual or mechanical control using pitchforks or rakes and, on a large scale, mechanical harvesters (Cilliers *et al.*, 2003; Hill, 2000). A well-known example was observed on the Ugandan side of Lake Victoria, where a mechanical harvester for the control of water hyacinth was shown to be effective (Center

et al., 1999). However, the operational cost of these harvesters is extremely high (Julien *et al.*, 2001). In larger infestations, manual removal is ineffective and extremely labor-intensive, and can also be risky as some African rivers are inhabited by crocodiles and hippopotamuses (Mallya, 1999). In some cases, barriers or fences have been used to limit the spread of the weeds, but with limited success (Cilliers *et al.*, 2003).

In Mozambique, in vast agricultural areas such as the Chinavane and Maragra sugar farms, mechanical control is used as a first attempt to control the weed, but it is impossible in terms of both cost and practicability. Herbicidal control has been used against water hyacinth. The chemicals most frequently used to control the infestation of invasive plants, including water hyacinth, are dichlorophenoxyacetic acid (2, 4-D), clorasán and glyphosate (Ueckermann and Hill, 2001). For example, in South Africa, water hyacinth control has largely depended on the use of herbicides since the 1970s (Julien *et al.*, 1999). Successful chemical control of a water hyacinth infestation was observed in the Hartebeespoort Dam on the Crocodile River near Pretoria, South Africa, using the herbicide, terbutryn (Ashton *et al.*, 1979). However, the drawback of using a herbicide is that several applications resulted in the sinking of large mats, followed by decomposition of the plants, water pollution and algal blooms (Bartram *et al.*, 1999). Even though herbicides work effectively in controlling water hyacinth infestations, they are not acceptable for use in most water bodies because of their non-selective characteristics, especially in areas where communities use untreated water for domestic use (Julien *et al.*, 1999). Relyea (2005) observed that people are suspicious of herbicide control, as they have stigmatized herbicides as being “poisonous”. Furthermore, herbicides can interfere with biological control agents where the two control methods occur in combination on water hyacinth (Ueckermann and Hill, 2001), since these herbivorous arthropods are totally dependent on the weed for food and habitat. Ajuonu *et al.* (2009) citing Greathead (2003), stated that the preferred method of controlling water hyacinth is biological control because it is environmentally friendly and has successfully reduced infestations in many African countries.

In Africa, several natural enemy species have been established on water hyacinth (Table 1.2) most notably the two weevil species, *Neochetina eichhorniae* (Warner) (Coleoptera: Curculionidae) and *N. buchi* (Hustache) (Coleoptera: Curculionidae) (Ajuonu *et al.*, 2003). The

mirid, *Eccritotarsus catarinensis* (Carvalho) (Heteroptera: Miridae) (Hill *et al.*, 1999b), released in South Africa in 1996 and later in Malawi and Benin (Ajounou *et al.*, 2009). The pyralid moth, *Niphograptia albiguttalis* (Warren) (Lepidoptera:Pyralidae), the galumnid mite, *Orthogalumna terebrantis* (Wallwork) (Acarina:Gulumnidae), and the pathogen, *Cercospora piaropi* (Tharp) (Hyphomycetes) (Ajounou *et al.*, 2009; Evans and Reeder, 2001; Julien, 2001; Hill, 2001; Hill and Cilliers 1999) have also been used. The most recent agent to be released is the grasshopper, *Cornops aquaticum* Bruner (Orthoptera: Acrididae), that was released in South Africa in 2010. Some important fungal pathogens are used as water hyacinth bio-control agents in South Africa. This group includes the introduced *Cercospora piaropi* and *Acremonium zonatum* (Sawada) Gams, and *Alternaria eichhorniae* (Jones, 2009) that is indigenous.

In Mozambique, some areas of water hyacinth have been effectively controlled by the weevils *N. eichhorniae* and *N. bruchi*. Both species of weevils were released and established in Mozambique in 1979 (Cugala, 2009, personal communication; Cilliers *et al.*, 2001; Phiri, 1997).

Table1.2 The natural enemy species established on water hyacinth in Africa (data modified from Cilliers *et al.*, 2003; Julien 2001; Harley, 1990).

	<i>Neochetina eichhorniae</i>	<i>Neochetina bruchi</i>	<i>Niphograptia albiguttalis</i>	<i>Eccritotarsus catarinensis</i>	<i>Orthogalumna terebrantis</i>	<i>Cercospora piaropi</i>	<i>Cornops aquaticum</i>
Benin	✓	✓	✓	✓	-	-	-
Burkina Faso	✓	✓	-	-	-	-	-
Congo	✓	✓	-	-	-	-	-
Côte d'Ivoire	✓	✓	✓	-	-	-	-
Egypt	✓	✓	-	-	-	✓	-
Ghana	✓	✓	✓	-	-	✓	-
Kenya	✓	✓	✓	-	✓	✓	-
Malawi	✓	✓	✓	✓	✓	-	-
Mali	✓	✓	-	-	-	-	-
Mozambique	✓	✓	-	-	✓	-	-
Niger Rep.	✓	-	-	-	-	-	-
Nigeria	✓	✓	-	-	-	✓	-

Rwanda	✓	✓	-	-	-	-	-
South Africa	✓	✓	✓	✓	✓	✓	✓
Sudan	✓	✓	-	-	-	-	-
Tanzania	✓	✓	-	-	-	-	-
Togo	✓	✓	-	-	-	-	-
Uganda	✓	✓	-	-	-	-	-
Zambia	✓	✓	✓	✓	✓	-	-
Zimbabwe	✓	✓	✓	✓	✓	-	-

✓ (present), - (not yet released)

1.6.1.3 Uses of water hyacinth

There have been a number of attempts to use water hyacinth profitably. The weed consists of more than 95% water but, with its fibrous tissue and high energy and protein content, it has a variety of useful applications. Some of these have been developed, and others are still in their infancy. Combined with other weeds or alone, water hyacinth can be used in the production of animal feed (silage) (Yang, 2004) and used as fertilizer (compost) (Thomson *et al.*, 2002). Water hyacinth can also be successfully used to treat industrial effluents because it is able to survive in the presence of toxic contaminants (Jayaweera and Kasturiarachchi, 2004). In India, water hyacinth is used as a medicinal plant mainly to treat goiter disease, and the fresh juice of water hyacinth can be applied as an antiseptic (Oudhia, 1999 a, b).

In Mozambique, people use weeds such as *E. crassipes* directly as cattle feed or as fertilizer on the land surrounding the water body. Experiments at the University of Lourenço Marques (today called Eduardo Mondlane University) with yeast fermentation of an *E. crassipes* and molasses mixture have produced a protein-rich end product (Oliveira, 1972).

1.6.2 *Pistia stratiotes*

1.6.2.1 Origin and distribution of *Pistia stratiotes*

Pistia stratiotes was first reported from Florida in the early 1900s (Stuckey and Les, 1984), which led to the belief that this plant was a native to North America. The presence of co-evolved herbivorous insects in South America (Cordo and Sosa, 2000; Dray *et al.*, 1993) suggested, however, that *Pistia stratiotes* originated from South America.

Like water hyacinth, water lettuce is one of the most widely distributed of all floating macrophytes, and occurs on all continents, except in Antarctica. It has now spread throughout the tropics and subtropics (Parsons and Cuthbertson, 2001). Water lettuce has been recorded as a weed in a number of countries around the world, and in Africa, has been reported as most troublesome in the Upper Nile, Zambia, Kenya, Zimbabwe and the regions of Angola and Mozambique (Henderson and Cilliers, 1991; Davies *et al.*, 1975), and in Benin, Côte d'Ivoire, Nigeria and Senegal (Ajuonu and Neuenschwander, 2003, Pieterse *et al.*, 2002, den Hollander *et al.*, 1998).

Although it is not clear when water lettuce was introduced into Mozambique, the weed was reported for the first time in the Cabora Bassa region in 1974 (Davies *et al.*, 1975; Macedo, 1974). In the last decade, water lettuce has caused trouble in the Umbeluzi, Incomati and Limpopo rivers (DNA, 2008; Davies *et al.*, 1975).

1.6.2.2 Methods of controlling water lettuce

Methods of controlling water lettuce include manual and mechanical removal. This is useful for short-term control, but re-growth is rapid and the control must be repeated, making mechanical control impractical (Cilliers *et al.*, 2003). Chemical control approaches that have been successful in treating *P. stratiotes* in Africa are herbicides such as endothall, terbutryn, glyphosate and 2-4 D-amine (Grobler *et al.*, 2000).

Another method of controlling water lettuce is biological control. There are a number of phytophagous species associated with water lettuce around the world (Center, 1994; Dray *et al.*,

1993). Neuenschwander *et al.* (2009) reported six species which feed on water lettuce in Florida. Of them, *Samea multiplicalis* Guané (Lepidoptera: Pyralidae) was by far the most common and damaging. In Argentina, 17 species were found feeding on *P. stratiotes* (Cordo and Sosa, 2000). In the Old World, *Bagous pistiae* Marshall (Coleoptera: Curculionidae) was recorded on *P. stratiotes* (Neuenschwander *et al.*, 2009). In Africa, eight species were counted feeding on *P. stratiotes* (Cordo and Sosa, 2000) and finally, in Asia and Indonesia, 13 species were identified feeding on *P. stratiotes*. However, with the exception of the species recorded in Argentina, most of these insects are either stenophagous or polyphagous; none feed exclusively on water lettuce (Dray and Center, 2002).

Pistia stratiotes has been successfully controlled by the weevil, *Neohydronomus affinis* Hustache (Coleoptera: Curculionidae) previously referred to as *N. pulchellus* (Thompson and Habeck, 1989) in Australia (Harley *et al.*, 1990), Congo (Mbatu and Neuenschwander, 2005), South Africa (Cilliers 1987), and Zimbabwe (Chikwenhere and Forno, 1991). *P. stratiotes* is reported to be under variable levels of biological control at many sites by *N. affinis* and *Spodoptera (Epipsamma) pectinicornis* (Hampson) (Lepidoptera: Noctuidae) in Ghana, Papua New Guinea, USA and Zambia (Julien and Griffiths, 1998).

In Mozambique, the weevil, *Neohydronomus affinis*, was not introduced, but it has been observed in some areas, probably having spread from neighbouring countries (Chiconela, 2009 personal observation).

1.6.2.3 Uses of *Pistia stratiotes*

Water lettuce has reportedly been used in Egypt since the time of Pliny (77 A.D) (Henderson and Cilliers, 1991) where it was used to heal wounds and bacterial infections affecting superficial layers of the skin. In Nigeria, *P. stratiotes* is used as part of a concoction for the treatment of influenza, (Obot and Ayeni, 1987). Investigation has shown that *P. stratiotes* has a tremendous capacity to remove metal ions from aquatic environments (Miretzky *et al.*, 2006; Odjegba and Fasidi, 2004). Because of its high reproductive rate and nutritive value, water lettuce has been

used for methane production, and as an animal feed (Henry- Silva and Camargo, 2000) or green leaf manure (Raju and Gangwar, 2004).

1.6.3 *Salvinia molesta*

1.6.3.1 Origin and distribution of *Salvinia molesta*

The free-floating aquatic fern, *Salvinia molesta* (giant salvinia), is one of the world's worst aquatic weeds (Holm *et al.*, 1991). Over the past 70 years, *S. molesta* has spread from its native range in South America to tropical and subtropical regions around the world (Pieterse *et al.*, 2003; Jacono and Pitman, 2001; Navarro and Phiri, 2000; Hill *et al.*, 1991). It was first observed outside its native range in Sri Lanka in 1939 and has since become a serious problem in over 20 countries (Storrs and Julien, 1996; Oliver, 1993; Room, 1990; Room *et al.*, 1989; Room, 1986a).

Salvinia molesta is presently established in the United States, Australia, New Zealand, Fiji, the Philippines, India, Indonesia, Malaysia, Singapore, and Papua New Guinea. It has also infested aquatic systems in Africa (Cotê-d'Ivoire, Ghana, Zambia, Kenya, Namibia, Botswana, South Africa, and Mozambique) (Room and Julien, 1995), South America (Columbia and Guyana), and two Caribbean countries, Cuba and Trinidad (Storrs and Julien, 1996; Holm *et al.*, 1991). Most recently, *S. molesta* was reported in southern Kalimantan (formerly Borneo), where rivers, swamps, and rice paddies have become increasingly overgrown (Jacono and Pitman, 2001).

In Mozambique, *Salvinia molesta*, formerly identified as *S. auriculata* Aubl. (Mitchell, 1969; Schelpe, 1961) was first recorded, together with water hyacinth, in Cabora Bassa in the Zambezi River in 1948 (Mitchell, 1972b). Mitchell (1972b) states that *Salvinia molesta* was introduced to Mozambique by a mission worker in the Zambezi area. The infestations of this weed occur along the Zambezi and its tributaries (World Wildlife Fund, 2008, Beilfuss *et al.*, 2001), and today the weed is found distributed in the Umbeluzi, Incomati and Limpopo rivers (DNA, 2008; Gustafsson and Jahanson, 2006; Cugala, 2006; 2004).

1.6.3.2 Methods of controlling *Salvinia molesta*

Salvinia molesta is usually controlled by mechanical removal for small areas of water, a method which is effective if every last piece of salvinia can be removed as the weed will not regenerate from spores. In larger areas of water, it is often too expensive to control *S. molesta* manually or mechanically because of the great weight of wet plant mass which must be removed and the speed at which the weed re-colonizes open water (Cilliers *et al.*, 2003). The weed invariably outgrows all efforts by manual removal (Cilliers *et al.*, 2003). Herbicides such as diquat, 2,4-dichlorophenoxy acetic acid (2,4-D amine), and glyphosate can be used to eradicate salvinia from small- to medium-sized water bodies which have little or no fringing vegetation, such as reeds, amongst which salvinia can escape detection and treatment.

Biological control is also used on salvinia. Twenty-five phytophagous species have been recorded from *Salvinia molesta* and 49 species from the four species of the *S. auriculata* complex. Four of these species have been used as biological control agents against *S. molesta*. The first three, namely a moth, *Samea multiplicalis* Guenée (Lepidoptera: Pyralidae), a grasshopper, *Paulinia acuminata* (De Geer) (Orthoptera: Pauliniidae), and a beetle, *Cyrtobagous singularis* Hustache (Coleoptera: Curculionidae), which were identified during early exploration (Bennett, 1966), have not been successful control agents. The fourth, *Cyrtobagous salviniae* Calder and Sands, was found during later surveys in Brazil (Sands, 1983) and has been extremely successful. Although this insect is not a particularly good disperser (Forno and Julien, 2000), it has been a successful biological control agent wherever it has been introduced in the world.

The weevil is recognized throughout the world as the preferred control method for *S. molesta* management. This agent has been used for control in the tropical areas of twelve countries on three continents including, but not limited to, Australia, Fiji, India, Kenya, Namibia, South Africa, Sri Lanka, Zambia, and Zimbabwe (Diop and Hill, 2009; Julien *et al.*, 2009; Mbatia and Neuschawander, 2005; Room *et al.*, 1981;).

In Mozambique, only the grasshopper, *P. acuminata* (Trinidad and Uruguay strains), was released on Cahora Bassa Dam to control *Salvinia molesta* (Jacob Guillarmod, 1979), but it is not certain if it established.

1.6.3.3 Uses of *Salvinia molesta*

Although the plant has some value, the multitude of economic, health and environmental drawbacks outweigh any economic value that *S. molesta* possesses. This value includes use as a compost and mulch, and in Asia, as a supplement to regular livestock fodder (Thomas and Room, 1986). However, *S. molesta* is not suitable as a sole source for fodder because the high content of crude ash, lignin, and tannins reduce digestibility (Moozhiyil and Pallauf, 1986).

1.6.4 Red water Fern (*Azolla* spp.)

1.6.4.1 Origin and distribution of *Azolla filiculoides*

The red water fern, *Azolla filiculoides*, is native to warm temperate and subtropical America throughout western North America (including Alaska). *Azolla filiculoides* was described as a species which, in former times, was native to Europe (O'Brien and Jones 2003; West, 1953), but which died out during the last Ice Age. Red water fern is considered a cosmopolitan weed that occurs in southern Africa (McConnachie *et al.*, 2004, 2003; Gratwicke and Marshall, 2001; Hill and Cilliers, 1999), Asia (Kitoh *et al.*, 1993), and Europe (Hussner and Lösch, 2005; Ferreira *et al.*, 1998). The red water fern was first recorded in South Africa in the Northern Cape Province (Oosthuizen and Walters, 1961) in 1948 and is now reported as an invasive plant in Zimbabwe, Zambia, Malawi, Uganda and Northern Mozambique (Hill, 1999).

Schelpe (1977, 1969) also records two indigenous species of *Azolla*, *A. pinnata africana* Desv. and *A. nilotica* Decne. The first occurs in northern Kwazulu-Natal (Pongolo River flood-plain), as well as other parts of South Africa and Botswana, in the warmer parts of the region, while *A. nilotica* is in the subtropical portion, being found in Malawi and northern Mozambique (Cook, 2004; Bond and Roberts, 1978).

In Mozambique, one *Azolla* species identified was probably *Azolla nilotica* Decne ex Mett. This *Azolla* was recorded in the catchment of Cabora Bassa, together with other weeds (*Salvinia molesta*, *Pistia stratiotes* and *Eichhornia crassipes*) during the pre-impoundment surveys (Bond and Roberts, 1978). Registers taken in 2002 by Santos *et al.*, (2002–unpublished), while doing their research on the weevil, *Stenopelmus rufinasus* Gyllenhal (*Curculionidae*), as a biological control agent of *A. filiculoides*, showed that this weed is widespread along the southern part of the country, except in the Inhambane Province (Govuro and Inharrime rivers). Currently, a species of *Azolla*, most likely *A. microphylla* (See Chapter 2), is distributed along the Umbelizi, Incomati, Limpopo and Zambezi rivers and their tributaries (DNA, 2008).

1.6.4.2 Methods of controlling *Azolla* spp.

Mechanical and chemical control options have been suggested for *Azolla* spp. However, these control methods are labour-intensive because of the rapid spread of the weed. It has been proved that it is economically impractical to control large areas through these methods because they must be applied repeatedly and indefinitely (Thomas and Room, 1986). The disadvantage of mechanical methods is that the rate of increase of the plant is such that a concerted effort is required to keep up with the daily production of even a small infestation, and if eradication is achieved, re-establishment of the weed from resistant spores in the substrate of the water body is inevitable (Hill, 1999; Lumpkin and Plucknett, 1982).

Chemical controls such as herbicides based on glyphosate, paraquat and diquat have been used to control red water fern (Axelsen and Julien, 1988). The disadvantages of herbicidal control for *Azolla* spp. are that it is expensive, especially in view of the extensive follow-up programme required to eradicate the plants that continually germinate from spores; that there is a danger of spray drift onto non-target vegetation, and that personnel must be trained to apply it (Hill, 1997).

Successful biological control of red water fern, *A. filiculoides*, has been achieved using the frond-feeding weevil, *Stenopelmus rufinasus* Gyllenhal (*Curculionidae*) (McConnachie *et al.*, 2004, 2003; Hill and Cilliers 1999; Hill, 1998). The weevil was imported from Florida (USA) to South Africa and released in December 1997. It has shown remarkable results, causing the

extinction of red water fern at most of the sites where it was released (McConnachie *et al.*, 2003), and it has also dispersed on its own (or via waterfowl) to many more weed-infested sites throughout the country. This means that the weevil has had a significant impact on the weed status of *A. filiculoides* in South Africa. The weevil has been exported to Zimbabwe, where it has been responsible for clearing a number of farm dams (Cilliers *et al.*, 2003; Chikwenhere *et al.*, 1999). In Mozambique, *Stenopelmus rufinasus* was not released, but has been found in the country and was probably dispersed from South Africa (Cilliers *et al.*, 2003) and other countries nearby (Santos *et al.*, 2002).

1.6.4.3 Uses of *Azolla filiculoides*

Various *Azolla* species have been distributed as biological fertilizers in many developing countries, which has increased the distribution of this plant to many parts of the world (Lumpkin and Plucknett, 1982). *Azolla filiculoides* is used as green manure in rice paddies (Kimura, 2005; Lumpkin and Plucknett, 1982) which improves the soil quality by increasing organic-nitrogen levels and improving water-holding and cation-exchange capacities of the soil. *Azolla* spp. can also be used as fodder for animals (swine, poultry, cattle, and fish) (Reyes and Fermin, 2003), but it cannot be used as the only protein source and should be supplemented with other feeds. Its advantages are that it has a high nutrient content, it grows quickly on natural water bodies, it is available throughout the year, and it does not need processing (Hill and McConnachie, 2009).

Azolla is used ornamentally on ponds and in fish tanks. In India, *Azolla* is eaten. It can be used in mosquito control, because a complete mat disrupts larval development. However, an incomplete mat increases mosquito problems as it protects the larvae from predators (Hill and McConnachie, 2009).

1.7 Thesis outline

According to Chiconela *et al.* (2002), there are currently five aquatic weeds which are especially problematic in Mozambique. These are water hyacinth, (*Eichhornia crassipes*), water lettuce, (*Pistia stratiotes*), kariba weed, (*Salvinia molesta*), parrot's feather, (*Myriophyllum spicatum*), and red water fern (*Azolla* spp.). In the presence of enriched waters and the absence of natural enemies, these aquatic weeds have proliferated to pose the biggest threat to the water resources of Mozambique. Since the floods in 2000, the problem of aquatic alien invasive plant species in Mozambique has increased significantly as these weeds infest rivers, lagoons and dams (Tamele, 2002). Mozambique is located downstream of international river basins in the SADC region. Because of its geographical position and hydrological structure, more than 50% of surface runoff is generated from the neighbouring countries upstream. The southern region of Mozambique is, in fact, composed of the alluvial plains of some large rivers that have their sources in countries located upstream: South Africa (Maputo, Incomati, and Limpopo rivers); Swaziland (Umbeluzi River) and Zimbabwe (Save River). Because of this dispersion, and water flowing from these infested countries upstream, levels of surface coverage and areas affected by these aquatic alien weeds have increased in Mozambique rivers (Tamele, 2002).

In addition, Mozambique is characterized by significant agricultural and industrial developments that provide basic conditions for the increase in nutrients and thus the spread of invasive aquatic plants. Other factors, such as human activities (passive flow) and natural dispersion (active flow) through stream waters, also contribute to the occurrence and spread of alien invasive aquatic species in the rivers. The major impact on the freshwater system in Mozambique comes from farms, sugar cane refineries and city sewage, all of which add pollutants and excess plant nutrients to nearby streams, rivers and lakes.

People in Mozambique live in total ignorance concerning the types of weed, their location, degree of infestation and density, the origins of the weeds, their mode of transfer from source to point, and the dangers that lie ahead if they should thrive. In many instances, there is very little awareness of the size of the threat posed by aquatic weeds. As a result, there is often little incentive for the relevant authorities to take appropriate corrective measures. For these reasons,

the water resources in Mozambique are under threat, not only through exploitation and pollution, but also because of biotic invasion.

Attempts to control invasive alien aquatic plants have been based on prevention (legislation), mechanical and/or manual removal, and biological control. Previous studies focused on identification of the aquatic invasive species and the general geographic locations of invasion, and a biological control programme that was undertaken in the 1990s using weevils against water hyacinth. However, no monitoring was done (Cugala, 2006). No studies on the levels of invasion have been carried out, no formal information about the environmental and socio-economic impact of the weeds has been provided in Mozambique. There is a lack of information on the status and distribution of aquatic invasive plants and their associated natural enemies. This study will increase the knowledge about aquatic invasive species along the rivers situated in the southern part of Mozambique, the impact of the weeds on riparian communities, as well as the impact of aquatic weeds on biodiversity. The above aims form the basis for all chapters, outlined in more detail below.

Chapter 2

Aquatic vegetation is essential to a healthy river, and a natural part of the aquatic environment. Vegetation provides a habitat for fish and other aquatic organisms; it oxygenates the water, and as it decays, it provides nutrients for the system. However, when aquatic plants grow excessively, they can harm the body of water and the aquatic biodiversity in a number of ways. Harmful effects include oxygen depletion caused by decaying vegetation, and eutrophication of water which changes the colour and odour of water. The chapter evaluates the aquatic plants (the indigenous and the invasive ones) in terms of occurrence, diversity and abundance along different rivers located in southern Mozambique, taking into account the physical characteristics of the rivers.

Chapter 3

The physical presence of aquatic weeds hinders human activity and interferes with the ecological functioning of rivers, lakes and dams. The impact of dense mats of aquatic weeds includes: the reduction in quality and quantity of water for urban, agricultural and industrial use; an increase in

siltation of rivers, dams and wetlands; a reduction in water surface area for recreation; clogging of irrigation canals and pumps; drowning of livestock that were unable to differentiate between pasture land and weed-covered water bodies; severe deterioration of aquatic biodiversity, and an increase in insect-borne human diseases. Using interviews with the relevant riverine populations, this chapter quantifies the socio-economic impacts of invasive water weeds on communities living in the Incomati River Basin.

Chapter 4

Communities have an important role in the control of the aquatic weeds. Several methods are used to attempt to minimize the impact of weeds in the Mozambican rivers. The people are reluctant and afraid to use chemical methods because they are increasingly aware of the ill effects of herbicides. In many cases the water is not treated by the riverine population before consumption. In Mozambique, biological control agents were introduced in 1978 and the establishment of natural enemies was reported in 1979. Since that time, there have been no further developments in the use of biological control agents and no monitoring has been done (Chiconela, 2009- personal communication). This chapter evaluates the biological control agents on aquatic weeds in terms of occurrence, diversity and the impact that they had on the aquatic weeds.

Chapter 5

Many rivers and dams in Mozambique receive run-off which is highly polluted with nitrates and phosphates from agricultural activities. This can affect the ecosystem's functioning by altering biotic diversity as water weeds normally occur in the form of dense mats. Dense mats of aquatic plants, including weeds, block light penetration for the submerged plants and reduce dissolved oxygen levels. Benthic macro-invertebrates are generally considered to be the most sensitive of aquatic organisms, making them ideal for monitoring impacts on the environment. The hypothesis tested in this study was that *Pistia stratiotes* would affect the diversity and abundance of macro-invertebrates. There are relatively few studies that quantify the impact of biological control on population of aquatic weeds and even fewer that have mentioned recovery of an ecosystem after control. The trial was designed to show how often and how easily the aquatic

macro-invertebrates recover after removing the water lettuce using herbicides and the biological control agent *Neohydronomus affinis*.

Chapter 6

This chapter interprets the findings on aquatic weeds in southern Mozambique rivers, the impact of the weeds on the human, environment and aquatic biodiversity, and the preferred control methods used by riverine populations to manage the aquatic weeds. Finally, the chapter comments on the implications of the findings for the biological control programme in Mozambique, and makes recommendations for the management of aquatic plants.

Distribution of aquatic invasive weeds in southern Mozambique rivers

2.1 Introduction

Despite the Cilliers *et al.* (2003) review, very little is known about aquatic weeds in Mozambique (Chapter 1), and only two studies have been published about the presence of weeds in the rivers, lakes, dams and drainage systems (Cugala, 2006; Chiconela *et al.*, 2002). However, as water resources become increasingly limited due to a burgeoning population, it is necessary to understand freshwater ecosystems better and, in particular, quantify the extent of the invasive threat to these systems that will put more pressure on the quantity and quality of freshwater.

The main aim of this study was to evaluate the levels of infestation of aquatic invasive weeds along the southern Mozambique basin (Maputo, Umbeluzi, Incomati, Limpopo, Inharime, Guvuro and Save rivers) and to provide a baseline record of the species of aquatic plants and their level of infestation. This study will aid in the development of an integrated management plan for aquatic plant invasion in Mozambique.

2.2 Specific objectives

The specific objectives of this study were to conduct a survey of the occurrence, diversity and abundance of invasive aquatic plants in the southern Mozambique rivers and to map the invasive aquatic plant species in these systems.

2.3 Material and methods

2.3.1 Sampling procedures

This study was conducted in the rivers of southern Mozambique. The river basins studied were Maputo, Umbeluzi, Incomati, Limpopo, Inharime, Guvuro and Save (Figure 2.1). Sampling was undertaken at as many sites as possible along these rivers, and thus the number of sampling points per river varied, depending on the size of the river. Sampling points were chosen taking into consideration the local population and other stakeholders, and accessibility to the river.

2.3.2 Characteristics of the sites sampled

Most of the rivers in Mozambique flow from west to east, draining the water of the central African high plateau into the Indian Ocean (Consultec, 1998). From the southern basin northwards, the Maputo, Umbeluzi, Incomati, Limpopo and Save rivers are all international rivers, that is to say, they are downstream of other countries. The rivers have high water flows during the months of October to March and low flows for the remainder of the year, corresponding to the marked wet and dry seasons. The rivers are characterized as well by low runoff coefficients, deep saline intrusion in the mouths (reaching up to 50 km inland), wide and shallow river valleys with low store and consequent high evaporation losses, and large flood-plain areas. The intensive use of water in the upstream countries, especially in Zimbabwe and South Africa, has reduced the flows entering Mozambique. The rivers are dry between April and September in a normal year, a situation that did not occur prior to 1980, since when many dams have been constructed upstream (Carmo Vaz, 2000). Agriculture is the most common economic activity along all of the rivers. High-value crops produced under irrigation in those areas include sugar cane, citrus and bananas. Activities such as intensive agriculture, livestock production and small-scale fishing can be observed along and in the following rivers: Umbeluzi, Incomati, Limpopo, Maputo and Save. The Guvuro and Inharrime rivers have clean and quiet waters for domestic use by the local population.

The Maputo River is an international river with a catchment area of 29 030 km², of which 27 460 km² (95%) is located in South Africa and the remaining 1 570 km² (5%) in Mozambique (DNA, 1999). Starting in South Africa, it flows into the Maputo Bay on a permanent basis with an annual average water flow of 28 500 million / m² (DNA, 1994). Its waters are used for fishing, livestock production, and irrigation in subsistence agriculture. The river has a strong flow rate and is rich in sediment.

The Umbeluzi River is also an international river with a catchment area of 5 460 km², of which 3 140 km² (58%) is located in Swaziland, 80 km² (1%) in South Africa, and the remaining 2 240 km² (41%) in Mozambique. Its upper reaches are located on the west of Swaziland at altitudes varying between 1 800 and 800 m (DNA, 1999). Its main tributaries are the Calichane and Movene rivers, upstream and downstream respectively, of the Pequenos Limbombos Dam.

The Umbeluzi River has an annual average discharge of approximately 395 million m³ and receives an average rainfall of 736 mm (Tembe and Baloi, 2001; DNA, 1994).

The Incomati River has a catchment of about 46 800 km² which is shared among South Africa (61%), Swaziland (6%) and Mozambique (15 500 km², 33%). The river rises some 2000 m above sea level in South Africa, in an area that is rich in coal deposits. It then flows into Swaziland and back into South Africa, where it is heavily used for agricultural purposes, before finally flowing into Mozambique where it discharges into the Indian Ocean just north of Maputo (UNEP/Nairobi Convention Secretariat and WIOMSA, 2009). The mean annual runoff of the main catchments within the Incomati basin is 3 587 (Mm³/a). Agriculture (large- and small-scale), industry and urban water use are all significant water consumers. The five dams in the basin, coupled with direct abstractions, have reduced the annual flow of the river significantly (Anon, 2006). The reduced flows in the lower reaches have lowered the potential of the river to absorb pollutants. The Incomati estuary contains an extensive mangrove forest covering approximately 5 000 ha around the mouth area, which has a beneficial impact on the marine habitats and the coastal zone, protecting it from erosion. However, the mangroves have suffered anthropogenic impact and large areas are being harvested for construction, charcoal production and firewood. Upstream impoundments have reduced the freshwater and sediments flowing into the estuary, which has changed the flow regime. In addition, the salt water from the coast enters the river, causing a salt intrusion problem (Carmo Vaz, 2000).

The Limpopo River Basin is located in the east of southern Africa, approximately between latitudes 20°S to 26°S and longitudes 25°E to 35°E. It has a mean altitude of 840 m above sea level (FAO-SAFR, 2004). The Limpopo River has a catchment area of about 412 000 km² which is shared among South Africa (47%), Botswana (18%), Zimbabwe (16%) and Mozambique (19%). It rises at an altitude of about 2 300 m near Lydenburg (South Africa) and drops into the alluvial plain in Mozambique (Carmo Vaz, 2000). The average annual flow at the border near Combomune is in the order 3 250 Mm³/a, while the normal average inflow to Massingir Dam is about 1 230 Mm³/a (DNA, 1996). There are 13 dams in the Limpopo Basin River, the largest one being Massingir Dam (present capacity: 1 200 million m³ (Brito *et al.*, 2009).

There is very little information on the hydrology of the Save, Govuro and Inharrime rivers. The Save River is the largest of the three. It crosses the country from west to east, roughly separating the dry southern part of the country from the more humid north. The Save River has a catchment of 92 100 km². For much of its 330 km course through Mozambique, the river flows in a well-incised bed some 1–2 km wide, but while in summer it is full, in winter, its flow is frequently confined to a central channel barely 45 cm deep and scarcely 50 m across. In the dry season, the river bed is a shining expanse of sand banks, with only occasional rocky or sandy pools and pebble banks. In some parts, a series of little muddy pools lies close under its banks, which may be quite steep.

The Govuro River has a catchment of 11 500 km², and although small, it is the most important river in the north of Inhambane Province. It starts in Inhambane, district of Vilanculos, and runs northwards for more than 150 km, through the districts of Vilanculos and Inhassoro, flowing into the Indian Ocean in the region of Macovane (DNA, 1999). Inharrime River, with a length of 150 km, has a catchment of 11 850 km², consisting totally or partially of the districts of Panda, Zavala and Inharrime (DNA, 1999).

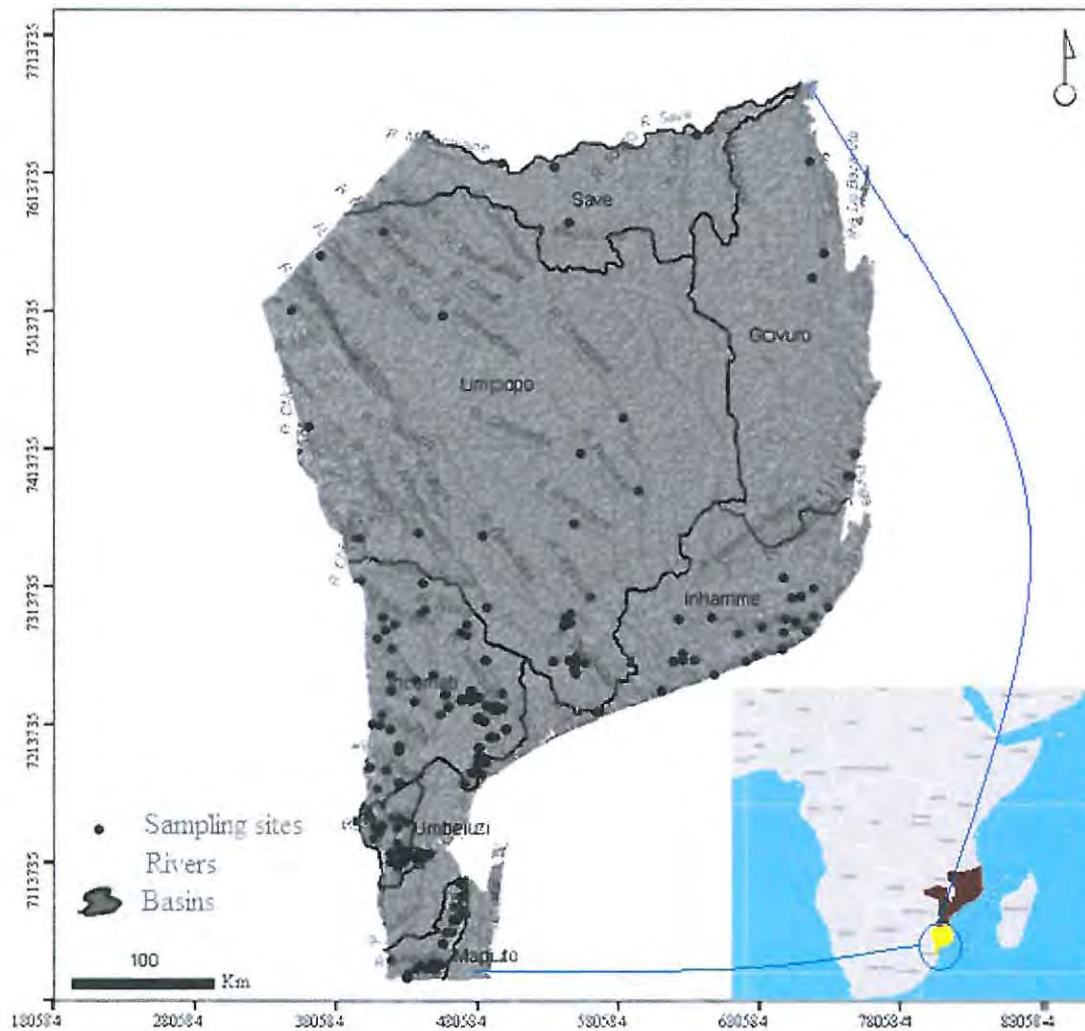


Figure 2.1 The southern part of Mozambique showing the rivers basins studied and the sampling sites on those rivers.

2.3.3 Survey of the occurrence, diversity and abundance of aquatic invasive alien plants

At each sampling site, ecological factors such as pollution from agricultural practices, industrial centres and human activities were recorded. Data were collected in May, June, October and November 2008. The number of sites varied for each river (Figure 2.1): 21 sites for Maputo, 25 for Umbeluzi, 50 for Incomati, 24 for Limpopo, 24 for Inharrime, five for Govuro and five for Save. An area of 4 m² was randomly marked at each sampling site in areas that had aquatic plants. In other words, the quadrat was not placed in open water. All plants in the marked square

were separated, counted and identified. The exact position of each sampling site was determined with the use of a GPS. In June and October 2009, a field trip was carried out to confirm the presence or absence of the invasive aquatic plants. The plants were identified using guides to the identification of the invasive plants namely, *Invasive Aquatic Plants* (Henderson and Cilliers, 2002) and *Alien Weeds and Invasive Plants* (Henderson, 2001). The *Azolla* plants found were identified by Martin Hill, using genetics analyses (Hill and Madeira, 2011).

2.3.4 Survey on the abundance of aquatic invasive plants

In order to evaluate abundance, the plants found in each 4 m² were categorized according to the number of plants per m² square. Based on Daubermire (1957), the following scale was used: 1- No occurrence (0 plants/m²); 2-Rare (1–5 plants/m²); 3-Less common (6–14 plants/m²); 4-Common (15–29 plants/m²); 5-Abundant (30–99 plants/m²); 6-Very abundant (>100 plants/m²).

2.3.5 Percentage cover of the aquatic macrophytes

During the survey, the number of macrophyte species (expressed as percentage) was determined by estimating their percentage cover. This was expressed on an ACFOR abundance scale (Kent and Coker, 1992): 1-Abundant (75–100%); 2-Common (50–75%); 3-Frequent (25–50%); 4-Occasional (5–25%); 5-Rare: (0-5%).

2.3.6 Mapping

A map was produced using the Land sat ETM+, the GPS (Garmin). To map the aquatic weeds in the study area, two steps were taken. Firstly, the species abundance was determined by applying a nominal scale of the abundance of species occurrence: No occurrence, Rare, Less Common, Common, Abundant and Very Abundant. Secondly, geographical coordinates were recorded for each quadrat, as well the number of each plant species.

2.3.7 Data analysis

For each 4 m², the number of individuals and the total number of species was measured. From these measurements the following were calculated by the following formula:

$$\% \text{ Frequency} = \frac{\text{Number of quadrats in which the species occurred} \times 100}{\text{Total number of quadrats studied}}$$

$$\text{Relative Frequency} = \frac{\text{Frequency value for a species} \times 100}{\text{Total of frequency values for all species}}$$

$$\text{Density} = \frac{\text{Total number of individuals of species}}{\text{Total number of quadrats used in sampling}}$$

$$\text{Relative Density} = \frac{\text{Total number of individuals of species}}{\text{Sum of all individuals of all species number}}$$

$$\text{Abundance} = \frac{\text{Total number of individuals of the species}}{\text{Number of quadrats in which they occurred}}$$

$$\text{Importance Value} = \text{Relative frequency (RF)} + \text{Relative Density (RD)}$$

Dominance was calculated using the Shannon-Wiener diversity index formula:

$$I_{Shannon} = H = -\sum p_i \ln(p_i)$$

The Evenness (equitability) was calculated from the formula (Pielou, 1975)

$$E = H' / \ln(p_i)$$

Descriptive statistics such as percentage of overall dominance, distribution and frequency were used. Data were analyzed and discussed using the Non-Parametric Test (Mann-Whitney U Test) to check whether there were differences between invasive and indigenous species within each river, and the ANOVA, Student t-Test was used to calculate if there was a significant difference in the mean number of invasive plants between the sampled sites. In both cases, data analysis was performed using the statistical package software–STATISTICA (Version 10).

2.4 Results

2.4.1 Relative density of aquatic plants along the southern Mozambique Basin rivers

A total of 11 aquatic plant species were found along the Maputo, Umbeluzi, Incomati, Limpopo, Inharrime and Guvuro rivers. Of these aquatic plants, four were invasive alien species, namely: *Eichhornia crassipes*, *Pistia stratiotes*, *Azolla microphylla* and *Salvinia molesta*. Seven indigenous plants were recorded, namely *Ceratophyllum demersum* (L), *Ludwigia stolonifera* (Guill and Perr) P. H. Raven, *Potamogeton schweinfurthii* A. Benn, *Lemna minor* (L) Bubani, *Spirodella polyrrhiza* (L) Schleiden, *Nymphaea alba* (L) and *N. nouchali* Burm. (these two species were grouped together) and *Trapa natans* (L) (Table 2.1). Table 2.1 shows the distribution patterns, the frequency, density and abundance and also the richness index of all the aquatic plants, including the invasive ones. The invasive plants found in the study sites are all of South American origin and are problematic. The opportunistic (indigenous) ones are native components of regional flora, which have become overly abundant or aggressive due to an increase in nutrients in the rivers (Henderson and Cilliers, 2002). *Nymphaea alba* and *N. nouchali*, *Potamogeton schweinfurthii* and *Ludwigia stolonifera* are naturally indigenous to Africa, but *Ceratophyllum demersum*, *Lemna minor*, *Trapa natans* and *Spirodella polyrrhiza* occur within and beyond the borders of Africa and are generally considered to be cosmopolitan.

Eichhornia crassipes was found in all rivers except the Save River. *Azolla microphylla* was found in all the rivers, except the Govuro and Inharrime rivers, which are located in the Inhambane Province and are pristine, that is, undisturbed by humans. *Azolla microphylla* and *E. crassipes* showed higher density and were more abundant compared to *S. molesta* and *P. stratiotes* along the rivers studied, but in one case, *S. molesta* in the Umbeluzi River, was more abundant than *E. crassipes* (Table 2.1).

There were probably other *Azolla* species along with *A. microphylla* because *Azolla* species are so similar and difficult to identify unless they have spores. This was the first record of *A. microphylla* for southern Mozambique rivers, but it was probably previously misidentified as *A. filiculoides* (Hill and Madeira, 2011). This species is native to central and North America and is also becoming widespread in the subtropical eastern regions of South Africa.

The presence of the four weeds was related to common environmental conditions. These weeds were found in rivers such as Umbeluzi, Incomati and Limpopo where there is a very high urban influence. Fewer weeds were observed in the Maputo River. This river receives less sewage inflow, since fewer farms and industries are located close to it. The Inharrime, Govuro, and Save rivers are situated close to roads without significant human influences. In these rivers, the impact of weeds was insignificant, or no impact was observed.

The indigenous species, namely *Ceratophyllum demersum*, *Ludwigia stolonifera*, *Potamogeton schweinfurthii*, *Lemna minor*, *Spirodella polyrrhiza*, *Nymphaea alba*, *N. nouchali* and *Trapa natans* were less frequent, dense or abundant compared to the invasive ones along the studied sites. In one case, *Nymphaea alba* and *N. nouchali* were more dense, frequent and abundant compared to all other indigenous plants. This phenomenon was observed in the Govuro River, where the plants reached a density of 87.5% (Table 2.1). *Potamogeton schweinfurthii* and *Ceratophyllum demersum* were restricted in their distribution along the different rivers but were abundant locally. *Lemna minor*, *Spirodella polyrrhiza*, *Ludwigia stolonifera* and *Trapa natans* were not distributed uniformly, did not appear in thick mats and were less frequent and less dense when found together with the invasive plants (Table 2.1). This suggests that the invasive plants suppress the indigenous ones.

Table 2.1 Phytosociological analyses of macrophytes along the southern Mozambique rivers. Species marked by * represent invasive aquatic plants; %Freq.=%Frequency; RF=Relative frequency; Dens.=Density; RD=Relative density; Abund.=Abundance; IV=Importance Value; H' =Shannon-Wiener diversity; E =Evenness.

Rivers/Species	% Freq.	RF	Dens.	RD	Abund.	IV	H' / E
Maputo							
<i>Azolla microphylla</i> *	9.52	12.5	8.3	10.9	58.3	23.4	1.29 0.21
<i>Eichhornia crassipes</i> *	33.3	43.8	3.1	4.1	8.3	47.9	
<i>Ceratophyllum demersum</i>	14.2	18.8	2.4	3.1	16.6	21.8	
<i>Ludwigia stolonifera</i>	4.8	6.3	1.3	1.7	27.0	7.9	
<i>Spirodela polyrrhiza</i>	9.5	12.5	9.5	12.5	100.0	25.0	
<i>Nymphaea nouchali</i> and <i>N. alba</i>	4.76	6.3	0.48	0.63	10.0	6.9	
Umbeluzi							
<i>Azolla microphylla</i> *	28.0	13.4	11.3	2.4	84.2	37.1	1.77 0.19
<i>Eichhornia crassipes</i> *	8.0	3.8	1.8	3.7	46.0	7.5	
<i>Salvinia molesta</i> *	12.0	5.8	2.8	5.8	47.6	11.4	
<i>Pistia stratiotes</i> *	8.0	3.9	1.4	3.0	35.5	6.8	
<i>Trapa natans</i>	20.0	9.6	1.8	3.7	18.4	13.3	
<i>Potamogeton schweinfurthii</i>	40.0	19.2	80	16.6	41.6	35.9	
<i>Ceratophyllum demersum</i>	12.0	5.8	0.26	0.56	4.7	6.32	
<i>Ludwigia stolonifera</i>	28.0	13.5	3.59	7.5	26.7	20.9	
<i>Nymphaea nouchali</i> and <i>N. alba</i>	40.0	19.2	0.94	2.0	4.9	21.2	
Incomati							
<i>Azolla microphylla</i> *	42.0	20.8	12.3	25.0	82.2	37.1	1.54 0.17
<i>Eichhornia crassipes</i> *	46.0	22.7	14.8	30.0	44.0	7.5	
<i>Salvinia molesta</i> *	4.0	2.0	1.5	3.0	47.6	11.4	
<i>Pistia stratiotes</i> *	30.0	14.8	5.4	11.0	37.5	6.8	
<i>Ceratophyllum demersum</i>	34.0	16.8	7.4	15.0	18.4	13.3	
<i>Ludwigia stolonifera</i>	6.0	3.0	0.67	1.4	41.6	6.9	
<i>Lemna minor</i>	22.0	11.0	2.9	5.8	4.7	35.9	
<i>Spirodela polyrrhiza</i>	10.0	5.0	1.38	2.8	26.7	6.3	
<i>Nymphaea nouchali</i> and <i>N.alba</i>	8.0	4.0	0.03	0.08	4.9	20.9	
Limpopo							
<i>Azolla microphylla</i> *	12.5	18.8	10.0	15.0	80.0	33.7	1.07 0.21
<i>Eichhornia crassipes</i> *	25.0	37.5	5.1	7.8	20.6	45.2	
<i>Trapa natans</i>	4.2	6.3	0.8	1.3	20.0	7.5	
<i>Ceratophyllum demersum</i>	4.2	6.3	0.8	1.3	20.0	7.5	
<i>Ludwigia stolonifera</i>	8.3	12.5	2.1	3.1	25.0	15.6	
<i>Nymphaea nouchali</i> and <i>N. alba</i>	12.5	18.7	0.2	0.31	1.6	19.0	
Inharrime							
<i>Eichhornia crassipes</i> *	0.25	0.27	28.6	7.8	0.24	8.0	1.17 0.29
<i>Ceratophyllum demersum</i>	0.04	0.05	6.0	0.27	0.01	0.30	
<i>Potamogeton schweinfurthii</i>	0.04	0.05	30.0	1.4	0.04	1.4	
<i>Lemna minor</i>	0.08	0.09	84.0	7.6	0.23	7.7	
<i>Nymphaea nouchali</i> and <i>N. alba</i>	0.54	0.59	25.0	14.7	0.46	15.36	
Govuro							
<i>Eichhornia crassipes</i> *	25.0	21.4	1.64	2.9	7.66	24.3	0.8 0.27
<i>Pistia stratiotes</i> *	12.5	7.1	0.42	0.75	6.0	7.9	
<i>Potamogeton schweinfurthii</i>	50	28.6	13.1	23.0	46.0	5.5	
<i>Nymphaea nouchali</i> and <i>N. alba</i>	87.5	50.0	22.5	39.5	45.1	89.5	
Save							
<i>Azolla microphylla</i> *							

In the Save River, only *Azolla microphylla* was observed (no other plants species were found) so no richness index could be calculated. The lowest value of the richness was recorded in the Govuro River ($H=0.8$). This means that very low species diversity (H) was found in that river compared to the others. The highest values of the richness species were found in the Umbeluzi River ($H=1.77$), followed by Incomati River ($H=1.54$), but the distribution of aquatic plants was heterogeneous ($E=0.19$ and $E=0.17$) compared with the Govuro River (Table 2.1). In the Maputo, Limpopo and Inharrime rivers, the index of richness varied from $H=1.07$ to $H=1.29$, equitability was $E=0.21$ to $E=0.29$; there were fewer species, and they were more homogenous than those in the Incomati and Umbeluzi rivers (Table 2.1). These ranges suggest that these rivers are poor in diversity of aquatic species. Typically, values ranged from 1.5 (low species richness) to 3.5 (high species richness) although in exceptional cases, the value could exceed 4.5 (Kent and Cooker 1994).

2.4.2 Percentage covers of aquatic macrophytes

Along the studied rivers, the number of invasive plants per quadrat was more frequent, dense and abundant compared to the indigenous ones (Table 2.1), with the exception of a few sites in one or two rivers. In addition, the invasive plants were also more abundant compared to the indigenous plants in terms of surface area cover and distribution along the rivers (Table 2.2). In this study, the weeds dominated the native plants and were found in high density, frequency and abundance in the majority of the rivers. This could be because the rivers are subject to many influences, in this case, nutrient availability that affects the plants growth.

The most problematic plants were *E. crassipes* and *A. microphylla* because, in most cases, they showed high density (Table 2.1) and a high percentage cover, reaching almost 95% (Table 2.2). *Salvinia molesta* and *P. stratiotes* were less abundant and they showed similarities in terms of percentage cover. *Salvinia molesta* covered areas from 25% to 65%, and *P. stratiotes* covered areas from 3% to 50% on the surface area of the Govuro and Umbeluzi rivers (Table 2.2).

Nymphaea alba and *N. nouchali* were found in all rivers except in the Save River. The maximum surface area covered by *N. alba* and *N. nouchali* was 75% and 95% in Govuro and Inharrime

respectively. *Trapa natans* was found to be abundant only in the Umbeluzi River, covering a surface area of about 25% maximum (Table 2.2). *Ceratophyllum demersum*, *P. schweinfurthii* and *L. stolonifera* occupied a maximum 25% surface area and finally, *Lemna minor* and *Spirodela polyrrhiza* occurred more rarely, with a maximum percentage cover of 5% (Table 2.2). It was quite difficult to determine the total percentage coverage of *C. demersum* and *P. schweinfurthii* because they are submerged plants

Table 2.2 Macrophyte diversity in the different Mozambican basin rivers expressed in an ACFOR scale, based on overall dominance according to Den Hartog and Segal (1964).

R=rare; O=occasional; F=frequent; C=common; A=abundant.

Species	Maputo	Umbeluzi	Incomati	Limpopo	Inharrime	Guvuro	Save
<i>Eichhornia crassipes</i>	3% (R)	75% (A)	95% (A)	30% (F)	5% (O)	7% (O)	0
<i>Azolla microphylla</i>	5% (O)	95% (A)	50% (C)	25% (O)	0	0	5% (O)
<i>Pistia stratiotes</i>	0	50% (C)	25% (O)	0	0	3% (R)	0
<i>Salvinia molesta</i>	0	65% (C)	25% (O)	0	0	0	0
<i>Nymphaea alba</i> and <i>N. nouchali</i>	5% (O)	30% (F)	5% (O)	10% (O)	75% (A)	95% (A)	0
<i>Trapa natans</i>	0	75% (A)	0	5% (O)	0%	0	0
<i>Ceratophyllum demersum</i>	5% (O)	25% (O)	30% (F)	10% (O)	5% (O)	0	0
<i>Potamogeton Schweinfurthii</i>	0	25% (O)	0	0	0	5% (O)	0
<i>Ludwigia stolonifera</i>	25% (O)	25% (O)	10% (O)	5% (O)	3% (R)	7% (O)	0
<i>Lemna minor</i>	0	0	3% (O)	0	5% (R)	5% (O)	0
<i>Spirodela polyrrhiza</i>	0	0	5% (O)	0	5% (R)	0	0

The mean number of invasive plants observed per quadrat varied within rivers, and there were significant differences in mean of the number of plants/quadrat along the rivers, (ANOVA: $F_{(6,150)} = 8.9322$, $p < 0.05$). The mean number of indigenous plants per quadrat also varied within rivers, and there was significant difference in the mean number of plants/quadrat along the rivers, (ANOVA: $F_{(6,150)} = 4.631$, $p < 0.05$).

The number of invasive plants/quadrat (abundance) was higher compared to the indigenous plants in the Umbeluzi, Incomati and Limpopo. However, the number of indigenous plants/quadrat was higher in the Inharrime and Govuro rivers. Significant differences were observed between invasive and indigenous plants/quadrat in all rivers except Umbeluzi and Maputo rivers (Figure 2.2).

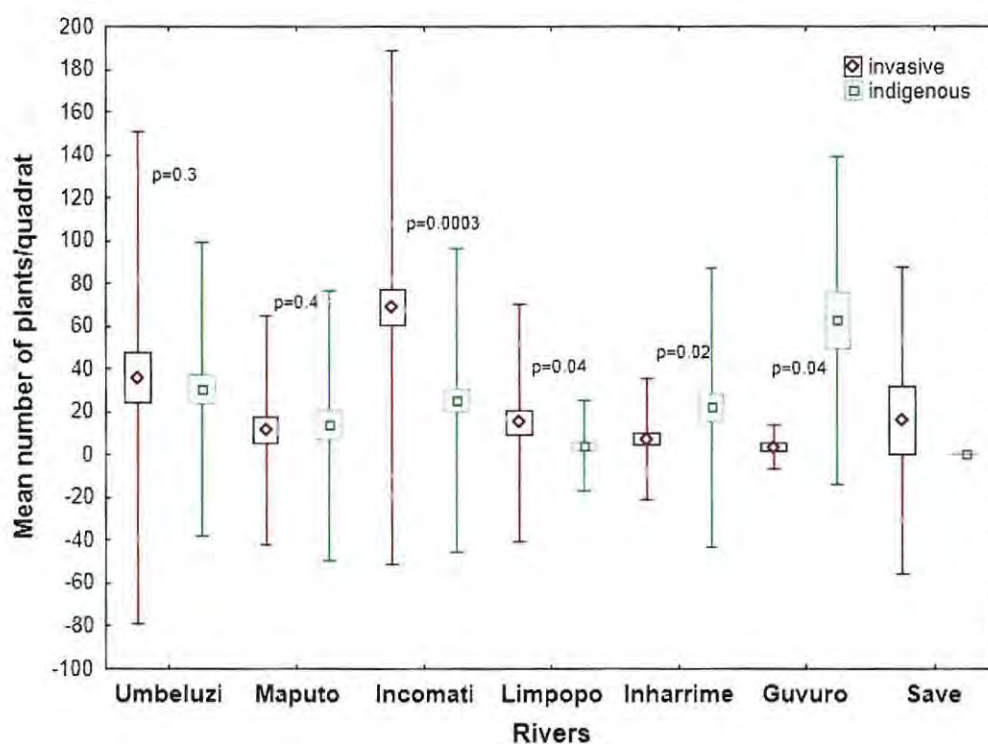


Figure 2.2 Comparison between the mean number of invasive and indigenous plants per quadrat in each river. Mann-Whitney U test shows the differences between mean number of invasive and indigenous aquatic plant per quadrat in Incomati, Limpopo, Inharrime and Govuro rivers ($p < 0.05$). Box represents Mean \pm SE and Whisker represents Mean \pm 2*SD. The errors bars in Figure 2.2 are big were because in some rivers plants were scare or absent, in other studied rivers numerous aquatic plants were found.

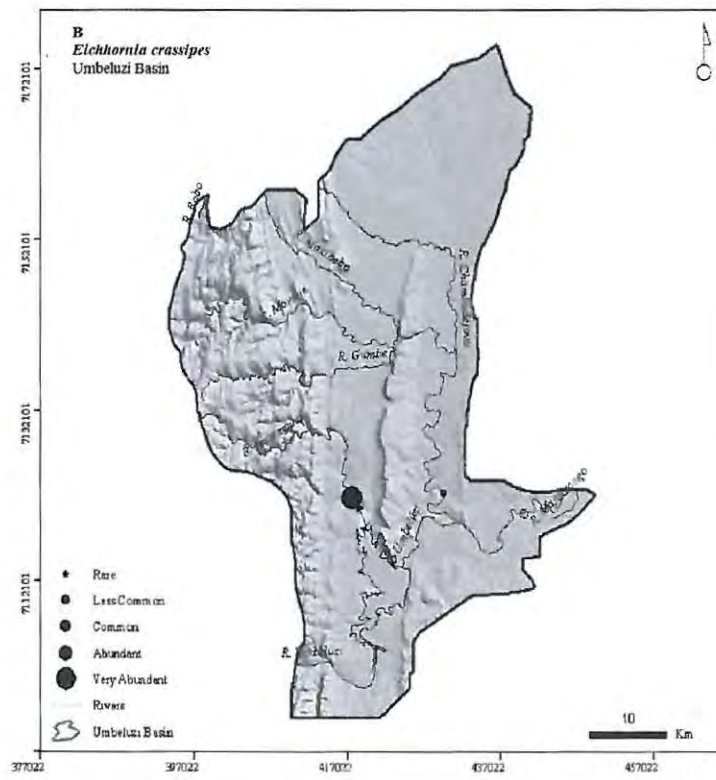
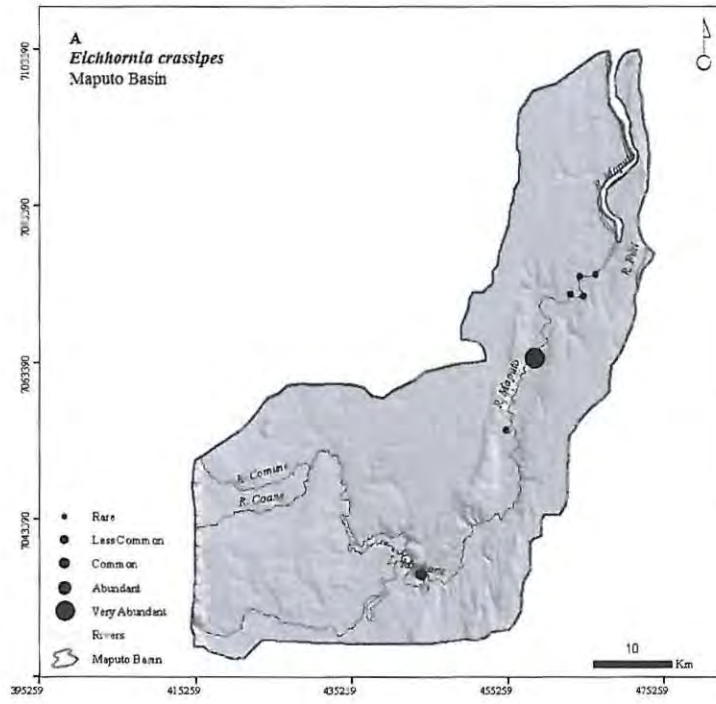
2.4.3 Distribution of different aquatic weeds

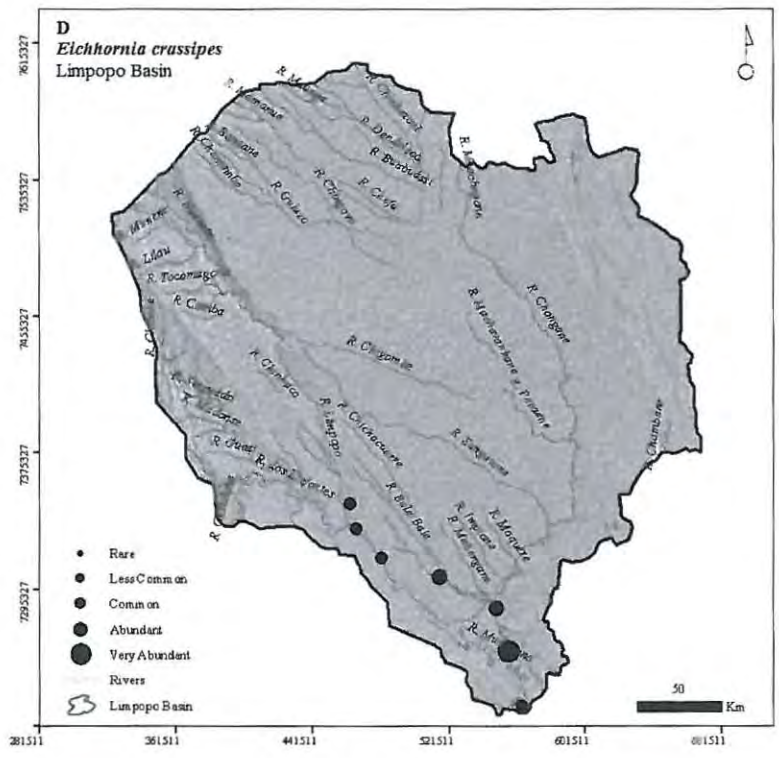
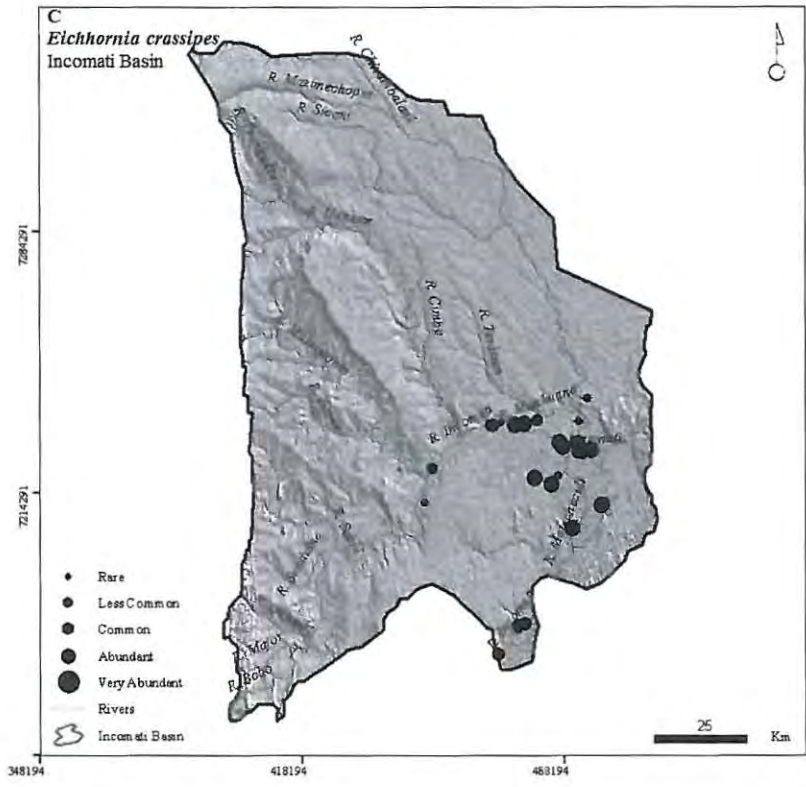
2.4.3.1 Distribution of the water hyacinth, *Eichhornia crassipes* along southern Mozambique rivers

Eichhornia crassipes occurred in all the study areas except the Save River. Its abundance varied from rare to very abundant. The maps below (Figure 2.3 A. B. C. D. E and F) illustrate the distribution pattern of *E. crassipes* along the study areas. It was widespread in the Maputo River where its abundance varied from rare to very abundant (Figure 2.3 A). The frequency (33.3%), relative density (3.1) and the importance value (47.9) of this weed was highest of all weeds in the Maputo River (Table 2.1). *Eichhornia crassipes* was found only twice in the Umbeluzi River (Figure 2.3 B) where it dominated other plants, and covered a surface area of 75% (Table 2.2). *Eichhornia crassipes* was abundantly widespread along the Incomati River, but in some areas was rare. Because of varying water quality in different parts of the Incomati, *E. crassipes* was distributed differently. It was rare in some areas, but abundant in others (Figure 2.3 C). It showed highest frequency (42.0%), highest density (12.8) and highest importance value (45.2) compared to the other plants (Table 2.1). In the Limpopo River, distribution of *Eichhornia crassipes* was common and abundant (Figure 2.3 D). Its frequency (25.0%) was higher in this river compared to other plants in the river; density was 5.1 and the importance value of the plant along this river was 45.2 (Table 2.1).

Eichhornia crassipes was found only in distinct localities in the Inharrime River, and its abundance was rare to common (Figure 2.3 E). The frequency was very low (25%), density was 28.6 and its importance value was 8.0 (Table 2.1). This weed was found also in the Govuro River, where its abundance was common (Figure 2.3 F). This weed had a frequency of 25%, density was 1.64 and importance value of the plant was 24.3 (Table 2.1).

There was a significant difference in the abundance of *E. crassipes* between different basin rivers, (ANOVA: $F_{(6,150)} = 5.67$; $p < 0.05$). Significant differences ($p < 0.05$) in abundance of *E. crassipes* were observed between the following basin rivers: Incomati and Limpopo; Incomati and Guvuro; Incomati and Inharrime; and Incomati and Maputo.





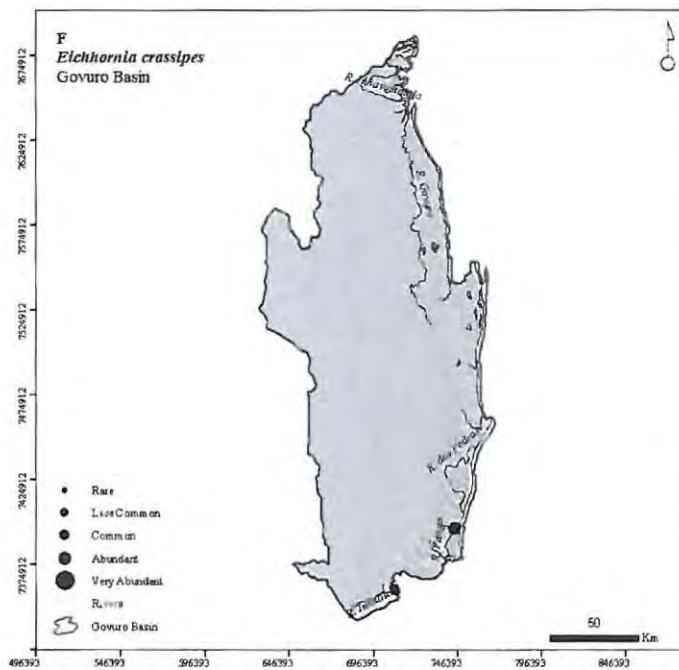
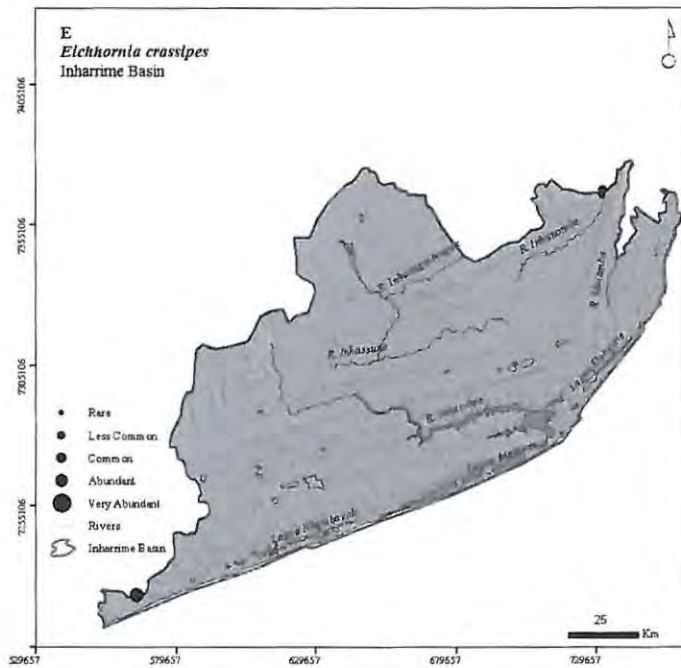
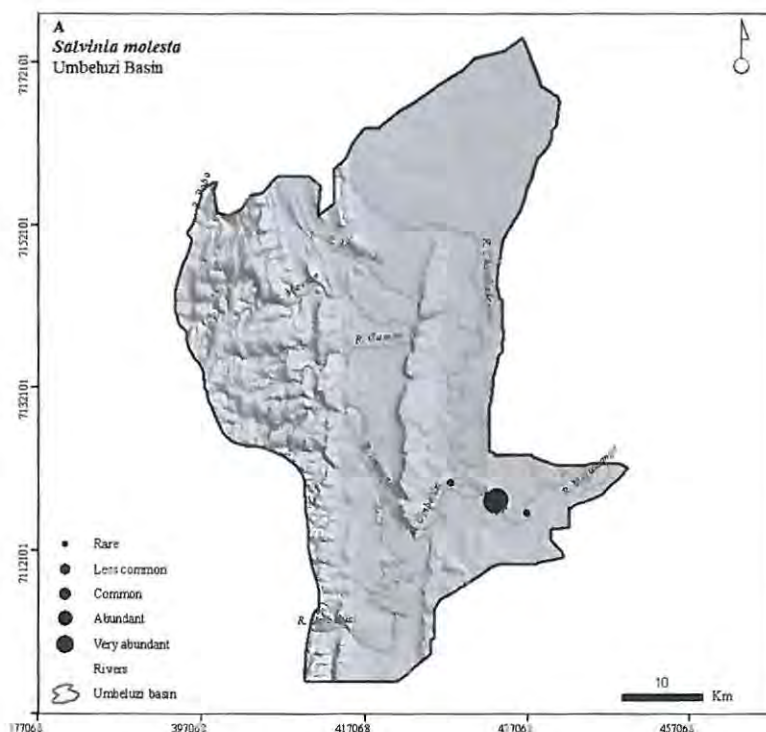


Figure 2.3 A, B, C, D, E and F Distribution of water hyacinth, *Eichhornia crassipes* in the southern Mozambique rivers in 2008. The following letters represent: A (Maputo Basin), B (Umbeluzi Basin), C (Incomati Basin), D (Limpopo Basin), E (Inharrime Basin) and F (Govuro Basin).

2.4.3.2 Distribution of *Salvinia molesta* along the southern Mozambique rivers

In the study areas, the infestation of *Salvinia molesta* was confined to the Incomati and Umbeluzi rivers (Figure 2.4 A and B). No significant differences were observed in the abundance of this weed between the two rivers ($P>0.05$).

The distribution pattern of *S. molesta* varied from rare to abundant in the Umbeluzi River (Figure 2.4 A). In this river, its frequency was 12.0 %, density was 2.8 and importance value was 11.4 (Table 2.1). In one case, *S. molesta* was abundant, with surface area coverage of 65%, but in two cases, this weed was rare, with a surface area coverage of 5% (Table 2.2). In the Incomati River, the distribution of *S. molesta* varied from abundant to very abundant (Figure 2.4 B). The frequency was 4.0%, density was 1.5 and importance value was 11.4 (Table 2.1). The maximum percentage cover of the weed was 25%.



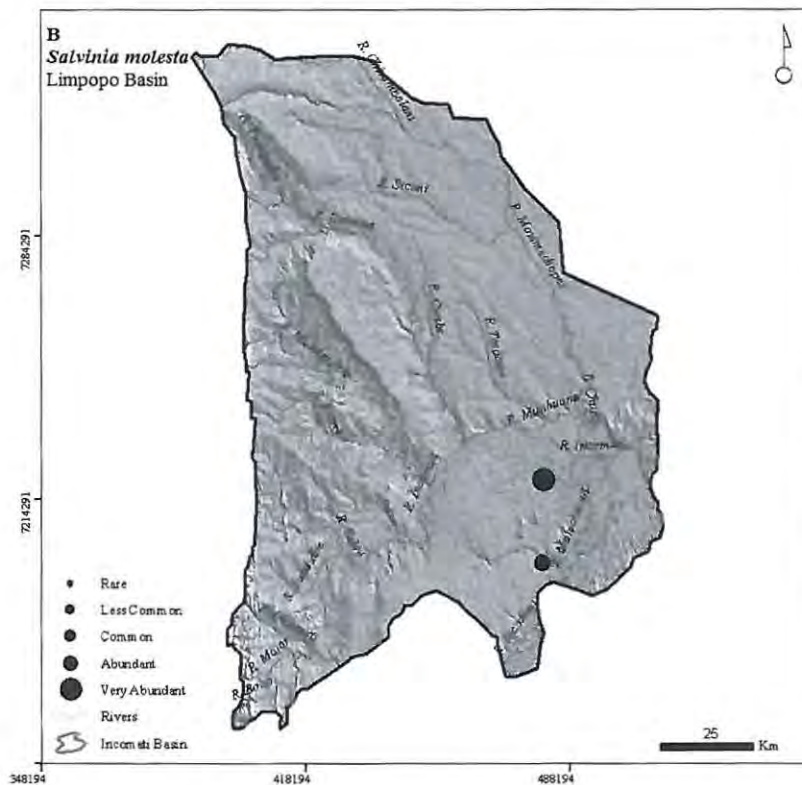


Figure 2.4 A and B Distribution of *Salvinia molesta* in the southern Mozambique Basin Rivers in 2008. The following letters represent: A (Umbeluzi River) and B (Incomati River).

2.4.3.3 Distribution of red water fern *Azolla microphylla* along southern Mozambique rivers

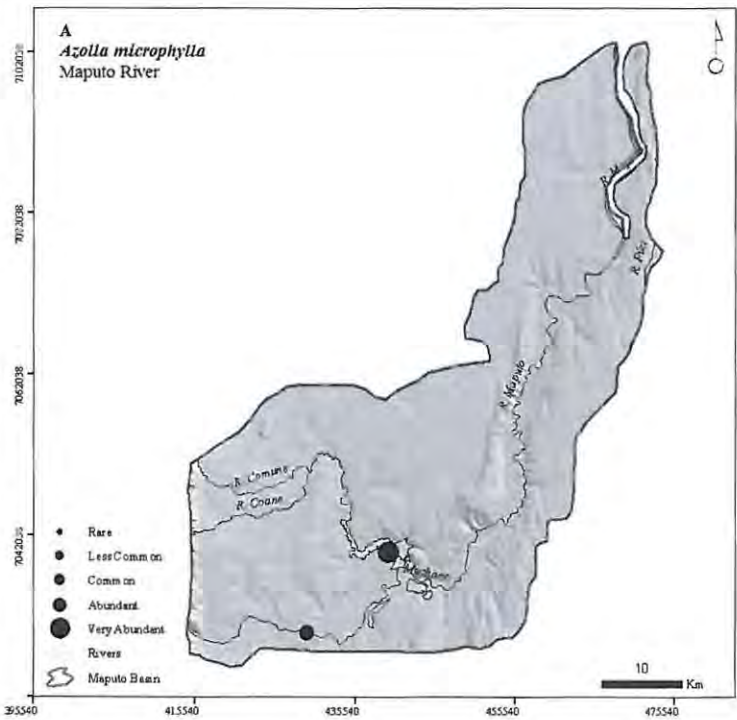
Azolla microphylla was not homogenously distributed along the southern Mozambique rivers, but it showed a wide distribution range in the Maputo, Umbeluzi, Incomati, Limpopo, and Save rivers (Figure 2.5 A, B, C, D and E). It was not found in the Inharrime and Govuro rivers. There was a significant difference in the abundance of *A. microphylla* between different rivers, (ANOVA: $F_{(6,150)}=2.60$; $p < 0.05$).

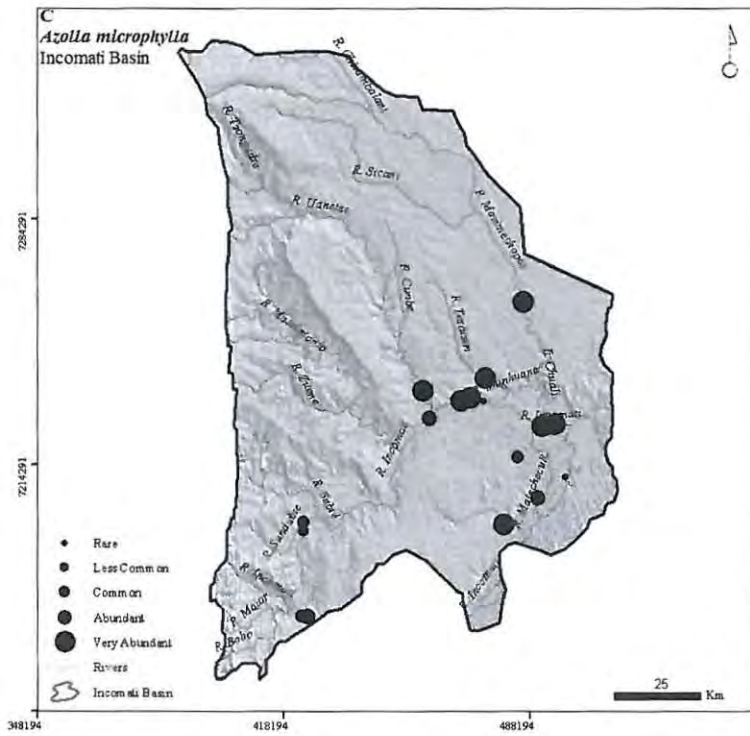
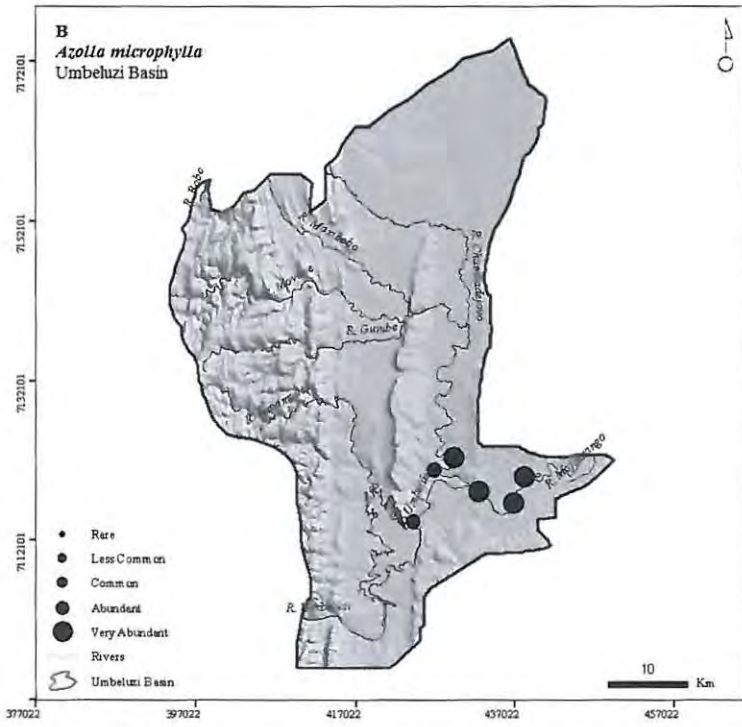
In the Maputo River, *A. microphylla* was found in two only areas. Its abundance on the water surface varied between abundant and very abundant (Figure 2.5 A), with a frequency of 9.52%, density was 8.3 and the importance value (IV) was 23.4 (Table 2.1). This weed was spread over

the water surface of the Umbeluzi River, where abundance varied from common to abundant (Figure 2.5 B). The *Azolla microphylla* showed a frequency of 28.0%, density 11.3 and importance value of 37.1%. Along the Incomati River, the abundance varied from rare to very abundant (Figure 2.5 C) with 42 % of frequency, density was 2.4 and its importance value was 37.

In the Limpopo River, *A. microphylla* was found in rare, common and very abundant distribution (Figure 2.5 D). Its frequency was 12.5%, density was 10.0 and the importance value of the plant along this river was 33.7. In the Save River, only *A. microphylla* was found but, although it was very abundant, it was confined to only one region (Figure 2.5 E).

Significant differences in abundance of *A. microphylla* were observed between the following rivers: Maputo and Umbeluzi; Maputo and Limpopo; Maputo and Incomati; and also between Save and Umbeluzi; Save and Limpopo; and Save and Incomati ($p < 0.05$).





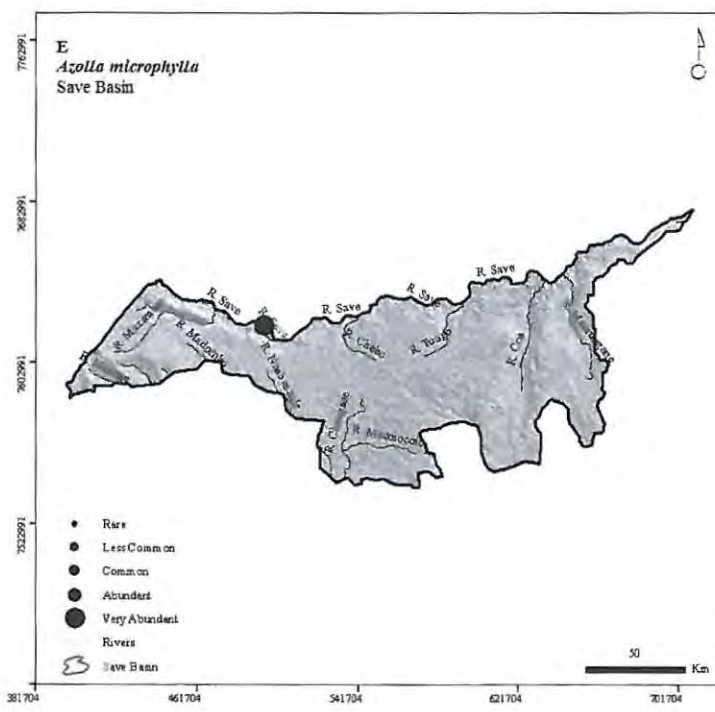
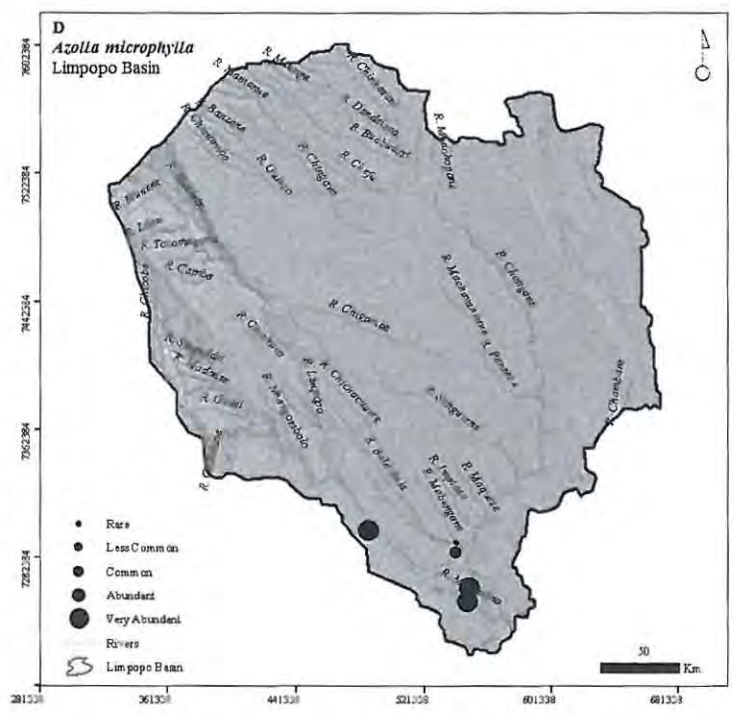


Figure 2.5 A, B, C, D and E Distribution of *Azolla microphylla* in the southern Mozambique Rivers in 2008. The following letters represent: A (Maputo River), B (Umbeluzi River), C (Incomati River), D (Limpopo River), and E (Save River).

2.4.3.4 Distribution of the water lettuce, *Pistia stratiotes* along southern Mozambique rivers

Pistia stratiotes covered big areas of the Umbeluzi and Incomati rivers but it was focused in only one area in the Govuro River. Significant differences in abundance of water lettuce were observed along the study area (ANOVA: $F_{(6,150)} = 3.62$; $p < 0.05$). In the Incomati River, *P. stratiotes* distribution was rare; less common to abundant (Figure 2.6 B) and its frequency was 8.0%, density was 1.4 and importance value was 6.8 (Table 2.1). In most areas of the Umbeluzi River, *P. stratiotes* was abundant, but in three areas it was rare (Figure 2.6 A). Its frequency was 30.0%, density was 5.4, and importance value (IV) was 6.8 (Table 2.1). Finally, in the Govuro River, *P. stratiotes* had a frequency of 12.5%, density was 0.42, importance value was 7.9 (Table 2.1) and *P. stratiotes* was rare and confined to only one region (Figure 2.6 C). There were significant differences in abundance between Incomati and Umbeluzi; Guvuro and Incomati; and Umbeluzi and Govuro ($p < 0.05$).



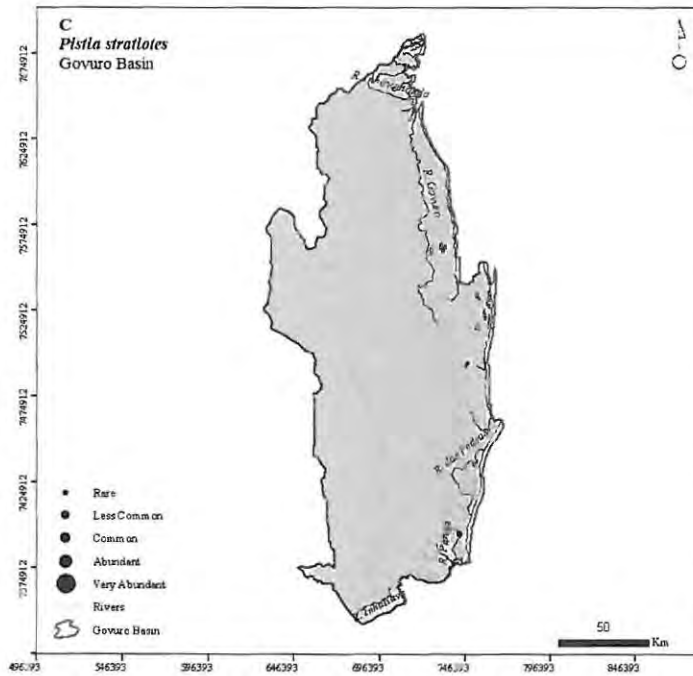
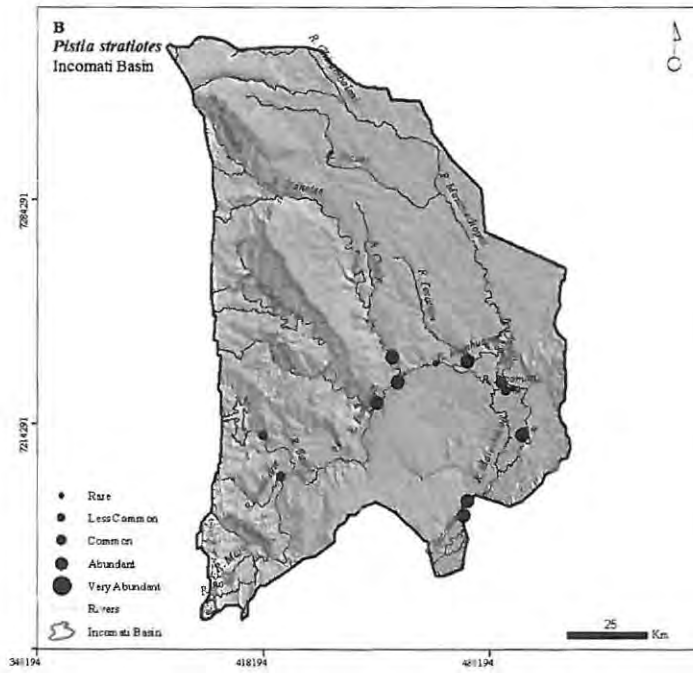


Figure 2.6 A, B and C Distribution of *Pistia stratiotes* in the southern Mozambique rivers in 2008. The following letters represent: A (Umbeluzi River), B (Incomati River) and C (Govuro River).

2.5 Discussion

The geographic location of each river (situated downstream or upstream of an international river) and/or water quality (enriched or not enriched with nutrients) could be an explanation why more aquatic plants were observed at the Umbeluzi, and Incomati rivers followed by the Limpopo and Maputo rivers, but fewer aquatic plants were found in the Inharrime, Govuro and Save rivers.

In the Umbeluzi, Incomati and Limpopo rivers, the invasive species were more abundant and variable, from 25% to 95% total dominance. The presence of weed species can be explained by the relatively low flow of the water in the Umbeluzi, Incomati and Limpopo rivers compared to the higher flow rate of water in the other rivers (Carmo Vaz and Lopes Pereira, 2000; DNA 1999, 1994). Depending on the rainfall, minimum flows can be very low. This situation is made worse by the intensive use of water in South Africa and Swaziland, and by the many storage dams that exist in those countries. This has led to situations of zero flow in some rivers during some periods in the last decade (Hatton *et al.*, 2001). In addition, rivers in the vicinity of big farms, such as Bananalandia, Citrum and Libombos Macadamia, Xinavane and Maragra sugar cane farms and tropical fruit farms, aquatic invasive plants were more abundant due to the runoff of fertilizers.

Robelas (1984) stated that the Mnjoli Dam waters in Swaziland receive nutrients from the farms beside it and those nutrients are the main vehicle for the growth of aquatic invasive plants. Rivers that have sources in South Africa and Swaziland are more likely to be nutrient-enriched and infested with plants (Robelas, 1984). Gustafsson and Johansson (2006) stated that the nutrient leakage from the sugar fields is not more than 5%. However, in the Umbeluzi River, plantations cover 20 000 ha and the average yearly application of fertilizer is 170 kg N/ha and 10 kg P/ha. In total, the leakage would thus be 170 000 kg N/year and 10 000 kg P/year. Assuming that all the excess nutrients reach the river, the additional concentration caused by the sugar estates would be roughly 0.59 mg N/l and 0.035 mg P/l if divided by the average border flow which, according to JURBS (Joint Umbeluzi River Basin Study) is 287.8 Mm³/y. It is unlikely that all these nutrients would be transported to the river since they can be consumed by other organisms, accumulated or lost to the atmosphere on their way to the river, but these figures still represent a considerable nutrient load.

The invasive species observed in the study area were similar to those observed by Chiconela *et al.* (2002) along the Mozambique rivers, such as the Maputo and Limpopo rivers and Cahora Bassa Dam. Surprising in this study was the absence of the parrot's feather, (*Myriophyllum aquaticum* (Vell.) Verdc. (Haloragaceae)). Parrot's feather has been reported in different aquatic ecosystems of Mozambique (Cugala, 2004, 2006), but was not recorded here.

In the others rivers, namely Govuro and Inharrime, the indigenous plants were more abundant and the total dominance or percentage cover varied from 5%-95% compared to the invasive ones (5% to 7%); only one or two invasive species were found. This means that these rivers are less problematic and remain more pristine than the other rivers. The richness index of plants was lower in the Inharrime and Govuro rivers compared to the Maputo, Umbeluzi, Incomati and Limpopo rivers. The reason why there was a lack of abundance and diversity of the invasive species in these rivers could be explained by the strong flow rate (higher water speed) that is a feature of these rivers. Rolon and Maltchik (2006) pointed out that variations of water speed, the depth, and the length of the streams are the factors that determine the dynamic distribution of aquatic invasive plants. Another explanation is that there are no extensive farming activities and or industrial water effluent near those rivers, hence there are no nutrients and sewage coming from these activities to stimulate the growth of the weeds.

A slightly higher number of plants in terms of frequency, density, and abundance of invasive plants was observed in Maputo River compared to the Inharrime and Govuro rivers. This could be the impact of the urban areas of Maputo Province on the Maputo River. In their study, Jafari *et al.* (2006) observed that as the rivers enter an urban influence, inflow of sewage increases the nutrients and phosphate, which in turn, increases the growth of plants. Another explanation is that because the Pongola River (Swaziland) is located upstream of the Maputo River, it probably releases water enriched with nutrients and also carries aquatic plants, including the weeds, into the Maputo River (DNA, 2011; UNEP/Nairobi Convention Secretariat and WIOMSA, 2009).

In this study, the distribution of invasive plants was successfully mapped. The mapping showed that the aquatic weeds are not homogenously distributed along the southern Mozambique rivers. Aquatic weed densities and abundance were higher in most of the study area and therefore had higher importance values (IV) when compared to indigenous plants. In particular, *E. crassipes*

and *A. microphylla* are the most widespread along the Southern Mozambique rivers. The importance values (IV) of both plants were higher in most cases. The “IV” provides an indication of dominance of species within a community, based upon both frequency and density (Smith and Smith, 2001). Frequency is a measure in percentage of the commonness and distribution of the species within a study area. The distribution pattern of *E. crassipes* and *A. microphylla* in the models confirms their importance values.

During the study period, it was noted that heavy floods each November (2008, 2009) washed all water hyacinth plants out of the river system. However, one year later, small vigorous plants and a few adult plants that survived the floods on the banks of river were growing, lining a previously infested area from seedling recruitment. The above phenomenon confirms reports of seeds in the sediments from Albano Pérez *et al.* (2011) and Jacot Guillarmod and Allanson (1978) in similar studies.

Azolla microphylla was successfully mapped in this study. Though the *Azolla* species are similar, probably other *Azolla* species were found mixed with *A. microphylla* in the study area. This suggested that there are different species of *Azolla* in the study area. Ashton and Walmley (1984) recorded *Azolla pinnata* in Pongola River (this river is positioned upstream of Maputo River). According to Hill (2009, personal observation in the field), this *Azolla* plant could be *Azolla filiculoides* or one of the native species found in Africa: *Azolla pinnata africana* (Burrows, 1999) or *Azolla nilotica* (Henderson, 2001). Hill (2003; 1999 b), and Oosthuizen and Walters (1961), in their studies, confirmed that the weed, *A. filiculoides* was recorded in South Africa and can be dispersed between water bodies, facilitating the increase in its distribution and abundance along the downstream river bodies. Santos *et al.* (2002) found different species in all the southern Mozambique rivers except in the Inhambane Province and this has now been confirmed as *A. microphylla* (Hill and Madeira, 2011). This study confirmed the absence of the *A. microphylla* in the Govuro and Inharrime rivers, which belong to the Inhambane Province. The following are reasons why *A. microphylla* has spread: firstly, the calm waters of Incomati, Limpopo and Umbeluzi provided an ideal situation for growth; secondly, plant nutrients in these rivers stimulated *Azolla* growth; finally, vegetative reproduction led to relatively rapid growth.

Pistia stratiotes and *Salvinia molesta* were least problematic, compared to the other two weeds. *Pistia stratiotes* was found in three rivers, while *S. molesta* was recorded in only two rivers. The distribution patterns are not homogeneously distributed along the rivers, their density and frequency were less, but their dominance was found to be between until 50% and 65% of percentage coverage. In this study, *P. stratiotes* was found in the Umbeluzi, Incomati and Govuro, but no samples were found in the Limpopo. Contrary to this study, Rodolfo (2007) and DNA (2011) have found this weed in the Limpopo River. The lack of *S. molesta* in southern Mozambique can be explained by the fact that most of the rivers in southern Mozambique were infested by water hyacinth and this out-competes salvinia. Earlier, Bond and Roberts (1978) had noted that in the Cahora Bassa Dam, the water hyacinth impedes the growth of *S. molesta*.

2.6 Conclusion

The spread of aquatic weeds in the southern Mozambique rivers and the consequent problems for both consumers and the watercourse indicate mismanagement of watersheds and harmful nutrient enrichment in the rivers. Because Mozambique is a member state of the Southern Africa Development Community (SADC), between 2003 and 2006 the country had to develop IAS databases, training programmes and centres of excellence. A report produced under the SADC Biodiversity Support Programme revealed that Mozambique has both terrestrial and aquatic invasive species. The aquatic weed species include *Eichhornia crassipes*, *Azolla filiculoides/microphylla*, *Salvinia molesta*, and *Pistia stratiotes*. Most studies done in Mozambique only focus on the presence and distribution of the weeds and on recommendations for training people to avoid spreading the weeds (Cugala, 2006); studies did not include quantitative surveys.

Previously, only the Zambezi River and the Cahora Bassa Dam were studied. It is known that most of these weeds are present in this dam but only *S. molesta* is controlled. No consistent information about the presence of the weeds in other rivers has been recorded. Although this information is available, Mozambique has not mapped any existing aquatic invasive species in the country, due to financial constraints (MICOA, 2007). This study successfully mapped aquatic weeds only in the southern rivers of the country and showed that *Eichhornia crassipes*, *Azolla microphylla*, *Salvinia molesta* and *Pistia stratiotes* still exist and are becoming aggressive in some watercourses in Mozambique, especially in the Umbeluzi and Incomati rivers.

Mozambique needs to manage the situation, because these weeds are replacing indigenous species and possibly having an economic impact (Chapter 3).

Socio-economic impact of water weeds in the Incomati River in Mozambique

3.1 Introduction

Aquatic vegetation introduced into rivers, dams and lakes throughout Africa represents one of the largest threats to the socio-economic development of the African continent (Gorgens and Wilgen, 2004; Cilliers *et al.*, 2003), (Chapter 1). African countries do not have the financial resources to control the invasions of aquatic weeds as the first-world countries do, and the cost in human distress in underdeveloped countries and subsistence communities is incalculable in monetary terms (Charudattan, 2001). Villamagna and Murphy (2010) pointed out a dichotomy of socio-economic impacts associated with invasive species. There are the benefits and costs that result from the presence of weeds, in particular the water hyacinth; and there are the benefits and costs of preventing, managing, or eradicating the species, including the ecological impacts of those actions.

From a socio-economic perspective, aquatic weed invasion into freshwater systems presents a problem for many human uses. Invasive plants affect biotic communities and ecosystem functions, indirectly displacing desirable species and reducing water abundance (via evapotranspiration) and impeding irrigation systems (Schooler *et al.*, 2005). Invasive aquatic plants can also impact the quality of life through loss of recreational activities by reducing navigation and fishing activities (Kateregga and Sterner, 2009; Opande *et al.*, 2004). In addition, aquatic weeds provide breeding grounds for schistosome (bilharzia)-carrying snails and malaria mosquitoes (Mack and Smith, 2011; Mooney, 2005; Mailu, 2001). Mats also block breeding, nursery, and feeding grounds for economically important species, such as tilapia and Nile perch (Twongo and Howard, 1998).

The socio-economic impacts of aquatic weeds vary in relation to the uses of the water body. An infestation has a greater socio-economic impact when the water body supports several human uses. Where the water source is primarily used for domestic water supply, impacts can be measured in terms of changes in water quality. It is difficult to assign a value to the loss of water

quality, so a surrogate estimate such as the cost of water treatment must be used. This technique is referred to as the replacement cost method (Holl and Howarth, 2000).

Socio-economic impacts may not be immediately recognized. Damage may increase over time or as a result of synergistic biological or economic interactions (Parker *et al.*, 1999). For example, reduced dissolved oxygen may occur as a result of dense weed mats, but it is the risk of fish kills that would be likely to draw socio-economic attention.

Studies have shown that a contingent valuation can be used to calculate impacts. Contingent valuation is a relatively time-consuming option, and therefore it is probably under-used in attempts to quantify the costs and benefits of invasive species (Holl and Howarth, 2000). The economic cost of controlling water hyacinth and other weeds is a function of the rate of removal, cost of labour, cost of equipment, and the frequency of treatment. Each of these aspects will vary, based on the extent of the infestation and the type of control used. Mechanical control, for example shredding water hyacinth, is cheaper than harvesting (Greenfield *et al.*, 2006), but there are significant consequences to allowing the plant to die and decompose within the system. Although mechanical and manual control may initially be less expensive than a herbicide treatment, over time, the chemical control may cost less due to the slower regrowth time associated with the herbicide treatments. Mechanical removal costs about US\$3,000 per hectare, and manual sinking and shredding costs US\$1,000 per hectare (World Bank, 2000). From a cost perspective, but without considering environmental impacts, chemical control is the next cheapest method, followed by habitat manipulation and mechanical control (Madsen, 2000). The World Bank estimates that chemical control of water hyacinth costs between US\$100 and US\$300 per hectare in the year 2000). Supporters of biological and chemical control often focus on the cost, but in many cases it is critical that high biomass aquatic weeds, such as water hyacinth, are removed from the water, as a large biomass of decomposing plant material can create anoxic conditions and toxicity, causing significant harm to aquatic biota (Perna and Burrows, 2005; Gutierrez *et al.*, 1994). An illustration is the case of the impact of water hyacinth in Lake Victoria. Although it is not known how water hyacinth first entered Lake Victoria, the resulting infestations become a massive problem between 1989 and 1997. The World Bank estimated that the first outbreak in 1995 cost the riparian nations between US\$6 million and

US\$10 million. During this period, there was reportedly a 70% decline in economic activity at the Kenyan port of Kisumu (Mailu, 2001). In Lake Victoria, the total direct costs attributable to the water hyacinth (at peak infestation period) were estimated to be US\$6–7 million p.a. with a net present value of US\$25–40 million (<http://www.iwlearn.net/docs/wio/wio05e.pdf>).

Addressing such a dynamic threat to the lake required Kenya, Tanzania, and Uganda to work together to combat the infestation, as the treatment options were expensive and depended on simultaneous response. The problem of weed infestation was solved by using a biological control, which involved releasing two species of weevil, *Neochetina eichhorniae* and *N. bruchi*. The stress caused by the weevils rendered the water hyacinth incapable of flowering and setting seed. This has been the most successful method to date, in some cases reducing the hyacinth population by as much as 30% to 50% (World Bank, 2000). At a cost of US\$30 and US\$50 per hectare, biological control was also the most cost effective and has, accordingly, been adopted as the primary strategy for managing infestations. However, the biological control method requires the greatest degree of coordination between the governments. To be most effective, weevil mass-rearing facilities must be established at multiple locations around the lake, and well-coordinated field releases involving local communities must be organized.

In South Africa, for example, controlling invasive aquatic plants costs South Africa millions of rand every year (ARC-PPRI, 2010). Van Wyk and Van Wilgen (2002) drew up a cost/benefit analysis for three separate control approaches for water hyacinth in South Africa and revealed that herbicide was the most expensive control option (US\$ 210/ha), biological control was relatively cheap (US\$0.51/ha to US\$ 44/ha, depending on the extent of the follow-up programme), then using integrated control was the best and cheapest (US\$39/ha) as control was achieved in a shorter time (less than 16 months) than a purely biological control programme (3–5 years).

The control options for water hyacinth have been described above. However, the implementation of control options for each site will vary, depending on the initial level of water hyacinth infestation, the acceptable level of control determined for that site, the role of the water resource and the financial resources available for control. Despite the example cited above, there are

relatively few studies on the socio-economic impact of water hyacinth. These studies are vital in convincing governments to take action in order to control invasive aquatic weeds.

The proliferation of aquatic weeds in the Incomati River in Mozambique could be associated with the agricultural developments of the Maragra and Chinavane sugar cane farmers. Ironically, it is the practices of some of these farms along the river that create the nutrients on which aquatic weeds thrive, and these farms that are most impacted by weed infestation.

3.2 Specific objectives

The main objective of this chapter was to evaluate the socio-economic impact of invasive aquatic weeds in general and methods of controlling them.

The specific objectives were:

1. To evaluate the perceptions of the local population concerning the aquatic weeds in the Incomati River,
2. To quantify the impact of the aquatic weeds on the health of the riverine population,
3. To estimate the impact of aquatic weeds on the income of the people living along the Incomati River.

3.3 The study area

The Incomati River Basin is located in the southeastern part of the African continent and covers parts of South Africa (63%), Mozambique (31%) and Swaziland (6%). This river is characterized by a diverse and important range of economic activities. According to Carmo Vaz and Van der Zaag (2003), the sectors providing the support to the economy in the basin are agriculture and forestry. Irrigation is the major water use in the Incomati River Basin, followed by urban and industrial water supply, forestry, conservation (estuary and coastal areas), livestock and sport (Carmo Vaz and Lopes Pereira, 2000). Some of the most important consumers of Incomati ground water are the sugar cane farms that also provide employment to a large labour force. The basin has six main tributaries: Crocodile, Sabie, Massintonto, Uanetze and the Mazimechope rivers (Figure 3.1).

The study areas in the Incomati River Basin (Figure 3.1) comprise the following:

1. Upper region: the drier part of the border to Sabie, where the Corrumana Dam regulates the flow to downstream irrigation;
2. Middle region: the wetter part where irrigation potential has been developed, comprising Manhiça, Magude, Marracuene districts, and
3. Lower region: from the Bobole River to the estuarine with the Indian Ocean.

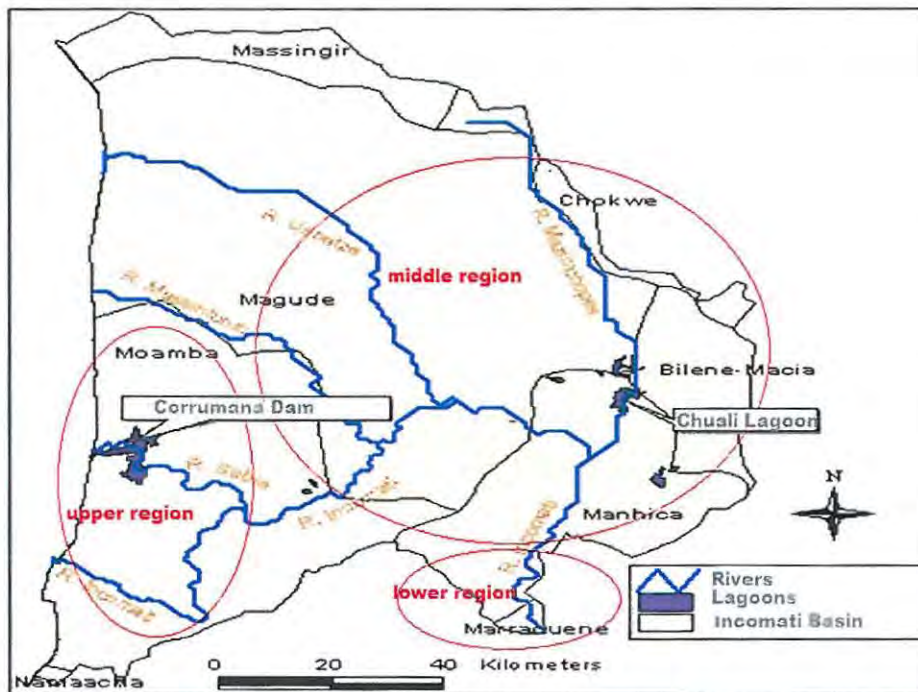


Figure 3.1 The three sampling sites (upper, middle and lower region) in the Incomati River Basin.

3.4 Material and methods

3.4.1 Sampling procedures

In order to evaluate the socio-economic impact of the invasive aquatic weeds along the Incomati River, surveys involving questionnaires were carried out from May to August 2010. Three regions were chosen in the Incomati River Basin namely, upper Incomati (six sites), middle Incomati (18 sites), and the lower region (11 sites); in total, 161 people were interviewed.

Questions posed involved integrated socio-economic data:

1. Questions related to the respondent (age, sex, number of children, number of dependents and number of wives).
2. Questions related to plants (identification of plants in the river; how the plants affect the life of the people; the nature of the impact (financial and/or health problems) that arise as a result of the weed infestation).
3. Questions related to the solutions adopted by users (what individuals and the community do to manage these problems).

In addition, the following activities were carried out:

1. Mapping the invasive aquatic plants that occurred in the upper, middle and lower Incomati River in order to estimate percentage cover.
2. Estimating the impact of the weeds on the fishing activity, using information obtained through the Provincial Fisheries Department. Sixteen professional fishermen were interviewed and information related to age, academic levels, length of time fishing, monthly quantity of fish caught during the year 2009 (September, October and November) and 2010 (March, April, May, June, July and August) was obtained. Of the 16 professional fishermen interviewed, five were from the upper region, six from the middle region, and five from the lower region of the Incomati.

Using data acquired from the Fisheries Department of the District, the following was calculated:

- a. The monthly average of fish catches by fishermen and the monthly income during the periods with and without peak infestation of weeds;
- b. The capture effort of the fishermen (expressed in monthly mean of fish catch per fishermen /total number of nets/total number of days) (Baloi *et al.*, 2007).

Only data from professional artisanal fishermen that worked for 22 consecutive days each month during the year was used.

3.4.2 Data analyses

The data were analyzed using the SPSS software, (Statistical Package for Social Sciences). Descriptive statistics were used to analyze the characteristics of the respondents and their perception of the weeds. Student t-Test was used in this study to test if there were significant differences between the income during different times (with or without peak of the weeds) at

different study areas (upper, middle and lower Incomati). A Non-Parametric Test, the Kruskal-Wallis test, was used to compare income before and during the aquatic weed peak infestation between sites.

3.5 Results

3.5.1 Characteristics of the respondents

Of 161 people interviewed in the upper, middle and lower Incomati River Basin, 80.1% (n=129) of the respondents were men and 19.9% (n=32) women, 18.6% (n=24) were males under the age of 19 years (Table 3.1). The majority of male respondents working in the Incomati Rivers Basin were between the ages of 40 years and 65 years. All 32 women interviewed were older than 20 years (Table 3.1 A). The calculated mean number of women per man was 1.94 and the number of children per family varied from 1 to 12. Most of the respondents (male and female) were uneducated. Some had primary education (Table 3.1 B). Only a few male respondents had secondary education, with very few having achieved matric (Table 3.1 B).

Table 3.1 A and B Biographical characteristics of the population living by the Incomati River A: the ages of respondents at different localities, and B: the educational level of the riverine population.

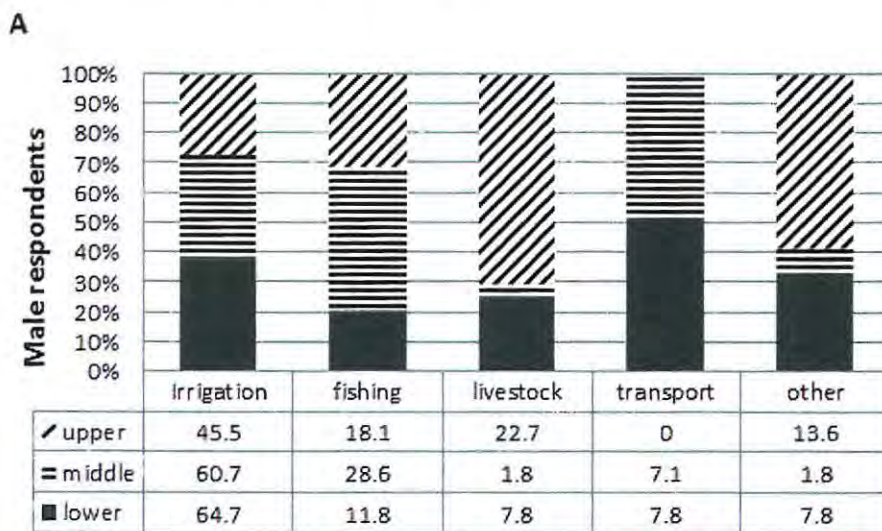
A			Age of the respondents							
Gender	Location		Do not know their age	0-19	20-29	30-39	40-49	50-59	>60	Total
Male	Upper	(n) %	1 0.8%	4 3.1%	7 5.4%	1 0.8%	2 1.6%	3 2.3%	4 3.1%	22 17.1%
	Middle	(n) %	1 0.8%	12 9.3%	4 3.1%	9 7.0%	5 3.9%	11 8.5%	14 10.9%	56 43.4%
	Lower	(n) %	0 0%	8 6.2%	3 2.3%	5 3.9%	15 11.6%	15 11.6%	5 3.9%	51 39.5%
	Total	(n) %	2 1.6%	24 18.6%	14 10.9%	15 11.6%	22 17.1%	29 22.5%	23 17.8%	129 100.0%
Female	Upper	(n) %	0 0%		3 9.4%	1 3.1%	0 0%	0 0%	3 9.4%	7 21.9%
	Middle	(n) %	0 0%		2 6.3%	6 18.8%	3 9.4%	3 9.4%	2 6.3%	16 50.0%
	Lower	(n) %	2 6.3%		1 3.1%	2 6.3%	0 0%	1 3.1%	3 9.4%	9 28.1%
	Total	(n) %	2 6.3%		6 18.8%	9 28.1%	3 9.4%	4 12.5%	8 25.0%	32 100.0%

B			Education					
Gender	Locality		(1-7) Primary	(8-10) Secondary	(11-12) Matric	Tertiary	Illiterate	Total
Male	Upper	(n) %	5 22.7%	0 0%	0 0%	0 0%	17 77.3%	22 100.0%
	Middle	(n) %	30 53.6%	6 10.7%	1 1.8%	1 1.8%	18 32.1%	56 100.0%
	Lower	(n) %	20 39.2%	0 0%	2 3.9%	0 0%	29 56.9%	51 100.0%
	Total	(n) %	55 42.6%	6 4.7%	3 2.3%	1 0.8%	64 49.6%	129 100.0%
Female	Upper	(n) %	2 28.6%	0 0%			5 71.4%	7 100.0%
	Middle	(n) %	7 43.8%	1 6.3%			8 50.0%	16 100.0%
	Lower	(n) %	4 44.4%	0 0%			5 55.6%	9 100.0%
	Total	(n) %	13 40.6%	1 3.1%			18 56.3%	32 100.0%

3.5.2 Activities performed along the Incomati River by local population

According to the respondents, aquatic plants, particularly water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*), interfered in their activities, specifically in irrigating the fields, fishing using nets, navigation and raising livestock. Further, the weed mats made it difficult to remove mud and reed bundles for house building. Red water fern (*Azolla microphylla*) affected the quality of water for domestic use by changing the odour, taste and colour.

Agriculture and fishing were the most important activities performed by men in the study area, followed by raising livestock and transportation (Figure 3.2 A.). The women, on the other hand, performed only three activities: agricultural irrigation, collecting water for domestic needs, and gathering mud and cane for house building (Figure 3.2 B). At the localities along the river where there was considerable agriculture irrigation (middle and lower) there was a higher abundance of weed (Figure 3.3) probably due to eutrophication from runoff from irrigation. Of the respondents, 82.6% considered aquatic weeds a problem, while the remaining 17.4% said that the weeds did not interfere with their activities.



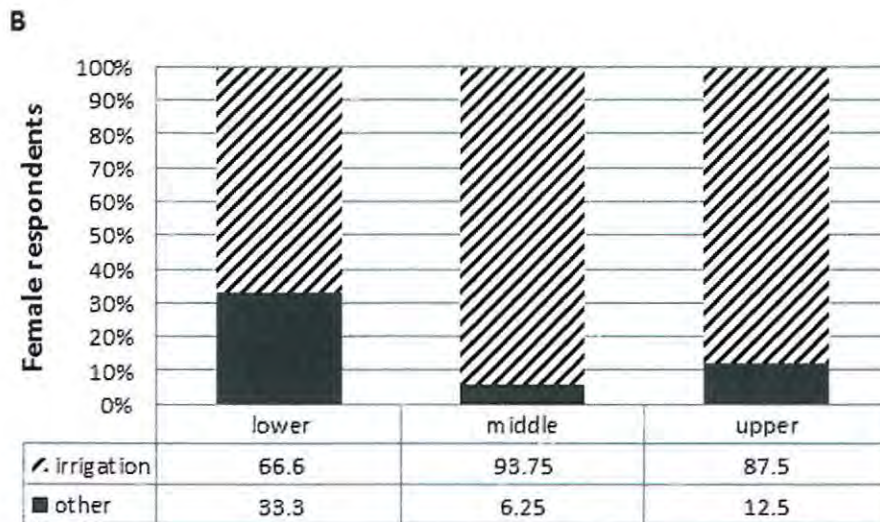


Figure 3.2 A and B Water usages in the Incomati River by the riverine population. A: activities performed by male respondents; B: activities performed by female respondents.

3.5.3 Weed distribution and coverage in three regions in the Incomati River

In some areas of the Incomati River, water weed coverage (mostly water hyacinth) was so dense that it affected navigation, fishing and agriculture activities. Figure 3.3 shows the areas where high densities (common to very abundant) of invasive aquatic plants were observed. Typically in these areas of the rivers, a carpet (stationary mat) covered between 50% and 100% of the water surface. This was similar in the area where activities such as irrigation were intensively carried out (middle and lower Incomati River) (Figure 3.2 A and B), such as at the two sugar cane refineries (Maragra and Xinavane) which are located in the middle and lower reaches of the river. In the upper Incomati, the weed density was not as high as in the middle and lower reaches (Figure 3.3).

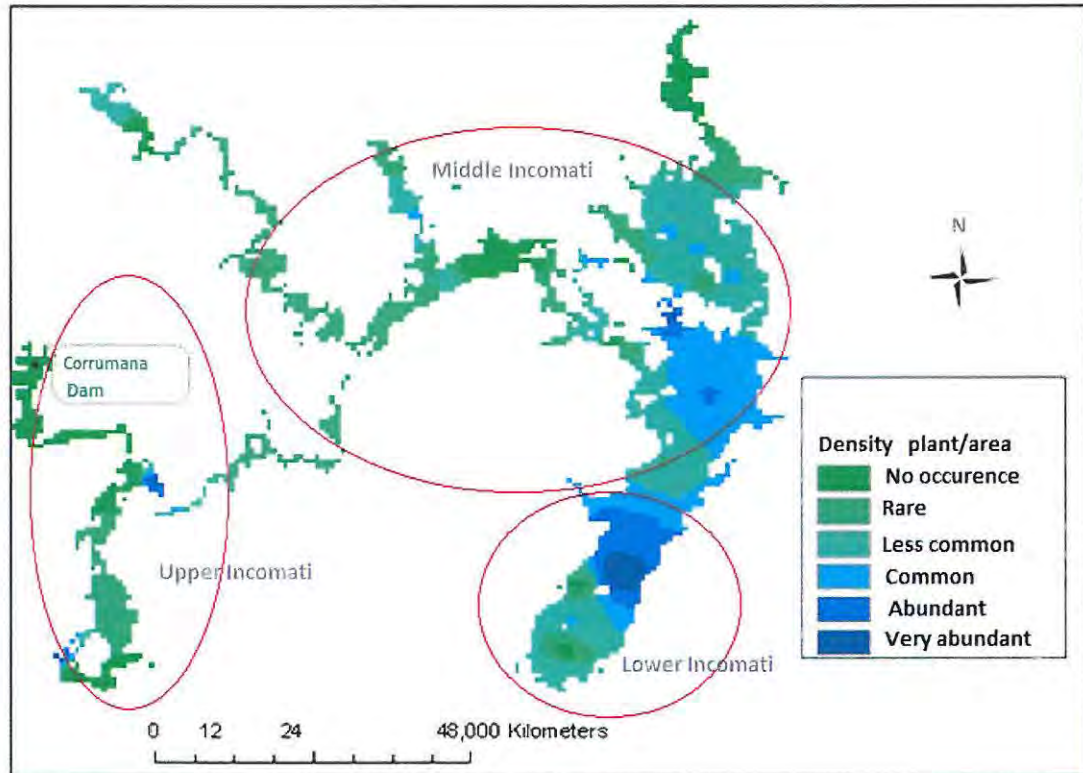


Figure 3.3 Distribution patterns of aquatic weeds in the upper, middle and lower Incomati River. The plants density varies from no occurrence, rare, less common, common, abundant to very abundant.

3.5.4 Local perceptions of aquatic weeds along the Incomati River

Almost all the 161 people interviewed said that they noticed the occurrence of aquatic weeds along the river, but due to illiteracy, they knew the name of the aquatic invasive plants only in their local language. Each respondent was able to recognize at least one of the weeds (Table 3.2). The weeds most readily recognized by the respondents (individually or collectively) were the water hyacinth (*E. crassipes*), water lettuce (*P. stratiotes*), and red water fern (*A. microphylla*) (Table 3.2). *Salvinia* (*S. molesta*) was the least common in the study area; most of the respondents did not know this aquatic weed and consequently it was mentioned less frequently (Table 3.2).

Table 3.2 Weeds mentioned by the local population in the upper (a); middle (b) and lower (c) Incomati River. The abbreviations (RF, WH, WL and S) refer to red water fern, water hyacinth, water lettuce, and salvinia, respectively.

			Weeds mentioned and recognized by each respondent in only at once								
Gender	Locality		RF	WH	RF, WH, WL, S.	RF, WL.	WH, WL.	RF, WH, WL.	RF, WH.	RF, WH., S.	Total
Male	Upper	(n)		2	0	0	8	10	2	0	22
		%		1.6%	0%	0%	6.2%	7.8%	1.6%	0%	17.1%
	Middle	(n)		2	11	1	13	28	1	0	56
		%		1.6%	8.5%	0.8%	10.1%	21.7%	0.8%	0%	43.4%
	Lower	(n)		5	5	0	12	26	2	1	51
		%		3.9%	3.9%	0%	9.3%	20.2%	1.6%	0.8%	39.5%
Total	(n)		9	16	1	33	64	5	1	129	
	%		7.0%	12.4%	0.8%	25.6%	49.6%	3.9%	0.8%	100.0%	
Female	Upper	(n)	1		0		2	4	0	0	7
		%	3.1%		0%		6.3%	12.5%	0%	0%	21.9%
	Middle	(n)	0		1		1	13	0	1	16
		%	0%		3.1%		3.1%	40.6%	0%	3.1%	50.0%
	Lower	(n)	1		0		3	3	2	0	9
		%	3.1%		0%		9.4%	9.4%	6.3%	0%	28.1%
Total	(n)	2		1		6	20	2	1	32	
	%	6.3%		3.1%		18.8%	62.5%	6.3%	3.1%	100.0%	

Of the respondents, 46.5% did not know the origins of aquatic weeds, 25.2% stated that the weeds had always been there, while others (25.3%) believed that the weeds were washed down in the floods in 2000. Only a few of them (3%) stated that the presence of nutrients in the water contributed to the presence of weeds. With regard to the period of the year in which the weeds occurred in high density, 107 (82.9%) male respondents and 19 (59.4%) female respondents noticed the weeds during the whole year (wet and dry seasons). The remaining 13 (40.6%) females observed the weeds only in the dry season and 3 (2.3%) male respondents noticed the weeds only in the wet season.

3.5.5 Impact of the aquatic weeds on the local population along the Incomati River

Water hyacinth was considered the most damaging plant in the irrigation, fishing and transport sectors. In an open-ended question, the respondents identified some indigenous emergent species that interfered with their activities, including water hornwort, *Ceratophyllum demersum*, and some grasses such as *Phragmites australis* (Cav.) Trin., *Typha capensis* (Rohrb) N.E.Br. and *Cyperus dives* (Delile). In this case they were not able to distinguish differences between the alien invasive plants and native plants since they caused the same problem. All the respondents stated that they did not know the difference between invasive aquatic plants, alien plants or native plants.

People were also asked to describe the impact of aquatic weeds, both negative and positive. The positive impacts that people recognized were that water hyacinth could be used as pig feed (only male, 3.9% respondents) and for medicinal use (4.7% men, 9.4% female), but most of the people interviewed did not identify any benefit (men 91%; female 90.6%).

The negative impacts of the weeds in the Incomati River, can be classified into social and economic. The most important economic impact (38.0% male and 40.6% female respondents) was on agricultural irrigation (Table 3.3). The second most important impact was on fishing, an activity performed only by men. Of the men, 4.7% said that it became difficult to cast the nets and 26.4% of men said that the weeds reduced the fish catches, while women, as expected, did not mention the different effects of water weeds on fishing, since it is typically a male activity and most wives help only by carrying the products to the market where the husbands sell them. Navigation in the river was mentioned more frequently by men (2.3%), and the lack of clean water was mentioned only by women (9.4%), since most of them used water for housework and for drinking (Table 3.3).

Table 3.3 Economic problems associated with aquatic weeds in the upper, middle and lower Incomati River.

Respondents		Natural of economic weeds				
Gender	Region	Interferes with irrigation	Reduces fish catches by inaccessibility to water	Difficult to cast fishing nets	Lack of clean water	Hampers navigation
Male (n=129)	Upper	9 (7%)	7 (5.4%)	0 (0%)		0 (0%)
	Middle	19 (14.7%)	12 (9.3%)	5 (3.9%)		1 (0.8%)
	Lower	22(17.1%)	15 (11.6%)	1 (0.8)		2 (1.6%)
	Total	50 (38.8%)	34 (26.4%)	6 (4.7%)		3 (2.3%)
Female (n= 32)	Upper	5(15.6%)			1(3.1%)	
	Middle	6(18.8%)			2(6.3%)	
	Lower	2(6.3%)			0(0%)	
	Total	13 (40.6%)			3 (9.4%)	

Inaccessibility to water points was highlighted by 8.5% male and 18.8% female respondents as one of the most important social impacts along the Incomati River (Table 3.4), followed by an increase in snake bites (8.5% men and 9.4% female respondents). Both males (3.1%) and females (6.3%) noticed that the aquatic weeds in the Incomati River were aesthetically unpleasing in some areas since the water was turbid and smelly.

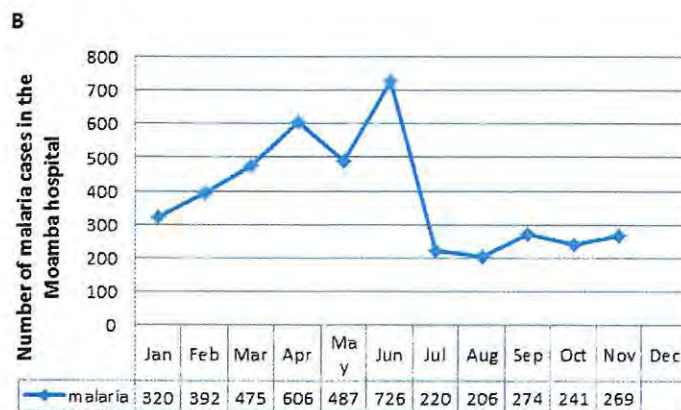
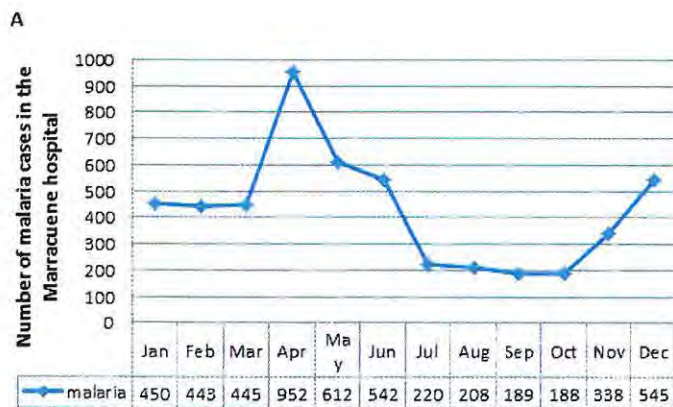
Table 3.4 Social problems associated with aquatic weeds in the upper, middle and lower Incomati River.

Respondents		Nature of social problems					
Gender	Region	Increased disease	Increased snake bite	Lack of clean water	Less access to water point	Transport hampered	Aesthetically unpleasing
Male (n=129)	Upper	1 (.8%)	0 (0%)		3 (2.3%)	0 (0%)	2 (1.6%)
	Middle	1 (.8%)	7 (5.4%)		3 (2.3%)	1 (.8%)	2 (1.6%)
	Lower	0 (0%)	4 (3.1%)		5 (3.9%)	2 (1.6%)	0 (0%)
	Total	2 (1.6%)	11 (8.5%)		11 (8.5%)	3 (2.3%)	4 (3.1%)
Female (n= 32)	Upper	0 (0%)	0 (0%)	1(3.1%)	1 (3.1%)		0 (0%)
	Middle	2 (6.3%)	3 (9.4%)	2 (6.3%)	1(3.1%)		1 (3.1%)
	Lower	1 (3.1%)	0 (0%)	0 (0%)	4 (12.5%)		1 (3.1%)
	Total	3 (9.4%)	3 (9.4%)	3 (9.4%)	6 (18.8%)		2 (6.3%)

The impact on health was another problem mentioned by the respondents (males 1.6% and female 9.4%). Specific effects were described as an increase in itching, malaria, diarrhea and bilharzia. Vital epidemiological data, relevant to incidences of human diseases, were obtained during this study from three rural hospitals in Moamba (upper Incomati), Magude (middle Incomati) and Marracuene (lower Incomati). In all areas (upper, middle and lower) the human diseases reported included itching skin, malaria, bilharzia and gastro-intestinal disorders. The rural hospitals were able to provide data on malaria and diarrhea.

Malaria is an endemic disease in Mozambique. Infection is common throughout the year, but is highest in the hot season from October to April, with symptoms lasting a week or more. Almost everyone that had been infected by malaria took medicine to treat it (96%). Many people visited traditional healers before seeking modern medical treatment from the hospital. Although resistance to most drug treatments is high in Mozambique, the most common medicine used was Fansidar, containing two active ingredients, pyrimethamine and sulfadoxine. Pyrimethamine is an antimalarial medicine and sulfadoxine is a type of antibiotic called a sulphonamide. The

malaria and gastro-intestinal disorders were recorded during the whole year in the rural hospitals. The critical time for malaria was during the months of April, May and June. The peak of aquatic weeds was June, July and August, so there appears to be no relationship between weed infestation and malaria. Gastro-intestinal disorders were observed during the whole year, but with a slight increase in the months of March to April, so once again, no direct causation could be applied. No record of any skin problems, bilharzia or snake bites were recorded in any of the hospitals. Figure 3.4 (A, B, C and D) illustrates the distribution of malaria and diarrhea cases confirmed by laboratory tests in year 2010 in the Moamba (upper Incomati River) and Marracuene (lower Incomati River) district. Table 3.5 illustrates the total number of malaria and diarrhea cases confirmed by laboratory tests at Moamba, Magude and Marracuene Districts. In the Magude district, only the total number of malaria and diarrhea cases was obtained and no distribution of the malaria and diarrhea per month was available (Table 3.5); both diseases were recorded in the hospital.



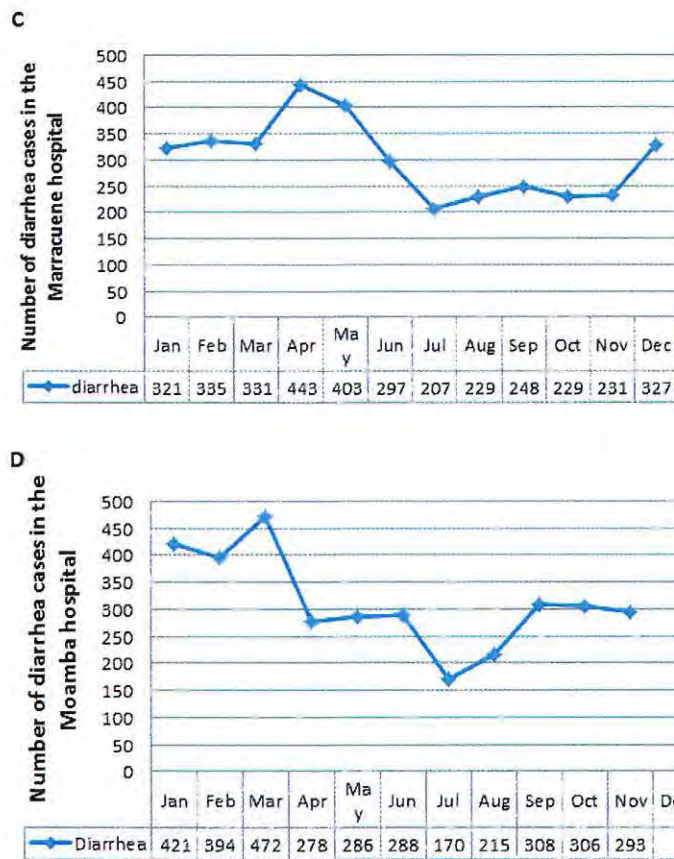


Figure 3.4 A. B. C and D Distribution of malaria and diarrhea disease at Moamba and Marracuene districts during 2010. Data represent only the number of malaria and diarrhea cases confirmed by laboratory test in the hospitals.

Table 3.5 Total number of malaria and diarrhea cases in three hospitals located in the Incomati River. These scores would probably be doubled if cases without a confirmed laboratory test were added.

Hospitals	Population (2005-census)	Number cases of malaria in 2010	Number cases of diarrhea in 2010
Moamba	62 392	7 132	3 601
Marracuene	60 471	5 132	4 603
Magude	62 434	4 142	6 560

3.5.6 Estimation of annual income from the main activities during 2010 in the Incomati River

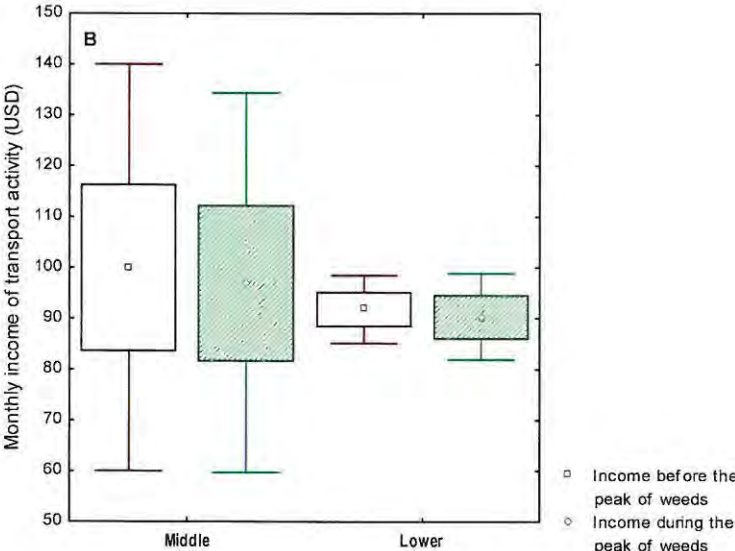
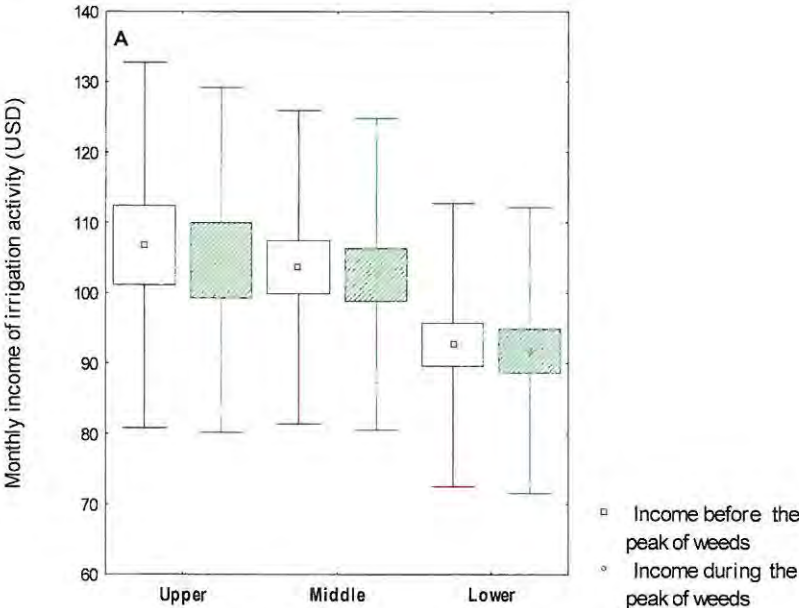
The yearly average income from agricultural irrigation, transportation or navigation and other activities was calculated for the period before the peak of weeds (September, October, November, December, January, February, March, April and May) and during the peak of the weeds (June, July and August) (Table 3.6). The Student T-test showed that the weeds did not have an impact on these activities along the Incomati River since no significant differences were observed during the period before the peak of the weeds and during the peak of weeds, ($p \Rightarrow 0.05$).

Table 3.6 The monthly income from different activities along the Incomati River during 2010 (Mt. means Meticaís, currency used in Mozambique).

Activity	Mean income before peak of weeds	Std. Dev.	Mean income during peak of weeds	Std. Dev.	df	P Value
Irrigation (n= 99)	US\$ 99.00/month (2937.50 Mt/month)	21.8	US\$ 98.00 /month (2870.50 Mt/month)	22.9	196	0.610
Transport (n= 10)	US\$ 96.00 /month (2813.00 Mt/month)	28.8	US\$ 94.00/month (2620.00 Mt/month)	28.2.5	18	0.879
Other activities (n=78)	US\$ 24.00/ month (718.00 Mt/month)	3.4	US\$ 23.00/ month (683.00 Mt/month)	3.5	154	0.550

The Non-Parametric Test used to compare income before the peak of weeds and the income at the peak of weeds showed no significant difference (Figure 3.5 A, B, and C) A: irrigation (Kruskal-Wallis test $H(2, N=99) = 4.4324, p = 0.610$); B: transport (Kruskal-Wallis test: $H(1, N=10) = .0014914, p = 0.879$); C: other activities (Kruskal-Wallis test: $H(1, N=78) = 3.189052, p = 0.550$). This indicates the water weeds did not have a significant impact on these activities. The livestock activities were carried out by schoolchildren younger than 18 years, with no

payment, as they worked for their parents. Further, no estimate of the impact on livestock industries was calculated because there was not enough information.



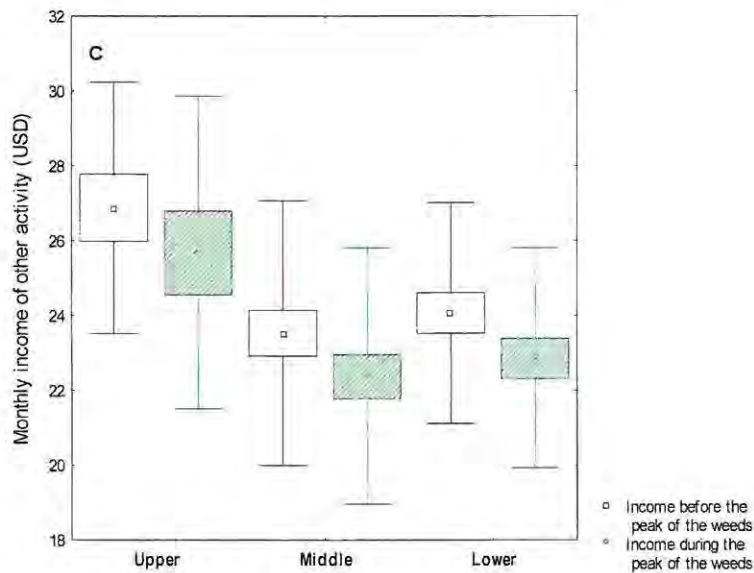


Figure 3.5 A, B and C Monthly incomes of different activities performed in the upper, middle and lower Incomati River. A: irrigation; B: transport and C: other activities.

In the Maragra sugar cane farms, those responsible for herbicide/insecticide control were interviewed to find out how much they spend combating the weeds and grasses in the drainage and on the river shores. Those interviewed explained that they use an excavator to reduce the weeds and grasses along the sugar cane farms. The cost of reducing the weeds in only the lower Incomati River was estimated for one day (eight hours) during the peak of weeds (Table 3.7). It was difficult to know how much was spent per month because not enough information about the number of days worked per month during the peak of weed infestation was obtained.

Table 3.7 Estimated costs of mechanical control of weeds according to the data obtained data from Maragra sugar cane farm. Mt= Meticais (Mozambican currency).

1 Excavator	40L/h X 8hrs X 26.7 Mt/L	8 544.00 Mt/day
2 Trucks	20L/hX4.5hrs X 26.7 Mt/L	42 72.00 Mt/day
Labor	8 people (4X233+4X183.3)	1 665.20 Mt/day
Total per day		14 481.20 Mt/day (US\$508.00/day)

An estimated 14 481 Mt/ day (US\$508.00) was used to reduce weed impacts only in the lower Incomati River. During the peak of weeds, the excavator is used three days every two weeks. Thus, about 86 886 Mt/month (US\$3 049.00 /month) was needed to control the weeds. During the time when there is no weed peak, the excavator is used two or three times per month. Around 43 444 Mt/month (US\$1 524.00) per month was needed.

The impact of the weeds was more pronounced in the fishing sector than it was in irrigation, transportation and other activities. The fishing season in Mozambique lasts between eight and nine months. The months of March, April, May, October and November were considered the months without a peak of weeds, while June, July and August and September had at least 50% cover.

Fisherman capture on average 26.3 kg (upper), 28.3 kg (middle) and 31.2 kg (lower) fish/ net, with a maximum of 37 kg/day and minimum of 21 kg/day. They fish, on average, 5.5 hours a day and at most, 9 hours. They fish, on average, for 4.7 days a week and, at the most, for 6 days. Each fisherman has his own wooden boat. Fishing was mostly affected by the weeds through reduced catch. An average of 834.3 kg (upper), 894.9 kg (middle) and 934.2 kg (lower) of fish/ month was caught during the period before the peak of weeds, and an average of 522.7 kg (upper), 554.2 kg (middle) and 619.5 kg (lower) of fish/ month was caught during the peak of weeds. Among the fish found in the Incomati River, the most frequently caught were the blue tilapia, *Tilapia rendalli* (Boulenger 1897); African catfish, *Clarias gariepinus* (Burchell 1822);

Mozambique tilapia, *Oreochromis mossambicus* (Peters 1852); banhine barb, *Barbus* sp. and lowveld largemouth, *Serranochromis meridians* (Jubb 1967). The income from fishing in the upper, middle and lower Incomati was slightly higher before the peak of infestation compared to the income during the peak of weeds (Table 3.8). The Student T-test showed that there was a significant difference in the monthly income between the time before peak of the weeds and at the peak of weeds in the upper Incomati, middle Incomati and lower Incomati ($p < 0.05$).

Fishermen also grow crops and vegetables for sale (Table 3.8) to supplement their annual income. No significant differences were observed in the income of the different groups over the second activity in the upper, middle and lower Incomati River. There was also no significant difference between the income during the time before the peak of weeds and at the peak of weed infestation ($p > 0.05$).

Table 3.8 Influence of aquatic weeds on income from fish and trade activities in September, October, November 2009, and March–August 2010. The time before the peak of weeds is October and November, 2009 and March, April, May 2010 and the peak of weeds was observed for only during four months, namely June–July and August–September 2010.

Activity	(n)	Locality	Yearly Income (USD/ person)					
			Before the peak of weeds		At the peak of weeds		Income impacted by weeds	
Fishing	5	Upper	707.3	(47.1)	443.0	(14.9)	264.3	33.3%
	6	Middle	758.4	(50.8)	563.6	(24.7)	194.8	24.4%
	5	Lower	791.8	(26.9)	489.3	(11.5)	302.5	38.0%
Mean	16		752.4	(42.5)	489.6	(60.8)	253.8	31.9%
Trade Of Crop	5	Upper	792.8	(105.7)	772.8	(108.8)	0	
	6	Middle	785.3	(107.2)	770.6	(107.2)	0	
	5	Lower	798.1	(104.5)	748.1	(121.0)	0	
Mean	16		792.0	(6.43)	763.8	(6.43)	0	

3.5.7 Control of aquatic weeds in Incomati River

Some of the strategies employed to manage aquatic weeds in the study areas were to cut the weeds, to remove the weeds by hand, or to cut and burn the weeds, but most people do not do anything (Table 3.9). Of the people interviewed, 45.1% had tried to manage the weeds using these strategies, but 54.9% did not manage them at all. Biological control was not mentioned by the population living along the Incomati River, given that few know about biological agents; only one respondent knew about the weevils, and he knew that they controlled water hyacinth. No chemical application to reduce the weeds was mentioned by the respondents in any of the regions in the Incomati River.

Table 3.9 Different strategies used by male and female respondents to reduce the aquatic weeds in the upper, middle and lower Incomati River.

Strategies to reduce the weeds' impact											
Gender	Locality	Cutting		Hand removal		Cutting and burning		Do nothing		Total	
		(n)	%	(n)	%	(n)	%	(n)	(%)	(n)	%
Male	Upper	0	0	8	6.2	1	0.8	13	10.1	22	17.1
	Middle	8	6.2	37	28.7	1	0.8	10	7.8	56	43.4
	Lower	7	5.4	27	20.9	4	3.1	13	10.1	51	39.5
	Total	15	11.6	72	55.8	6	4.7	36	27.9	129	100.0
Female	Upper	1	3.0	5	15.2			2	6.1	8	14.2
	Middle	3	9.1	8	24.2			5	15.2	16	48.5
	Lower	2	6.1	3	9.1			4	12.1	9	27.3
	Total	6	18.2	16	48.5			11	33.3	33	100.0

People worked individually or were organized into groups to control the weeds, especially at the peak period. These groups varied in size (number of people per group), depending on other activities carried out on the Incomati River, (Figure 3.6). People who were irrigating their fields were organized in groups of 1–5, 6–10, 11–16, or more than 16 people, depending on the size of their farms, and they cleaned up the weeds in the watercourses along the Incomati River. Usually the fishermen stopped their fishing activity during days when weed density was very high and together they cleaned the affected areas. People who used the river for transport cleared the weeds themselves. Most respondents (42.2%) recognized that some people did not try to reduce the weeds at all, since the mat of weeds was mobile and went away in some periods. Only a few did not know what happened to the weeds since they saw them in some seasons and not in others.

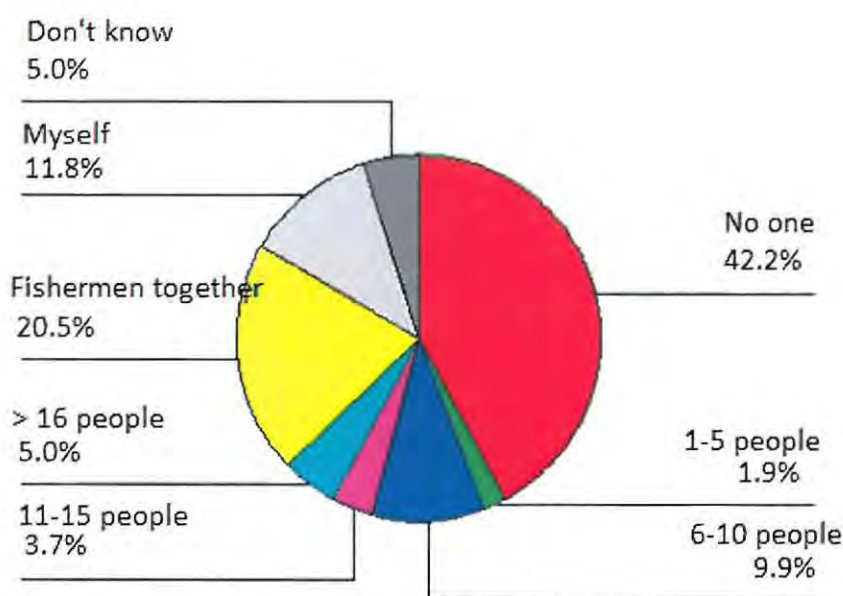


Figure 3.6 The percentage presented refers to the number of people that were needed to control the weeds' impact in the Incomati River at the peak of weeds.

In the Incomati River, approximately 85 641.00 Mt (US\$2 946.00) was necessary to reduce the impact of the weeds. This calculation was for approximately 15 days during the month of July when the impact of the weeds was significant (Table 3.10). The manual method was used. A

total of 125 people spent 3.5 hours/day removing the aquatic weeds. Each person stopped their other activities (3.5 hours) to participate in weed removal, and one hour of labour is equivalent to 13.00 Mt (US\$0.45) (Table 3.10).

Table 3.10 Estimated cost of manual control of water weeds during July 2010.

Number of people removing weeds	125
Cost of labor / hour	13.00 Mt/ hour (US\$0.45/hour)
Time spent / day removing weeds	3.5 hours/day
Total spend /day	5709.00 Mt (US\$197.00/day)
Total spend during 15 days	85 641.00 Mt (US\$2 946.00)

3.6 Discussion

3.6.1 Major threats to the Incomati River

During the peak of the aquatic weeds, the local population observed significant changes in their activities which consequently had socio-economic impacts. The most notable economic impact that was reported was the blockage of the irrigation canals whenever mats of water weeds covered the river. Controlling the weeds in Mozambique either mechanically or manually involves an extra cost. The costs obtained in this study were relatively low when compared to those calculated in Uganda, but this result supports studies done in other regions related to the economic impact of aquatic weeds. Uqueio (2008) reported that the water weeds, in particular water hyacinth, cause disruption to agricultural activity by reducing the water intake of the irrigation pump in the Umbeluzi River in Mozambique. Similar blockages and/or massive interference caused by water weeds, in particular water hyacinth was reported by Opande *et al.*, (2004) and Mailu (2001), in studies done in Kenya. Mailu (2001) showed how water hyacinth impacted the Uganda economy in 1995. He estimated about US\$3–5 million was required to maintain a clear passage for ships to dock at Port Bell in Uganda; US\$1 million to clear the intake screens at Owen Falls hydroelectric plant; a loss of about US\$0.2 million in fisheries, and finally, US\$0.35 million lost in water supplies for domestic, stock and agricultural purposes.

Comparing results obtained by Opande *et al.*, (2004) with this study, the impact of weeds in Mozambique would not seem to be very serious. However in Mozambique, the results obtained for fishing activities were based on only one year, small-scale fishing, small boats with two to eight nets per fisherman, producing an income of about US\$2 903.00 per fisherman per year. Furthermore, Mozambican fisherman did not report a problem of being unable to sell their fish, nor did they report other problems such as fish kills caused by deoxygenation as a result of weed growth. In contrast, studies in Kenya focused on industrial fishing, involving millions of people, large fishing boats, fish landing spots and fishing gear with an annual income worth about US\$83,000, 000 per annum (Opande *et al.*, 2004; Atonga, 2001).

Mailu (2001) explained that water hyacinth also poses problems for the lake ecology by using available oxygen reserves, resulting in fish kills. Economic losses were significant: the World Bank estimated that the first outbreak of water hyacinth on Lake Victoria in 1997 cost the riparian nations between US\$6 million and US\$10 million (2000). During this period, there was reportedly a 70% decline in economic activity at the Kenyan port of Kisumu. However, this study shows that fishing was one of the activities most severely impacted by weeds compared to other activities performed on and along the Incomati River, and the impact of the aquatic weeds was serious. Respondents reported that as a result of water weeds (particularly water hyacinth), land and water were inaccessible, boats were unable to sail through water covered by weeds, given the thick mats created by meshed roots, and casting nets in the water was difficult. All these hampered the fishing activity and consequently fish catches and the income of the fishermen declined considerably during the peak months of weed growth.

A problem recorded by Willoughby *et al.* (1993) was that mats significantly depressed the fish diversity and biomass, but Twongo and Balirwa (1995) noted a small increase in fish diversity along the edge of water hyacinth mats. The problem that led to the decline in fishing activity in Mozambique could be related to the permanent carpet of weeds that occupied long stretches of the rivers. Added to this aspect, the mats of water hyacinth were usually associated with other, indigenous aquatic plant species, such as *Ceratophyllum demersum*, and grasses that obstructed nets, blocked boats and finally, hampered the fishing activity. Thus, the decline in fish caught

over the peak of weeds in the upper, middle and lower Incomati River could be associated with the inability of fisherman to access the fishing ground for some species of fish because of the weed infestation, in particular, water hyacinth.

All the weed mats found along the Incomati River provide breeding grounds for mosquitoes and other disease vectors. This study showed 1.6% of males and 9.4% of females, living along the Incomati River, reported an increase in malaria, bilharzia, diarrhea and itching skin problems due to the increase of all kinds of weeds in the Incomati River. The above observation is supported by the research of Opande (2002), Mailu (2001) and Opande *et al.* (2004) who reported that the weed enhanced transmission of encephalitis, coughs and schistosomiasis. Dray and Center (2002) recognized that water lettuce also provides a breeding ground for mosquitos, but the costs associated with mosquito-borne diseases are unknown. Finally, Navarro and Phiri, (2000), Mehra *et al.*, (1999) reported that water hyacinth facilitates the spread of diseases such as schistosomiasis and malaria, in addition to cholera and typhoid. However, sound data on this are not available. Feikin *et al.* (2010) confirmed in their research that yearly water hyacinth coverage on the Kenyan side of Lake Victoria was positively associated with the number of cholera cases reported in Nyanza Province. All rural hospitals reported malaria cases throughout the year. This study showed an increasing number of malaria cases between April and June which suggests that the presence of weeds could be an explanation for the increase in malaria cases, but we could not show the correlation. With regard to diarrhea, the rural hospitals reported that this disease was prevalent during the whole year without a significant peak in disease during the year. But in the study, it was observed that diarrhea was more common during the peak of the weeds. Rural hospitals were developing counseling programmes to minimize some diseases like diarrhea. So, no relevant information was obtained from the hospitals to explain the increase of disease incidences as a result of the enhancement of the vector-breeding weeds.

Another problem related to the mats of weeds in Mozambique rivers was the danger caused by snakes, while the presence and the danger of crocodiles and hippo were also reported by the riverine population. Navarro and Phiri (2000) stated that water weeds (water hyacinth) harbour poisonous snakes, crocodiles and hippos, increasing the danger for the people working with water.

3.6.2 Management of aquatic weeds

In this study, the methods used by the local population to reduce the weeds' impact were manual methods such as cutting, removing from water, and burning. Hill and Olckers (2001) reported that manual removal of water weeds was used in different lakes in Africa, but it was labour-intensive and ineffective in larger infestations. The population living on the Incomati River was unanimous in saying that herbicides were not used at all to control aquatic weeds. However, in many other areas of Africa, herbicidal control is widely practiced. For example, in South Africa, herbicides containing the active ingredients glyphosate, glyphosate trimesium, diquat and butryn have been used with great success (Ueckermann and Hill, 2001).

In this study, the majority of respondents were not able to comment on the biological control of weeds because they had never heard about any biological control agents. Only one respondent was able to recognize the water hyacinth weevil. This means that the practice of biological control of weeds is unknown in the Incomati River community. Other studies showed that the local populations can become aware of aquatic weeds and biological. Contrary to this study, De Groote *et al.* (2003) had noticed that about 50% of the population interviewed in their study in Benin were aware of biological control of weeds, particularly water hyacinth.

3.7 Conclusion

One of the keys to successful biological control programme on Lake Victoria was the public awareness campaign, educating local communities about biological control and teaching them how to implement it. This approach should also be implemented in Mozambique, but the status of the biological control programme on aquatic weeds in Mozambique is not known (Chapter 4).

Status of aquatic weeds associated with biological control agents in the southern Mozambique rivers

4.1 Introduction

The release of biological control agents has reduced the problems caused by many invasive weeds throughout Africa (Cilliers *et al.*, 2003; Ajuonu and Neuenschwander, 2003). Despite considerable research invested in pre-release studies, the outcomes of releasing agents, especially in developing countries, are seldom quantified (Wilson *et al.*, 2006). However, there are some quantified studies in the literature. For example, in South Africa, red waterfern, *Azolla filiculoides* was controlled within a year by the weevil *Stenopelmus rufinasus* (McConnachie *et al.*, 2004) and water lettuce was controlled within ten months after the first field release of *N. affinis* (Cilliers, 1987); and salvinia, *S. molesta*, was controlled in Papua New Guinea within two years after the introduction of the weevil *Cyrtobagous salviniae* (Room *et al.*, 1981), and, in South Africa, within 1–3 years, depending on the size of the infestation and the climate (Cilliers 1991).

In 1972, in Mozambique, the first biological control agents released were *Neochetina eichhorniae* to control water hyacinth (Julien and Griffiths, 1998). *Neochetina bruchi* was also recorded in 1972, but there is no record of how it got there (Julien, 2001). Other biological control agents on aquatic weeds, including *Stenopelmus rufinasus* on *A. filiculoides*, *Neohydronomus affinis* on *P. stratioides*, and *Cyrtobagous salviniae* on *S. molesta* are present in the Mozambican rivers, but nothing is known of their establishment and impact. None of these three agents was released into Mozambique rivers, but it is assumed that they were spread from the region where the weevils were successful, such as South Africa, Zimbabwe and Zambia (Cilliers *et al.*, 2003).

4.2 Specific objectives

The aim of this chapter was to quantify the status and efficiency of the biological control agents on the aquatic weeds in southern Mozambique rivers.

Specific objectives were:

1. To identify the biological agents associated with water hyacinth, water lettuce, salvinia and red water fern found along the southern Mozambique rivers;
2. To evaluate the impact of *Neochetina eichhorniae* and *N. bruchi* on the water hyacinth (*Eichhornia crassipes*), *Neohydronomus affinis* on water lettuce (*Pistia stratiotes*), *Cyrtobagous salviniae* on *Salvinia molesta* and *Stenopelmus rufinasus* on the water red fern (*Azolla filiculoides/A. microphylla*) in the different rivers.

4.3 Material and methods

4.3.1 Description of the study area

The rivers situated in the southern part of Mozambique (Maputo, Umbeluzi, Incomati, Limpopo, Inharrime, Guvuro and Save rivers) were chosen to study the impact of the biological control agents because these rivers contained infestations of invasive aquatic macrophytes (Chapter 2). At each sampling point, coordinates were taken. Water quality parameters such as temperature, pH, hardness, nitrate, phosphate were measured during the dry season (June, 2009) and in the wet season (November, 2009).

4.3.1.1 Govuro, Inharrime and Save reference sites

The Govuro, Inharrime and Save rivers are situated near main roads and close to the residential areas. The agricultural lands in this area are sparse, with no evidence of rural settlement runoff or agricultural activity (Chapter 2). Continuous reeds and grasses, as well as shrubs and trees, occur on the banks of these rivers. Residential areas have not had an impact, nor is there any water abstraction.

4.3.1.2 Maputo and Limpopo rivers

The Maputo and Limpopo rivers are situated close to roads, residential areas and farming activities. There is more agricultural activity in the Limpopo River area than along the Maputo River (Chapter 2).

4.3.1.3 Umbeluzi and Incomati rivers

These sites are impacted by abstraction, deposits of sediment runoff from informal settlements, fruit cultivation (Umbeluzi), sugar cultivation (Incomati), and an extensive residential area (Chapter 2). The Incomati River is situated below the Chinavane and Maragra sugar cane refinery. A flood that occurred during the high flow period affected the rivers because fertilizer and animal manure from cultivated fields, together with aquatic plants, was washed down into rivers from Maragra and Xinavane sugar cane fields.

4.3.2 Sampling procedures for assessment of weevils, *Cyrtobagous salviniae*, *Neohydronomus affinis* and *Stenopelmus rufinasus*

In each sampling area, 100 plants each of *Salvinia molesta*, *Pistia stratiotes* and *Azolla microphylla* were randomly collected to quantify the presence of the respective weevils, that is to say, *Cyrtobagous salviniae*, *Neohydronomus affinis* and *Stenopelmus rufinasus*. The leaves and apical buds were inspected for characteristic damage. The samples were taken once each in June 2009 (dry season), and in November 2009 (wet season), in different localities, according to the distribution of the weeds along the southern Mozambique rivers namely, the Maputo, Umbeluzi, Incomati, Limpopo, Inharrime, Govuro and Save rivers.

4.3.3 Sampling procedure for assessment of weevils *Neochetina eichhorniae* and *N. bruchi*

There were six rivers at which the populations of *N. eichhorniae* and *N. bruchi* were assessed, namely Maputo, Umbeluzi, Incomati, Limpopo, Govuro and Inharrime. At each sampling site, ten water hyacinth plants were collected for the purpose of measuring the damage caused by the biological control agents. In each of the rivers sampled, several plant and insect parameters were measured (Table 4.1).

Table 4.1 Water hyacinth plant and biological agent parameters measured in the study area.

Parameter	Description
Water hyacinth plant	<ul style="list-style-type: none"> -length of longest petiole on the plant -number of flowers per water hyacinth plant -number of leaves per water hyacinth plant -maximum root length -number of ramets attached to the sampled plant -fresh weight per water hyacinth plant
Weevil: - <i>Neochetina eichhorniae</i> - <i>Neochetina bruchi</i>	<ul style="list-style-type: none"> - number of <i>N. eichhorniae</i> adults - number of <i>N. bruchi</i> adults - number of feeding scars on leaf 2 - number of larval instars - petioles mined - pupae present
Mite: - <i>Orthogalumna terebrantis</i> Pathogens: - <i>Acremonium zonatum</i> - <i>Alternaria eichhorniae</i>	<ul style="list-style-type: none"> - mite damage (% of damage on the lamina) - pathogen damage (% of damage on the lamina)
Moth - <i>Niphograpta albiguttalis</i>	<ul style="list-style-type: none"> - moth larvae (presence or absence) - moth pupae (presence or absence)
Mirid - <i>Eccritotarsus catarinensis</i>	<ul style="list-style-type: none"> - number of adult leaf damage (proportion of leaf 4 showing mirid feeding damage) - nymphs present or absence

4.3.4 Statistical analyses

Plant and insect parameters were analyzed between the wet and dry period using Student T-test. The ANOVA, Non -Parametric Test (Kruskal- Wallis) was used to compare the plant sizes in the different sampling localities, between dry and wet seasons, namely in June and November 2009. All analyses were conducted at a critical P level of 0.05. The computer program STATISTICA, version 10, was used.

The formula $\{0.0336 \times (\text{Average number of feeding scars})^{0.775}\}$ (Wright and Center, 1984) was used to calculate the number of adults on water hyacinth plants during the dry and wet season.

4.4 Results

4.4.1 Estimation of weevils *Neohydronomus affinis*, *Stenopelmus rufinasus* and *Cyrtobagous salviniae*, on their host plants along the southern Mozambique rivers

Water lettuce, *Pistia stratiotes*, was found only in three rivers, namely Umbeluzi, Incomati and Govuro, covering a surface area of 50%, 25% and <5% respectively (Chapter 2). Observations in June and November 2009 (dry and wet seasons) showed that the weevil *Neohydronomus affinis* was present in the water lettuce communities in both seasons (Figure 4.1). Significant differences were observed in the mean number of *N. affinis* between the dry and wet season in the Incomati River (Kruskal-Wallis test: $H(1, N=200)=134.6695$ $p < 0.0001$) and Umbeluzi River (Kruskal-Wallis test: $H(1, N=200)=13.42622$ $p < 0.00013$). In the Govuro River, there were very few water lettuce plants, but they were vigorous, without scars on the leaves and without any *N. affinis*.

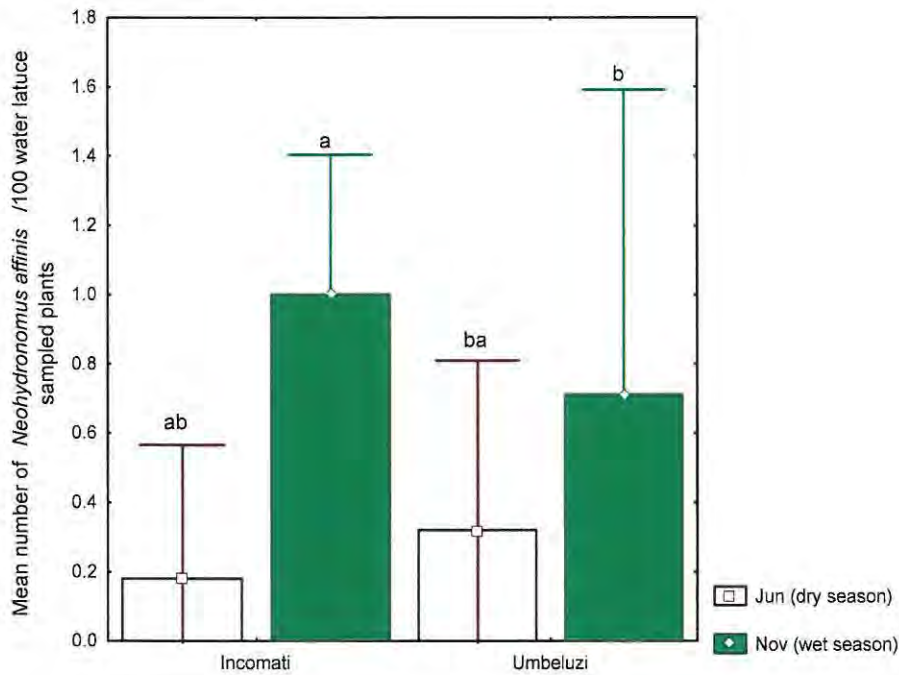


Figure 4.1 Mean numbers of *Neohydronomus affinis* per 100 sampled water lettuce plants along the Incomati and Umbeluzi rivers. Each bar represents mean \pm Standard Deviation of each sampling time. Means marked with letters within each sampling time are significantly different at $P < 0.05$.

The tropical red water fern, *Azolla mycrophylla*, showed very little damage on the leaves and the weevil *S. rufinasus* was found in very small numbers in these plants (Figure 4.2). Comparing the infestation levels of the dry and wet seasons using the non-parametric test, no significant difference was observed between the seasons ($p > 0.05$).

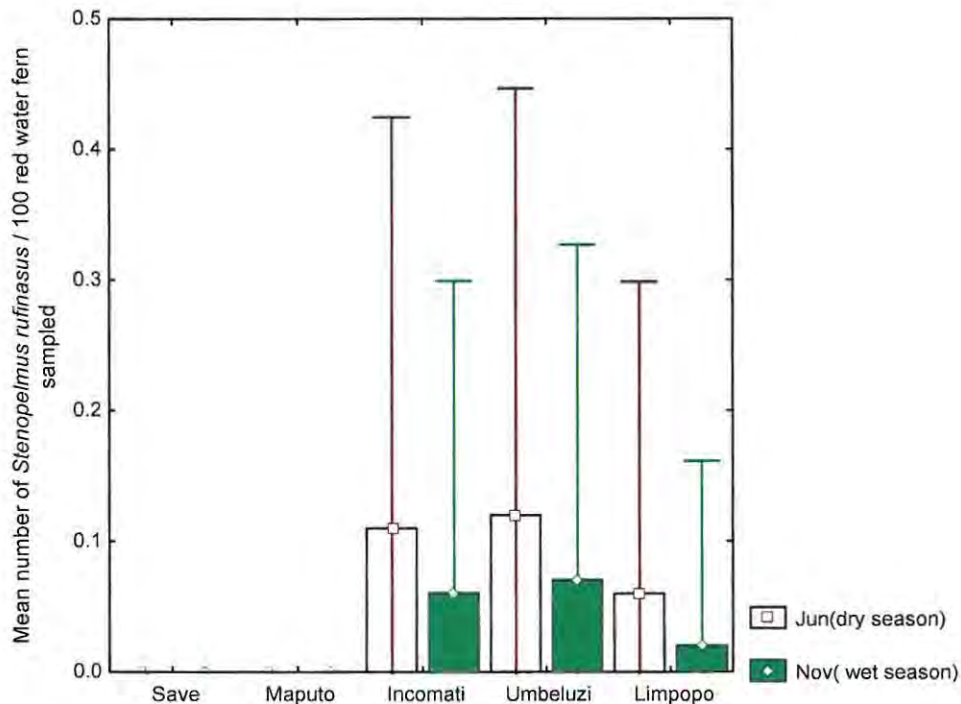


Figure 4.2 Mean number of weevils, *Stenopelmus rufinasus*, per 100 sampled *A. microphylla* along the southern Mozambique rivers. Each bar represents mean \pm Standard Deviation of each sampling time.

By the dry season of June 2009 and wet the season in November 2009, only a few *Salvinia molesta* plants (less than 2% coverage) were found in the Umbeluzi River. At that time, leaves were inspected and found to be unscarred. No *Cyrtobagous salviniae* were found.

4.4.2 Characteristics of water hyacinth plants in the southern Mozambique rivers

Comparing measurements of water hyacinth plants in the different study areas revealed that plant communities were small in the Inharrime, Govuro, Maputo and Limpopo rivers in the dry season (June 2009) since the mean of the longest leaf length plants was small, but increased from June to November (Figure 4.3).

Water hyacinth plants found in the Incomati and Umbeluzi rivers were taller than those found in Govuro, Inharrime, Maputo and Inharrime rivers. The longest leaf of water hyacinth plants in Incomati and Umbeluzi rivers did not increase during the study period (Figure 4.3), possibly due

to the effect of biological control agents *Neochetina* spp. during the different study times, namely June 2009 (dry season) and November 2009 (wet season). The mean of the longest petiole length of water hyacinth communities measured in Incomati and Umbeluzi rivers did not increase during the study time (Figure 4.1). There was no evidence of the weevils *N. eichhorniae* and *N.bruchi*, or scars on the leaves in water hyacinth plants in the Govuro and Inharrime rivers.

There was substantial growth in the length of the longest leaf, root length and fresh weight in the water hyacinth plants found in the Govuro and Inharrime from June to November 2009, and in the same rivers, water hyacinth plant communities showed seasonal growth since there were significant differences between the growth pattern of the dry and wet seasons (Figure 4.3; Figure 4.4; Figure 4.7).

The water hyacinth plants in the Maputo and Limpopo rivers were slightly bigger than those from Govuro and Inharrime. However, there was an increase in the growth of longest leaf and root length, and also the fresh weight between wet and dry seasons. The water hyacinth population at Govuro, Inharrime, Maputo and Limpopo showed seasonal changes in measured parameters typical of normal growth. The seasonal pattern consisted of a change from few, small plants in the dry season to numerous, large plants in the wet season. Seasonal increases in individual plant size included increases in both elongation of leaves, roots and weight.

The water hyacinth population in the Umbeluzi and Incomati rivers did not show seasonal changes in the measured parameters such as the elongation of leaf, roots and fresh weight; in fact, in these rivers, there was a decrease, unlike the other rivers. There were significant differences in the mean of longest leaf between the different rivers during the dry season ($F_{(5,54)}=153, 3; p<0.00001$); and the wet season ($F_{(5,54)}=31.3, p<0.00001$).

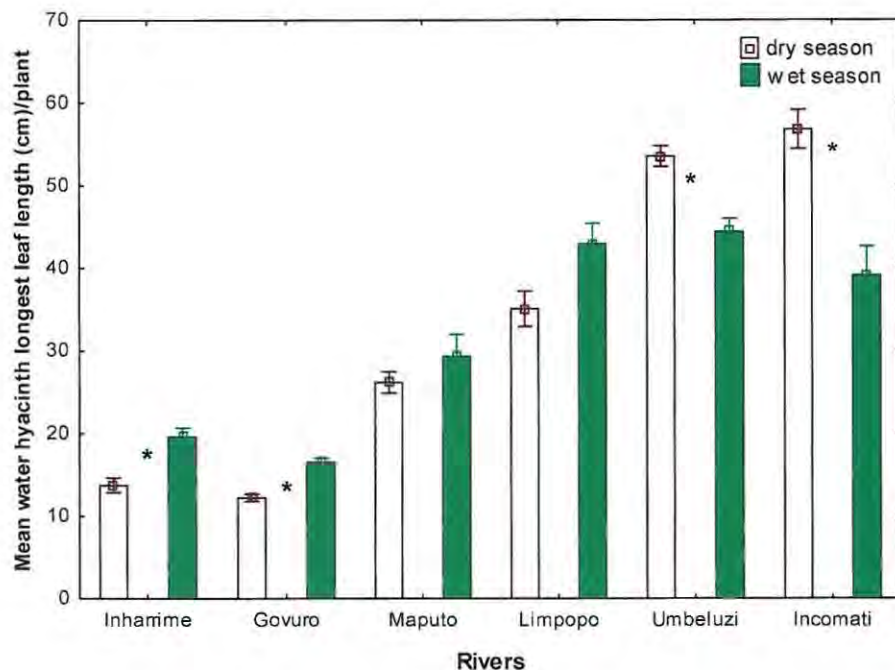


Figure 4.3 Mean water hyacinth plant longest leaf length per plant in dry season (June) and wet season (November) sampling 10 plants at each of six sampling sites. There were significant differences in the length of longest leaf between dry and wet seasons at Govuro ($F=1.13$; $df=18$; $p < 0.005$); Inharrime ($F=1.29$; $df=18$; $p < 0.0003$); Umbeluzi river ($F=1.52$; $df=18$; $p < 0.0002$) and Incomati ($F=4.19$; $df=18$; $p < 0.004$) sampling sites. (* denotes significant differences)

The length of the root systems varied in size in the different rivers in the dry season ($F_{(5,54)}=98.1$, $p < 0.0001$) and the wet season ($F_{(5,54)}=36.5$, $p < 0.0001$). The length of roots increased in all water hyacinth plant communities, except those found in the Umbeluzi River. The mean of the longest root system was measured on the water hyacinth plants present in the Umbeluzi river, namely, dry season 59.5 cm (± 8.8) and wet season 52.2 cm (± 6.1) (Figure 4.4). There were no significant differences in longest roots between dry and wet seasons in any rivers studied. Further, the root length of the water hyacinth population in all rivers studied showed no seasonal changes and there was no significant difference between the root size in dry and wet seasons (Figure 4.4).

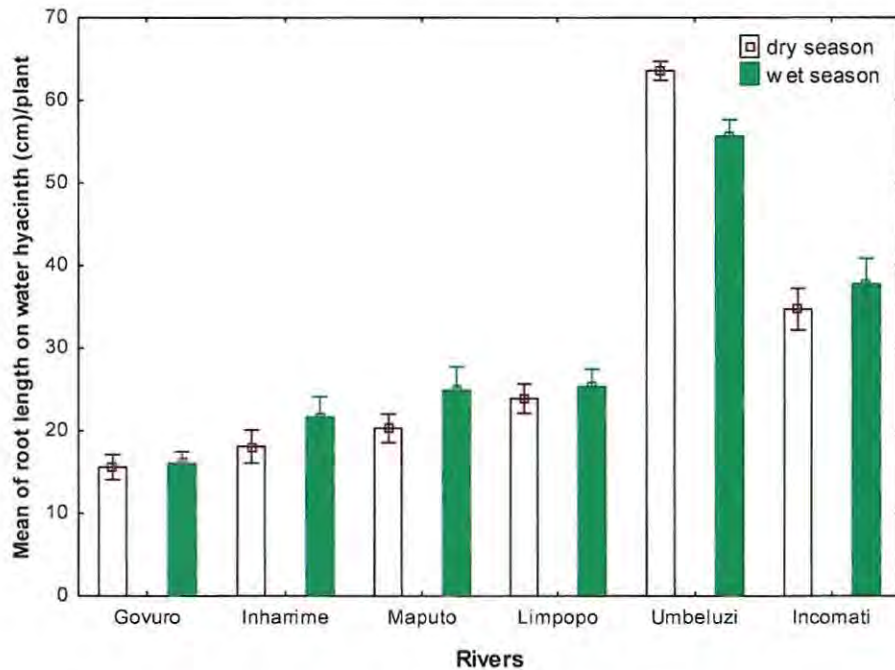
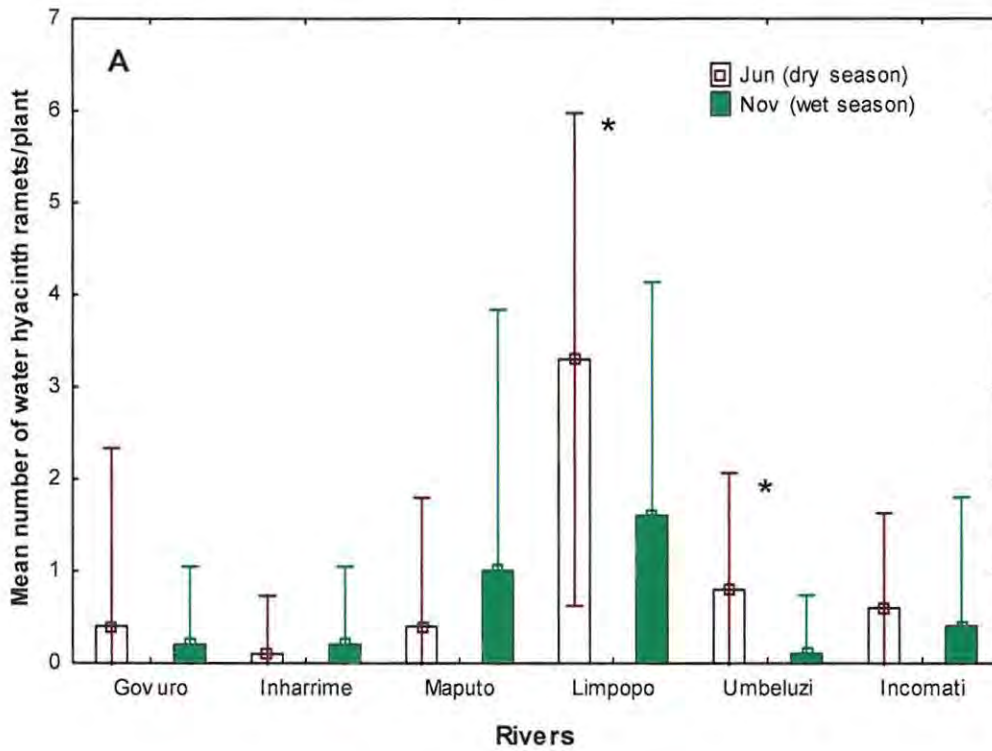


Figure 4.4 Mean water hyacinth plant length of longest root per plant in dry season (June) and wet season (November) sampling 10 plants each at six sampling sites. There were no significant differences in the mean of root length on water hyacinth plant between dry and wet seasons ($p>0.05$).

In all sampling sites, there were few ramets and flowers on the water hyacinth plants. Both ramets and flowers were found only in relatively high numbers in the Limpopo River. The highest numbers of ramets was observed in the Limpopo River in both the dry (3.30 ± 1.3 ramets/10 plants) and wet seasons (1.60 ± 1.2 ramets/10 plants), (Figure 4.5 A), and the highest mean number of flowers observed was also in the Limpopo River in both the dry (1.2 ± 0.9 flowers/10 plants) and wet seasons (1.3 ± 1.1 flowers/10 plants), (Figure 4.5 B).

No flowers were observed in the water hyacinth plant communities in Govuro and Inharrime rivers, but flowers were found in both seasons on the water hyacinth plant communities in Maputo, Umbeluzi, Limpopo and Incomati. The average number of inflorescences per plant for each site in each dry and wet season was generally low. No definite seasonal trend was observed, but some spatial variation was noted.

There were significant differences in the number of ramets in the dry season ($F_{(5,54)}=21.1$, $p<0.0001$) and the wet season ($F_{(5,54)}=4.6$, $p<0.001$) and also in the number of flowers: dry season ($F_{(5,54)}=4.59$, $p<0.001$), and wet season ($F_{(5,54)}=6.64$, $p < 00007$) along the different sampling sites. No significant differences were observed in the mean number of flowers between dry and wet seasons ($p>0.05$) in any rivers.



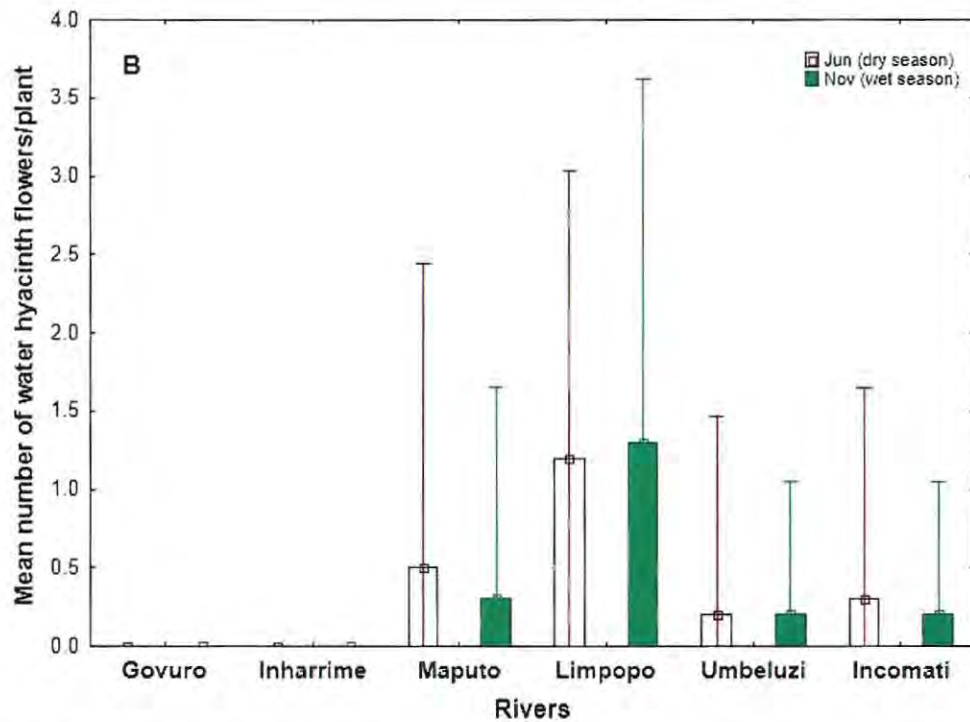


Figure 4.5 A and B Comparison of mean number of ramets (A) and number of flowers (B) on water hyacinth plant communities during June 2009 (dry season) and November 2009 (wet season) at the different sampling sites. (* denotes significant differences)

The average number of leaves per plant for each site on each sampling date ranged from 8.8 (± 2.4) to 10.9 (± 1.6) in the dry season, to 8.4 (± 1.5) to 10.3 (± 2.6) in the wet season. The variation was not significant between the plants in the different sampling sites, namely in the dry season (June) $F_{(5, 54)}=0.99$, $p > 0.432$ and the wet season (November) $F_{(5, 54)}=0.79$, $p > 0.564$.

In this study, the number of leaves is not included as a parameter for measuring the growth of the plant since there was no significant variation between dry and wet seasons at each sampling site. There was no obvious seasonal variation in leaf number: both the high and low number of leaves for sampling dates averaged across rivers occurred during dry and wet seasons.

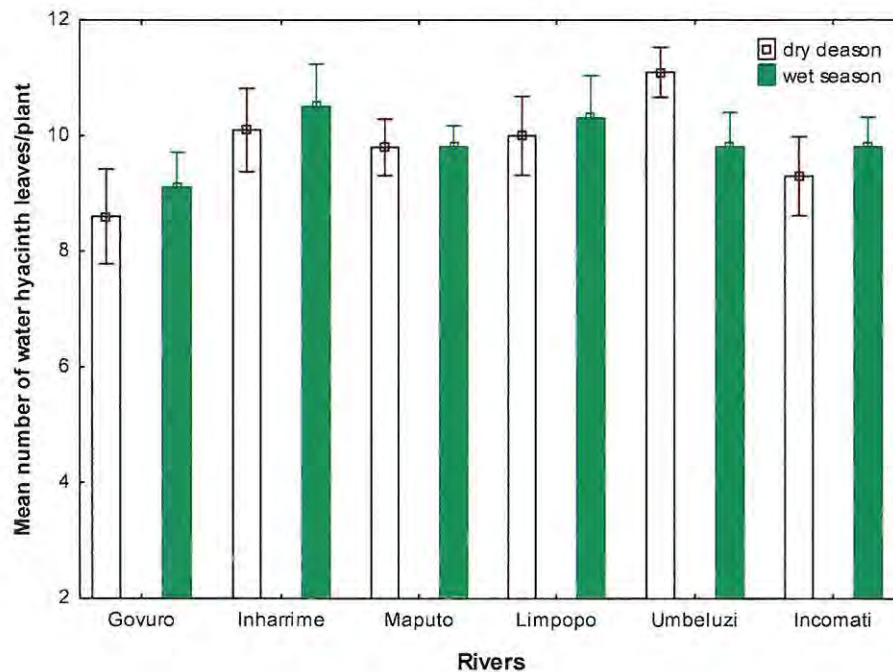


Figure 4.6 Mean water hyacinth leaves per plant in dry season (June) and wet season (November) sampling 10 plants each at six sampling sites. There were no significant differences in the mean of leaves on water hyacinth plant between dry and wet seasons ($p > 0.05$).

Similar patterns observed for longest leaf length were observed in the fresh weight. The water hyacinth plant communities did not have the same weight at the different sampling sites. An increase in the fresh weight of water hyacinth plant communities was observed in the wet season in Govuro, Inharrime, Maputo and Limpopo; however, the fresh weight did not increase in Umbeluzi and Incomati rivers (Figure 4.7). Significant differences occurred in fresh weight across sampling sites in the dry season ($F_{(5, 54)} = 20.0$, $p < 0.0001$) and wet season fresh weight, ($F_{(5, 54)} = 9.06$, $p < 0.0001$).

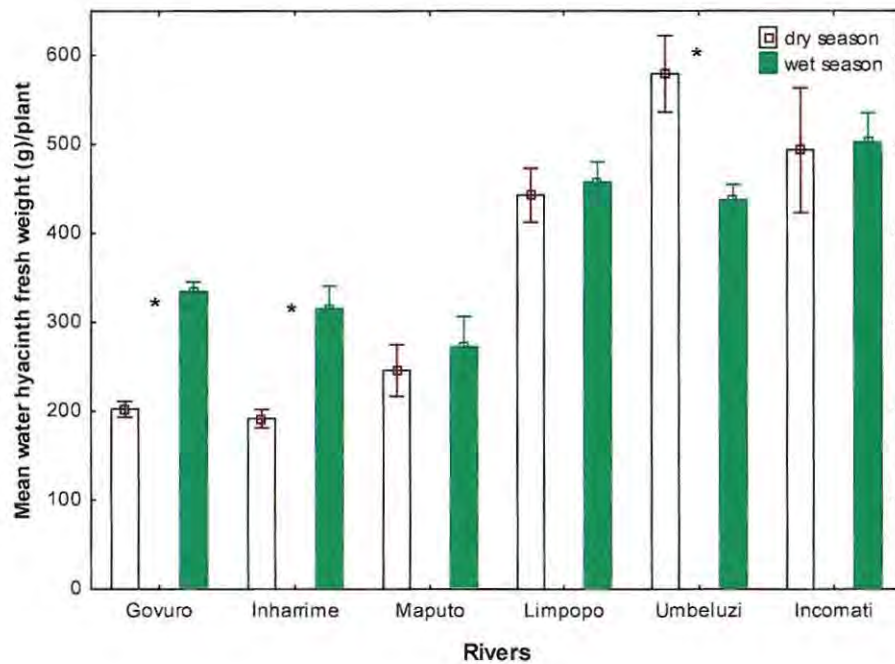


Figure 4.7 Mean water hyacinth fresh weight per plant in dry season (June) and wet season (November) sampling 10 plants at each six sampling sites. There were significant differences in fresh weight between dry and wet seasons in Govuro, Inharrime and Umbeluzi rivers ($p < 0.05$). (* denotes significant differences)

The density of *Neochetina* weevils per plant varied significantly at the sampled rivers. *Neochetina eichhorniae* and *N. bruchi* were not found on the water hyacinth plants in the Govuro, Inharrime, Maputo and Limpopo rivers (Table 4.3). The fresh weight also varied in the different rivers across and over the time (Figure 4.7). Plants without leaf scars, or with a very few leaf scars tended to increase during the time period (from June 2009 to November 2009) (Table 4.3; Figure 4.7). Water hyacinth plants with a higher fresh weight tended to have fewer *Neochetina* spp. feeding scars, compared to those with less fresh weight, $r=0.59$; $n=160$; $p<0.05$ (Figure 4.8).

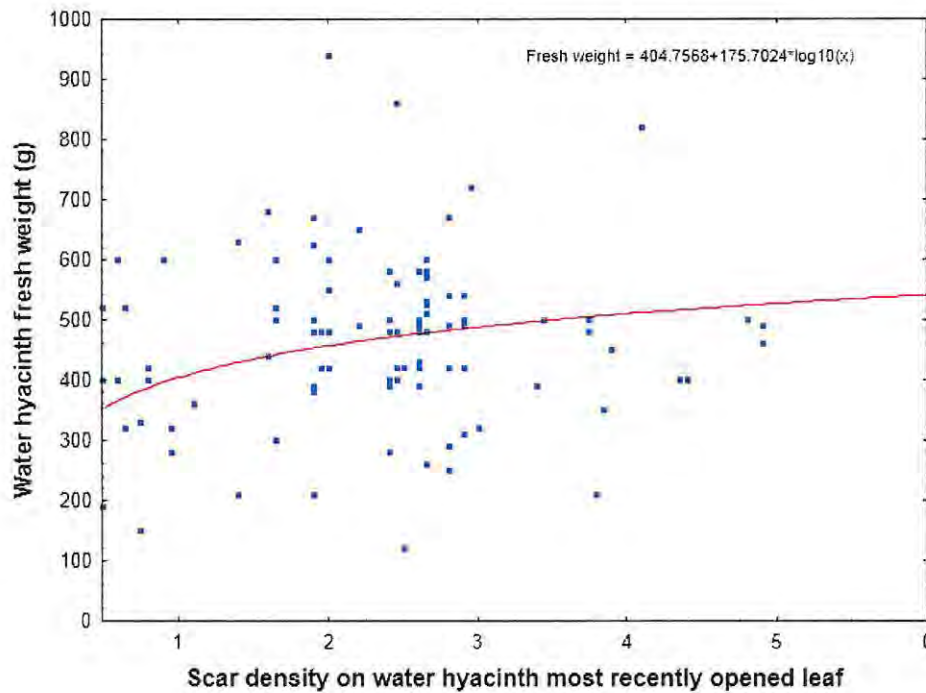


Figure 4.8 Plots of leaf scarring by water hyacinth weevils against fresh weight based of the impact of weevil feedings. Each plot represents the average from 10 plants; n= 40 samples from two sampling times (June 2009 and November 2009).

4.4.3 Effect of the weevil *Neochetina eicchorniae*, *N. bruchi*, mite and pathogens on the water hyacinth plants along the southern basin rivers

The water hyacinth in the Maputo, Govuro, Inharrime and Limpopo rivers were healthy, since no weevils were found on the plants, even though there were some old scars on the leaves on plants in the Maputo and Limpopo rivers (Table 4.2). Water hyacinth appeared to be in poor health in the Umbeluzi and Incomati rivers: the plants had brownish leaves, and in some places, the water hyacinth mats were mixed with grasses.

In the Limpopo River, no adult weevils were found, but there was some evidence of the presence of the weevil, such as scars on the most recently opened leaf in both periods (wet and dry seasons); very few leaves damaged by mites were recorded (Table 4.2).

Table 4.2 Assessment of water hyacinth condition in terms of mean number of weevils, larvae, pupae, mines and percentage of feeding scars and mites on the water hyacinth leaf found in southern Mozambique rivers.

River	Season	<i>N. eichhorniae</i>	<i>N. bruchi</i>	Larvae	Pupae	Mines	Scars leaf 2	Mite leaf 5 Damage
Govuro	dry (N=10)	0	0	0	0	0	0	0
	wet (N=10)	0	0	0	0	0	0	0
Maputo	dry (N=10)	0	0	0	0	0	1.6 (2.8)	0
	wet (N=10)	0	0	0	0	0	1.5 (2.7)	0
Umbeluzi	dry (N=10)	0.6 (0.5)	1.4 (0.5)	0.5 (0.5)	0.1 (0.3)	0.2 (0.4)	57.9 (12.6)	57.5 (25.9)
	wet (N=10)	1.2 (0.6)	2.5 (1.5)	0.8 (0.4)	0.1 (0.3)	0.2 (0.4)	81.7(13.9)	35.0 (18.8)
Incomati	dry (N=10)	0.3 (0.6)	0.1 (0.3)	0.3 (0.5)	0	0.1 (0.3)	47.2 (12.0)	34.0 (10.2)
	wet (N=10)	0.4 (0.5)	0.8 (0.6)	0.3 (0.4)	0	0.2 (0.4)	40.0 (13.3)	52.0 (22.1)
Limpopo	dry (N=10)	0	0	0.1 (0.3)	0	0	7.5 (8.1)	0.5 (1.5)
	wet (N=10)	0	0	0	0	0	8.2 (11.5)	0
Inharrime	dry (N=10)	0	0	0	0	0	0	0
	wet (N=10)	0	0	0	0	0	0	0

The evidence of damage caused by the weevil *N. eichhorniae* on the water hyacinth leaves was remarkable only in the Umbeluzi and Incomati rivers, as shown by the relatively higher number of scars on leaf per total number of weevils found in each plant during the two sampling occasions (Table 4.2). The number of scars per most recently opened leaf in the Maputo and Limpopo rivers was very low compared to that from Umbeluzi water hyacinth communities (Table 4.2). No *Neochetina* feeding scars on the leaf most recently opened water hyacinth plants were found in the Govuro and Inharrime rivers (Table 4.2). Applying the formula devised by Wright and Center (1984), it was calculated that the mean weevil numbers per plant was higher in the Umbeluzi and Incomati Rivers than in the other rivers (Table 4.3).

Table 4.3 Mean weevil numbers per plant in different locations in southern Mozambique rivers during dry and wet seasons. (The formula used to calculate number of adults on water hyacinth plant was $\{0.0336 \times (\text{Average number of feeding scars})^{0.775}\}$ (Wright and Center, 1984)).

Rivers	Number of adult weevils/ plant	
	Dry season	Wet season
Maputo	0.04	0.03
Umbeluzi	1.5	2.1
Incomati	1.2	1.0
Limpopo	0.1	0.2

The number of scars per most recently opened leaf varied from 0 to 98 per plant and the maximum number of *N. eichhorniae* adults per plant was two, the maximum number of *N. bruchi* per plant was six. The number of scars was the least on the most recently opened leaf in the Incomati River, varying from 40.0 and 47.2 scars per leaf, in the dry and wet seasons respectively. The maximum number of weevils per plant was two (Table 4.2). The water hyacinth plants in Umbeluzi were more damaged by the weevils than those found in the Incomati River. About 57.9 and 81.7 feeding scars were counted during dry and wet seasons respectively, and the maximum number of weevils counted per plant was seven (Table 4.2).

There was no evidence of damage caused by the moth, *Niphograptia albiguttalis*, on the water hyacinth petiole or by the mirid, *Eccritotarsus catarinensis*, on leaf 4 of any water hyacinth plants sampled during the dry and wet seasons in all sampling areas.

The *Neochetina* scars in water hyacinth plants found in the Umbeluzi, Incomati and Limpopo were associated with different pathogens, as shown in the figures below (Figure 4.9; Figure 4.10 and Figure 4.11). These pathogens associated with weevils could influence the decrease of the plant growth, decreasing the fresh weight and length of the longest leaf in the period between the dry and wet seasons.

Acremonium zonatum was found only on the Incomati water hyacinth plants, but *Orthogalumna terebrantis* and *Alternaria eichhorniae* were found on the leaves of water hyacinth in the Incomati, Umbeluzi and Limpopo rivers.



Figure 4.9 Adult feeding damage by *Neochetina spp.* and mite, *Orthogalumna terebrantis* on the leaves of *Eichhornia crassipes* in Umbeluzi River (Mozambique).



Figure 4.10 Scars of *Acremonium zonatum* on water hyacinth plants in Incomati River (Mozambique), (photographed by Julie Coetzee).

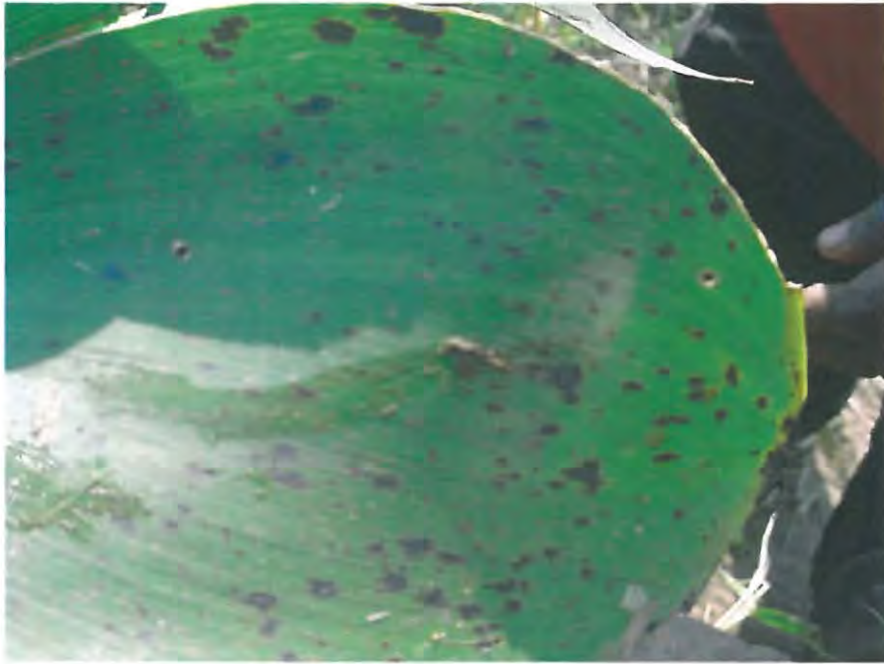


Figure 4.11 Scars of *Alternaria eichhorniae* on water hyacinth leaves in Incomati River (Mozambique).

Water quality parameters presented in Table 4.4 were used to test whether any of these variables could explain the growth of the aquatic invasive plants and whether they could influence the presence of the weevils on the plants. It was apparent that only nitrate was related to the growth of the plant. Levels of nitrate were higher in Maputo, Limpopo, Umbeluzi and Incomati rivers compared to the Govuro and Inharrime rivers. The low levels of nitrates in these last two rivers could be explained by the fact that there is less agricultural activity along these rivers.

Table 4.4 Water quality parameters during the dry season (June 2009) and wet season (November 2009) in the southern Mozambique rivers. (n=number of sampling sites on each river).

		Dry season	Govuro (n=2)	Inharrime (n=2)	Maputo (n=2)	Limpopo (n=8)	Umbeluzi (n=5)	Incomati (n=7)
Temp °C	Min.		21.3	24.3	23.2	21	16.8	23.1
	Max.		28.5	26.8	24.1	24.86	26.1	30.6
	Mean±SD		24.9±5.0	25.5±1.76	23.6±0.6	23.2±1.28	22.6±3.5	24.4±2.56
pH	Min.		7.39	7.47	7.9	7.06	7.65	6.97
	Max.		7.44	7.51	8.19	7.73	8.3	8.6
	Mean±SD		7.41±0.03	7.49±0.03	8.04±0.2	7.34±0.21	7.99±0.3	7.5±0.5
Hard mg/L	Min.		170.7	120.5	114	40	125	102
	Max.		185.3	135	119	235	623	166
	Mean±SD		177.8±10.1	127.2±10.2	116.5±5.3	94.1±5.95	229±54.2	124.3±38.6
NO₃⁻	Min.		0.18	0.1	5.91	4.67	5.34	5.24
	Max.		2.21	0.18	6.42	11.6	9.23	11.5
	Mean±SD		1.19±1.4	0.001±0.06	6.16±0.36	7.4±2.2	6.95±1.9	7.04±2.2
		Wet season	Govuro (n=2)	Inharrime (n=2)	Maputo (n=2)	Limpopo (n=8)	Umbeluzi (n=5)	Incomati (n=7)
Temp °C	Min.		-	-	24.8	21.8	24.8	26.2
	Max.		-	-	36.4	30	38.7	31.3
	Mean±SD		-	-	27.8±4.8	25.3±3.0	28.2±5.8	28.7±1.6
pH	Min.		-	-	7.2	7.24	7.2	6.66
	Max.		-	-	8.43	8.2	9.2	7.67
	Mean±SD		-	-	7.97±0.46	7.7±0.38	8.14±0.7	7.35±0.3
Hard.	Min		-	-	160	99.6	78	50
	Max.		-	-	360	212.7	360	398
	Mean±SD		-	-	202.4±88.5	137.4±33.1	188±102.7	178.6±112
NO₃⁻	Min.		-	-	1.2	32.7	-	0.5
	Max.		-	-	3.6	62.4	-	60
	Mean±SD		-	-	2.2±0.9	31.1±13.1	-	19.9±18.5

(-) indicates that no temperature, pH, hardness and nitrate data were recorded in Govuro, Inharrime and Umbeluzi these during the wet season due to lack of trained people to collect data (Information obtained by ARA-SUL)

4.5 Discussion

According to the Convention on Biological Diversity, African countries are also obliged, in terms of Article 8(h) to “prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats and species.” Since invasive species are a cross-cutting issue, all sectors of society need to become involved in managing this serious threat. It is imperative that Mozambique also seek out all available technologies to manage this insidious threat, particularly biological control, long considered one of the most effective ways of managing invasive species.

4.5.1 Biological control of *Azolla microphylla*

Azolla microphylla was found abundantly in the sampled rivers (Chapter 2) and had the greatest negative impact on human livelihoods (Chapter 3). It was very difficult to find *Stenopelmus rufinasus* on the plant. This study expected to find *S.rufinasus* in a relatively high density since it was released in South Africa as a biological control agent of the weed, but this was not the case. There are two reasons for the absence or near absence of *S. rufinasus* in the river studied: firstly, the manual and mechanical methods that are used in the southern Mozambique rivers tend to reduce the herbivores’ density. Secondly, *Azolla mycrophylla* is not the natural host of *S. rufinasus*, and it did not suit the weevil, which was never deliberately introduced into Mozambique. The feeding by *S. rufinasus* on *A. mycrophylla* is considered to be spill-over feeding and it is unlikely that the weevil can maintain a population on *A. mycrophylla* in the absence of its preferred host, *A.filiculloides* (Hill and Madeira, 2011).

4.5.2 Biological control of *Pistia stratiotes*

Surveys in this study showed that the weevil *Neohydronomus affinis* was found in the rivers studied but at a very low density, too low to effectively control *Pistia stratiotes*. The weevil was not introduced in Mozambique, but it is found in many rivers that are located upstream of Mozambique’s rivers. Successful biological control of *Pistia stratiotes* was recorded in Zimbabwe (Chikwenhere and Keswani, 1997), South Africa (Coetzee *et al.*, 2011) and in Benin where the impact of *N. affinis* was monitored for seven years and the total collapse of the water

lettuce biomass was documented (Ajuonu and Neuenschwander, 2003, De Groote *et al.*, 2003; Ajuonu *et al.*, 2009). Since the weevils are beginning to appear at water lettuce infestations where they have not been released in Mozambique, it means that they can spread without human intervention. Therefore, the possibility that *N. affinis* will become established throughout Mozambique and will prove to be invaluable in controlling the problematic *P. stratiotes* is regarded with optimism. Further efforts to release *N. affinis* at other sites should be undertaken to reduce the time required to establish *N. affinis* populations throughout Mozambique.

4.5.3 Biological control of *Salvinia molesta*

Salvinia molesta was abundant in two rivers in the southern Mozambique rivers and no *Cyrtobagous salviniae* was found along the studied rivers. There are several possible reasons for the absence of the weevil, *C. salviniae*, during the study period: low density of *S. molesta*; mechanical and manual control of *S. molesta*, because this removes the weevils; and the effective control of the weed in neighbouring countries. *Cyrtobagous salviniae* is a poor disperser and needs to be introduced in Mozambique.

4.5.4 Water hyacinth growth in the southern Mozambique rivers

4.5.4.1 Growth variation of water hyacinth between the studied rivers

Water hyacinth population varied between the wet and dry season and the sizes of the plants varied between rivers. The growth of water hyacinth correlated with the availability of nutrients in the rivers. Low levels of nutrients (nitrate) were found in the Govuro, Inharrime and Maputo rivers, not reaching a maximum level of 10 ml/L at any time of the year, unlike the remaining rivers that had more than 10ml/ L during the wet season. Higher levels of nitrate were found in the Limpopo and Incomati rivers, with maximum ranges of 62.4 mg/L and 19.1mg/L respectively, during the wet seasons. These could explain why the water hyacinth plants showed longest leaf and highest fresh weight in these rivers. Results reported in studies by Coetzee *et al.* (2007); Ripley *et al.* (2006); Xie *et al.* (2004); Heard and Winterton (2000) Reddy *et al.* (1999) showed that manipulating water nitrate and/or phosphate levels had significant effects on water

hyacinth, namely attaining higher biomass, longer petioles, and higher numbers of daughter plants and leaves.

This study anticipated a change in root length and the length of longest leaf in the Umbeluzi and Incomati rivers during the study period (from dry to wet season), since the growth responds to an increase of nutrients in water. However, it was noted that the root growth and length of the longest leaf did not increase between the dry and wet seasons. Neither did root length change significantly in any of the rivers studied. Xie *et al.* (2004) made a similar observation: they explained the fact that, in their trials, root lengths did not change over time was not unexpected, since water hyacinth root growth responds to water chemistry. Coetzee *et al.* (2007) stated that the large variations observed in root lengths could be due to the relatively small sample size.

Statistical analysis showed that the length of longest leaf and fresh weight of water hyacinth in Govuro, Inarrime and Maputo Rivers increased significantly from dry to wet season. This could be explained by the absence of weevils in the water hyacinth in these rivers.

In this study the only parameter that was not affected by the level of nutrients in the water was the number of daughter plants (ramets), flowers and leaves. Different levels of nutrients did not significantly affect the number of leaves produced by plants in either the dry or wet season. However, Wilson *et al.* (2006) noted that leaf production was affected by interaction among nutrients, the level of nutrients and time of exposure. They explained that plants in water containing higher levels of nutrients produced roughly twice the number of leaves as plants in water with low levels of nutrients.

4.5.4.2 Biological control agents recorded on water hyacinth plants in Mozambique

In Mozambique, two arthropods fed on water-hyacinth plants, namely *Neochetina eichhorniae* and *N. bruchi*, and they varied from site to site; the number of feeding scars indicated that *Neochetina* insects and mites were feeding on the plants. Although this study was not designed to determine the relative efficacy of the arthropods that feed on water hyacinth, observations of the

amount of feeding damage and the sheer number of individuals suggest that the water hyacinth weevils, *Neochetina eichhorniae* and *N.bruchi*, would be damaging hyacinth.

It is known that the weevils are more active during summer than winter. The number of weevils per plant showed that the number of weevils was different in different rivers (Maputo, Umbeluzi, Limpopo and Incomati) but those numbers did not show significant seasonal differences. The number of feeding scars per the most recently opened leaf in some rivers, for example in the Umbeluzi River, peaked in the dry season, but peaked in the wet season in the Incomati River. This could be explained because temperatures in Mozambique vary so little throughout the year; therefore temperature is not a good parameter for measuring the growth of the plants.

The number of *Neochetina eichhorniae*, *N. bruchi* feeding scars on the most recently opened water hyacinth leaf was significantly higher in the Umbeluzi and Incomati rivers compared to the Maputo and Limpopo rivers. A higher number of feeding scars was found in the Umbeluzi and Incomati rivers where a higher level of nutrients (nitrate) was measured. This study confirms analyses by Heard and Winterton (2000) who observed the population growth rate of weevils is faster at higher nutrient concentrations. Coetzee *et al.* (2007) noted in their trials, that the temporal development of the growth parameters shows a gradual decline in growth of weeds in the medium and low nutrient treatments, even in the absence of herbivores.

Orthogalumna terebrantis and *Alternaria eichhorniae* were found associated with the weevils in the Umbeluzi and Incomati rivers, but *Acremonium zonatum* was found only in the Incomati River.

The numbers of weevils in both rivers were not enough to effectively control the weeds. Aguilar *et al.* (2003) reported that the density of adult weevils required to attain control was about six weevils per plant, based on their observations in the field. Ogwang and Malo (2003) reported an effective number of weevils to control growth of water hyacinth plants was 17.4 weevils per plant in Lake Kyoga, and 25 weevils per plant at Lake Victoria. In the Umbeluzi and Incomati rivers, the *Neochetina* spp. feeding scars in the water hyacinth population varied from 0 to 98 scars per leaf. This number is not significant compared to that found by Ajuonu *et al.* (2003).

Based on their observations in the field two to three years after the release of *Neochetina* spp in Benin, the highest average number of feeding scars reached 250 per leaf, but most stayed between 25 and 150.

In Mozambique where the weevils were combined with pathogens, the plants were more damaged. This study confirms observations by Martínéz and Balandra (2007) who noted that the combined action of insects, plant pathogens, weather conditions, as well as the phenological stage of *E.crassipes*' growth cycle, together contributed to dramatic reduction of the weed.

However, to improve the effectiveness of biological control in Mozambique, it is necessary to introduce higher numbers of of *Neochetina* spp. and also to introduce new biological control species such as the mirid *Ecrcritotarsus catarinensis*; the grasshopper, *Cornops aquaticum*, and *Megamelus scutellaris*.

4.6 Conclusion

This study will serve as a baseline of biological control of aquatic weeds in southern Mozambique rivers and should be added to over time. For biological control methods to be effective, it is recommended that the number of biological control agents in the weeds be increased and monitored further.

Studies on biodiversity recovery following management of the invasive aquatic weed *Pistia stratiotes* L. (Araceae) in pools

5.1 Introduction

Invasive aquatic weeds change the composition of aquatic biodiversity assemblages (Michelan *et al.*, 2010; Midgley *et al.*, 2006; Mack *et al.*, 2000). A change in invertebrate assemblages, including the macro-invertebrate assemblages, can directly and indirectly affect the rest of the food web, causing ecological and economic change. Aquatic invertebrates are primarily affected by the structure of the macrophyte community (Meerhoff *et al.*, 2006; Masifwa *et al.*, 2001), turbulence, light intensity, temperature, food availability (Maceina *et al.*, 1992; Richards *et al.*, 1985), and dissolved oxygen (Kiorboe and Saiz, 1995).

The impact of aquatic weeds on biodiversity has seldom been quantified (Chapter 3), but the few studies that have been published have shown it to be significant (Midgley *et al.*, 2006). Biological control is said to offer the most sustainable control option for aquatic weeds (Cilliers *et al.*, 2003) but it, too, has seldom been quantified (Chapter 4). In order to assess the effectiveness of biological control, standard measures such as individual plant measures (height, biomass, number of ramets (Chapter 4) and population (percentage cover)) are recorded, but for any weed control methods to be completely successful, indigenous biodiversity should recover post-control, and this aspect has not been studied.

Although biological control of aquatic weeds has been successful throughout the world (Coetzee *et al.*, 2009), there are some proponents of herbicide application because control is rapid (Van Wyk and Van Wilgen, 2002). However the benefit of an immediate control intervention might be offset by the negative effects of a rapidly sinking mat of biomass after control. These impacts have not been investigated, but are addressed here.

Biodiversity measures have been widely used as indicators of ecosystem status, and play a critical role in assessing human impacts on ecological systems (Leitner and Turner, 2001).

However, because the biodiversity of any ecosystem is too complex to be comprehensively quantified, suitable indicators of biodiversity are needed (Duelli and Obrist, 2003). Practically, species richness, such as the number of species present in a spatially and temporally homogeneous community, seems the most intuitive and direct parameter to measure biodiversity (Gotelli and Colwell, 2001). However, determining the true richness of a community is not a simple task (Magurran, 2004). For example, it is known that the number of observed species increases with sampling effort. As a result, to obtain an accurate measurement of the true richness in a biological community, sampling should provide an exhaustive and complete inventory.

Estimators of species richness attempt to determine the number of species of a certain biological community from an incomplete survey (O'Hara, 2005; Leitner and Turner, 2001). Of the large number of methods proposed for estimating richness in a local community, one of the most important is the extrapolation of species accumulation curves as a function of sampling effort, where total richness is considered as the number of species that would be found with a hypothetical infinite sampling effort. Estimating the number of still unreported species after computing species-abundance distributions, and using non-parametric estimators based on the prevalence of rare species allows the estimation of the number of unreported species that could be added to the list of those already discovered (Chao, 2005; Leitner and Turner, 2001). Non-parametric estimators have been considered the most significant advance in biodiversity measurement in more than a decade (Magurran, 2004).

In aquatic ecosystems, biodiversity can be reduced and conservation value affected when they are colonized by weeds such as *E. crassipes*, *S. molesta* and *P. stratiotes*. A dense cover of aquatic weeds drastically reduces and may prevent light penetrating of the water. Without light, phytoplankton and submerged plants cannot photosynthesize (Mironga *et al.*, 2011); oxygen levels decrease and carbon dioxide increases, with catastrophic effects on the aquatic fauna (Howard and Harley, 1998). The uptake of nitrogen and other nutrients by aquatic weeds may affect normal nutrient cycling by native plants, for example papyrus, and mineral elements will probably be immobilized (Howard and Harley, 1998).

Mats of the aquatic weeds can be controlled using manual removal when the infested area is small but herbicide application is a quicker solution although it raises concerns about changes in water quality. Although biological control takes longer, it is a safe method and is a “long-term solution”.

Herbicides sprayed onto surface waters (from spray-drift or run-off) can alter the species composition of aquatic communities and affect fish and invertebrates. Public opinion all over the world is against the use of herbicides in water bodies, but the use of herbicides seems to be unavoidable in certain circumstances and, if they are used properly and with caution, environmental problems can be avoided. Among the herbicides, glyphosate is one of the safest for use in water, but the cost of application is prohibitive in some countries. In order to avoid eutrophication caused by decaying plant mass, any herbicides should be applied in specific infested sites but never over the whole infested area (Hill *et al.*, 2012). Herbicidal control usually conflicts with biological control by killing the weed, which results in extermination of the biocontrol agent (Cilliers, 1991) with subsequent resurgence of the weed from seeds or untreated plants. In contrast, as biological control acts slowly (two to five years), the gradual reduction in weeds results in far less rapid decay and less impact on the water quality. In many situations, management of the weed requires an integrated approach that can include careful herbicide application, with a minimal impact on the biocontrol agents and the environment (Center *et al.*, 1999).

In the past, several researchers have shown that aquatic weeds negatively impact benthic biodiversity (e.g. Mironga *et al.*, 2011; Perna and Burrows, 2005; Mangas-Ramirez and Elias-Gutierrez, 2004; Rommens *et al.*, 2003; Masifwa *et al.*, 2001), but no studies have measured biodiversity recovery after control, so, the main aim of this experiment was to evaluate the impact of *Pistia stratiotes* on macro-invertebrate biodiversity and to quantify macro-invertebrate recovery once *P. stratiotes* had been controlled with a herbicide or biological control.

5.2 Materials and Methods

The experimental set-up for the study included four treatments: a pool with no *Pistia stratiotes*, a *P. stratiotes* pool, *P. stratiotes* treated with the biological control agent *Neohydronomus affinis*,

and *P. stratiotes* treated with herbicide. The effect of these treatments on biodiversity was measured over a period of 12 months. Each treatment was replicated three times.

The study was conducted outside the greenhouse at Rhodes University (Grahamstown). The experimental design comprised 12 pools of 265 cm x 67.5 cm. One bag of artificial substrate was placed in each pool. The sample bags, each containing around 90 pebbles (artificial substrate), were left for six weeks in each experimental situation, the time required for complete colonisation by invertebrates (Thirion, 2000). This was repeated between December 2010 and December 2011. The bags were collected every six weeks and separated according to the pool and treatment. To prevent loss of organisms, the macro-invertebrates attached to the pebbles were put in a sieve, washed in water and preserved in plastic flasks in 70% ethanol. The organisms from each plastic flask were sorted in the laboratory and identified to family level. The biodiversity of each pool was analysed using a Shannon-Winner Diversity Index, Richness (d) and Abundance evenness (J').

5.2.1 Weed control treatments

Approximately 1 500 water lettuce plants were put in each pool and later, a total of 750 *Neohydronomus affinis* weevils were collected on water lettuce plants in the tunnel at Rhodes University, Grahamstown, and distributed in three pools (250 weevils per pool). The stocking density was one weevil for every six water lettuce plants.

5.2.2 Herbicide treatments and water chemistry

The herbicide used was Roundup[®] (glyphosate 3%, as recommended) and was sprayed using a standard knapsack sprayer on three occasions. Three pools (controlled by herbicide) were sprayed twice in March and once in April at weekly intervals to guarantee killing all water lettuce plants in the pools controlled by herbicide.

Water chemistry data were collected from all the pools three times, in April, July and October 2011. Water temperature and dissolved oxygen were measured using a portable YSI 550A Multi-

parameter probe directly in the pools. This study sought to examine how the presence of water lettuce and herbicide influence the physical and chemical proprieties of water of each pool. From each of the four treatments, namely under cover of water lettuce, water lettuce controlled by weevils, water lettuce controlled by herbicide, and open water (without water lettuce (see below)), separate water samples were collected in a 250 ml water bottle (one bottle per pool) on three sampling occasions (April, July and October) and were analysed in the laboratory. Nitrate and phosphate were analysed as parameters of water quality, using a Filterphotometer.

5.2.3 Experimental design

The experimental design consisted of 12 large plastic pools, each one stocked with artificial substrates (25 cm x 50 cm bag of about 90 pebbles), similar to those used by Thirion (2000).

Three Steps were undertaken in this experiment (Figure 5.1).

Step 1. The substrates placed in all twelve pools (O) were evaluated after six weeks for macro-invertebrate colonization on only one occasion (Figure 5.1, Step 1). The purpose of this stage was to test how quickly the micro-invertebrates colonize substrates.

Step 2. In this step, nine pools were each 100% covered with *P. stratiotes* (about 1 500 *P. stratiotes* plants per pool) and three remained as uncovered controls (Figure 5.1, Step 2). This stage was used to test the impact of the weeds (water lettuce) on the colonization of macro-invertebrates. After six weeks, and on only one occasion, the artificial substrates were removed and evaluated for macro-invertebrates colonization.

Step 3. In this step, the pools were randomly selected and the experiment was replicated by replacing the artificial substrates in the original pools as follows: three pools colonized by water lettuce (W); three other pools were then each treated with about 250 adult weevil *Neohydronomus affinis* (N); three other pools were treated with herbicide, a glyphosate formulation at the recommended concentration of 3% (H); and finally, three more pools remained open or uncovered as a control (without *P. stratiotes*) (O). The artificial substrates

were removed and evaluated every six weeks during six sampling events over 36 weeks (Figure 5.1, Step 3).

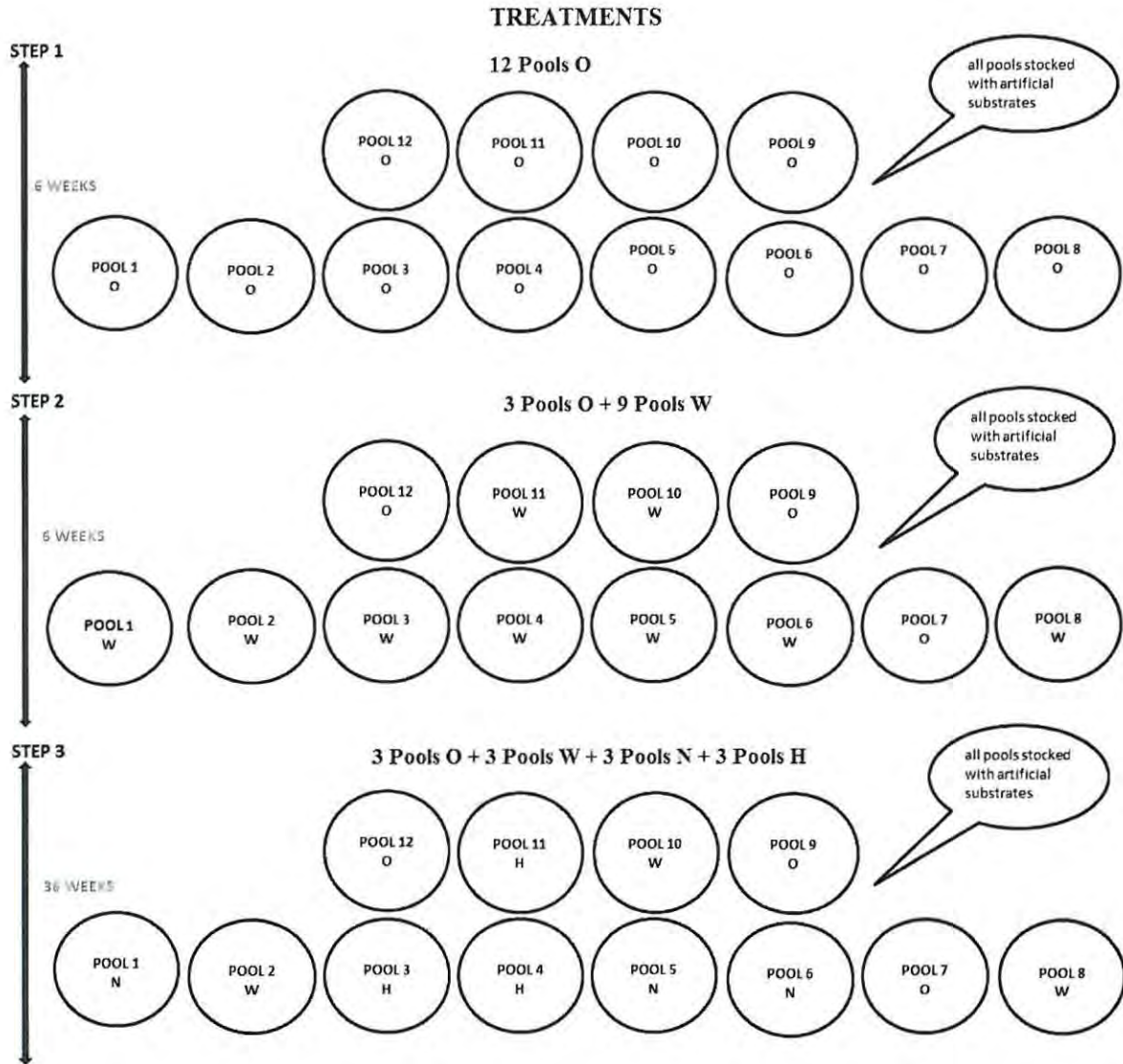


Figure 5.1 Flow chart of the experimental design for the experiment. Step 1, 2, and 3. The O, W, N and H refers to: open water pools (O), water lettuce pools without control (W), water lettuce pools controlled by weevils (*Neohydronomus affinis*) (N), water lettuce pools controlled by the herbicide glyphosate (H).

5.3 Statistical analyses

Specimens were identified to family as good keys to this level are available for aquatic invertebrates in South Africa. The recorded data were analyzed statistically using the Non-Parametric Test (Kruskal-Wallis test) to see if there were any significant differences in the mean of % cover, dissolved oxygen, temperature, nitrate, phosphate, mean number of individuals and mean number of families.

5.3.1 Biodiversity indices

In this study, five measures of diversity were used: total number of individuals (N); total number of taxa; richness (d); abundance evenness (J') and Shannon-Wiener diversity index (H). The following practice was taken into account to calculate richness, abundance and Shannon-Wiener index.

Richness (d)

Magurran (2004) suggests that there are two main methods of expressing estimates for species richness: numerical richness and diversity. However, the real challenges in biodiversity assessment concern poorly documented (usually invertebrate) taxa.

Abundance evenness (J')

As a heterogeneity measure, the Shannon-Wiener index takes into account the degree of evenness in abundance of the taxa. The ratio of observed diversity to maximum diversity can be used to measure evenness, where $(J')=H'_{\max}=H'/\ln S$.

The Shannon-Wiener index (H')

Shannon-Wiener assumes that individuals are randomly sampled from an infinitely large community and that all taxa are represented in the sample (Magurran, 2004). The Shannon-Wiener index is calculated by $-\sum p_i \ln(p_i)$.

5.3.2 South African Scoring System version 5 (SASS5)

The SASS version 5 is a rapid bio-assessment method used to determine the condition of an aquatic system. Aquatic macro-invertebrates are recognized as valuable organisms for bioassessments, because of their visibility, ease of identification, rapid life cycle and sedentary habits (Dickens and Graham, 2002). In this study, scores of the SASS5 were compared to the macro-invertebrates scores obtained in open water pools, water lettuce pools without control, three water lettuce pools controlled by weevils, and three water lettuce pools controlled by the herbicide. Indirectly, this provided another measure of water quality.

5.3.3 Determination of accumulation curve

In order to determine if sufficient sampling was undertaken, three based accumulation curves were compiled using the analytically calculated S_{obs} (Mao Tao) (number of taxa expected) for each collecting method to establish the sampling representivity Estimate S V 8.2.0 (Colwell, 2005). Both the Michaelis-Menten Mean (MMMean) estimator (Toti *et al.*, 2000) and the incidence-based coverage estimator (ICE) were used to evaluate sample size adequacy (Chazdon *et al.*, 1998).

5.3.4 Community analyses

Multivariate data analyses were employed to examine the taxon abundance and sampling period data using the PRIMER 6.1 software package (Clarke and Gorley, 2006; Clark and Warwick, 1994).

A cluster analysis plot and non-metric multi-dimensional scaling (MDS) ordination plot were constructed from a similarity matrix to examine the relationship between communities beneath water lettuce mats (W), those in water lettuce mats controlled by weevil (N), those in water lettuce mats controlled by herbicide (H), and those in open water (O). The process involved the production of a similarity matrix (Bray-Curtis coefficient and a double fourth root abundance data transformation). Differences in the community structure among treatment levels were illustrated with non-metric multi-dimensional scaling (MDS) on the basis of Bray-Curtis

dissimilarities of transformed data. Similarity Percentage Analysis (SIMPER) (Clarke, 1993) was used to identify the percentage contribution of each taxon to any observed differences between communities. The technique uses a Bray Curtis similarity algorithm (Clarke and Warwick, 2001). The resulting plot, known as an ordination, shows the distribution of sites and samples to each other. Sites with similar assemblages are located close together in the ordination plot. Data from all samples were subject to a Bray-Curtis dissimilarity to obtain a matrix used in the MDS.

When a group of sites was clearly evident in the ordinations, it was tested using a one-way Analysis of Similarity (ANOSIM) to determine the significance of the similarity/dissimilarity within and across the groups. Similarity percentages (SIMPER) from Bray-Curtis measures were used to determine the contribution of macro-invertebrates accounting for the similarity within or the dissimilarity between the groups observed in the ordination. Then, on the groups identified by the MDS, the SIMPER programme of PRIMER was run to calculate the Bray-Curtis similarity of each group and the dissimilarity between groups. This analysis identified those species contributing the most to the similarity or dissimilarity. The number of taxa shared by each group with each of the other groups was calculated.

5.3.5 Canonical correspondence analysis (CCA)

CCA is a multivariate statistical analysis used to elucidate the relationships between biological communities and their environment (Ter Braak and Verdonschot, 1995). CCA is frequently used to determine which environmental variable(s) is/are important in structuring the biological community. In this study, CCA was applied to elucidate the relationship between macro-invertebrate community assemblage, the measured chemical water quality variables, and water lettuce % cover, with a view to determining the important variables responsible for the observed spatial and temporal distribution of the macro-invertebrate community. CCA and cluster analysis were performed using the computer programme Environment Community Analysis 1.33 package (ECOM) (Pisces Conservation Ltd, 2000).

5.4 Results

5.4.1 Macro-invertebrates recruitment in 12 open water pools (O) in the 1st sampling occasion (Step 1)

When macro-invertebrates were recorded after six weeks in the artificial substrates stocked in the 12 open-water pools (O), a high diversity and abundance of aquatic invertebrates had colonised the substrate. A total of 1 149 individuals in 11 taxa were identified to family level (Figure 5.2) with the dominant taxon being the Chironomidae (86%), followed by Baetidae (6%) and Libellulidae (3%). The remaining 5% consisted of Ceratopogonidae, Baetidae, Pleidae, Caenidae, Dryophidae, Dytiscidae, Gomphidae, Corixidae and Coenagrionidae.

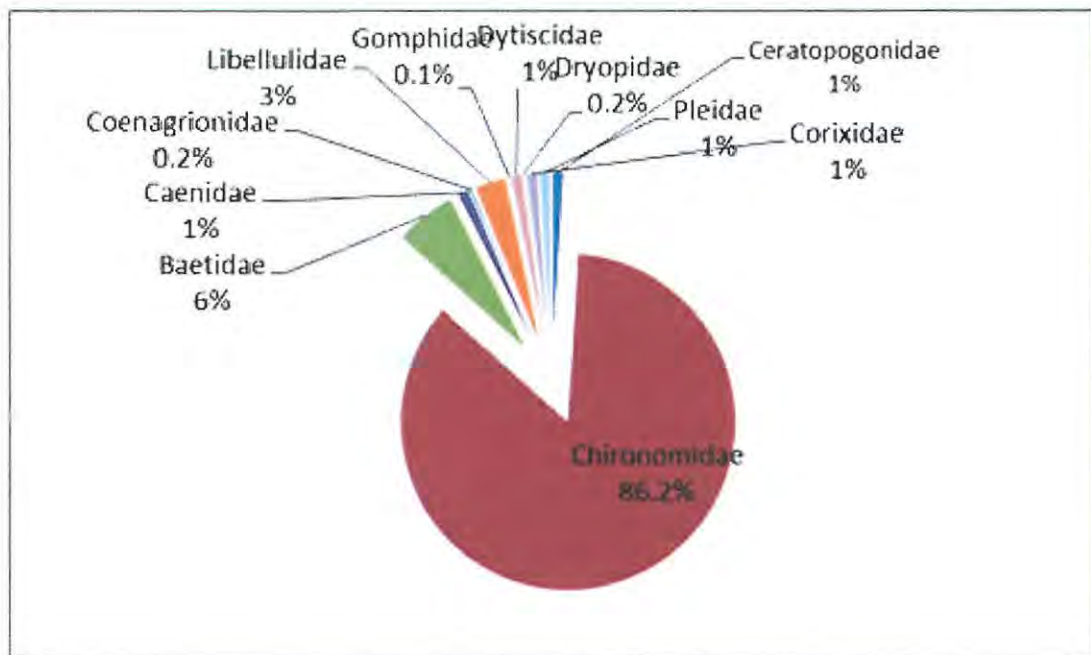


Figure 5.2 Percentage of the macro-invertebrates sampled in 12 open pools (O) after six weeks in the first step of the experiment.

5.4.2 Macro-invertebrate recruitment in three open water pools (O) and nine pools with *Pistia stratiotes* (W) in the 2nd sampling occasion (Step 2)

In the second step, macro-invertebrates were recruited in the three pools with open water (O), (no infestation by *Pistia stratiotes*). An increase in number of macro-invertebrates occurred between the first sampling occasion and the second sampling occasion, but on both occasions the numbers of taxa remained the same. A total of 7 810 individuals in nine taxa were identified to family level. The dominant taxa were Chironomidae (89%) followed by Ceratopogonidae (6.9%) and Baetidae (2%), (Figure 5.3). Unexpected in this study was the absence of macro-invertebrates in the nine pools covered by *Pistia stratiotes*; it is possible that the once-off insecticide application to the surface of water lettuce plants might have deterred adult insects from laying eggs. This effect had disappeared by the third sampling event.

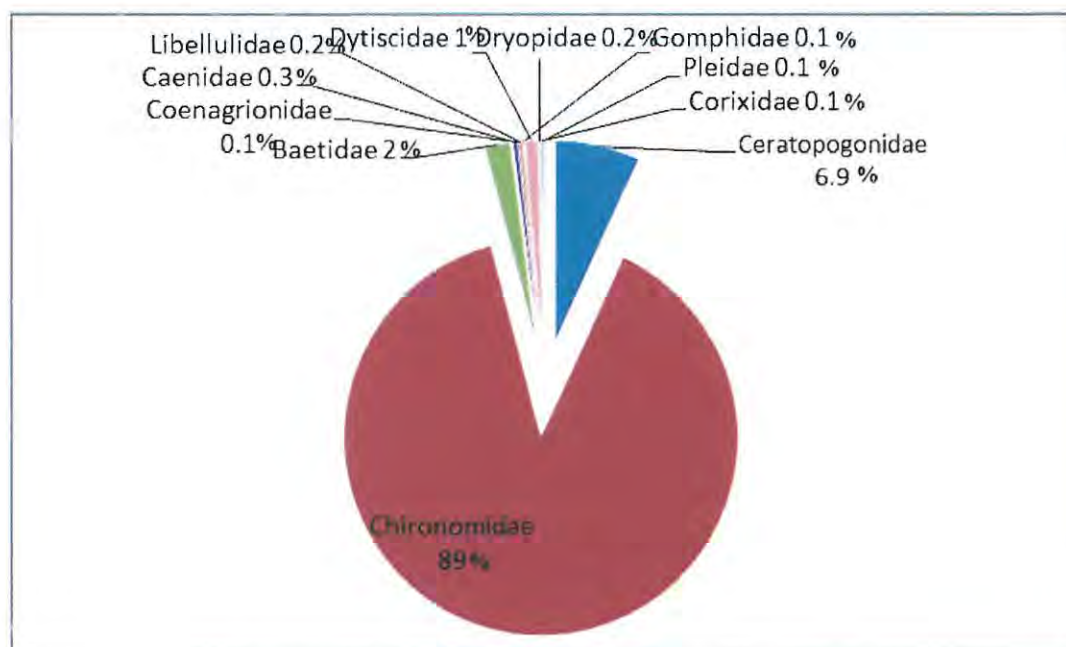
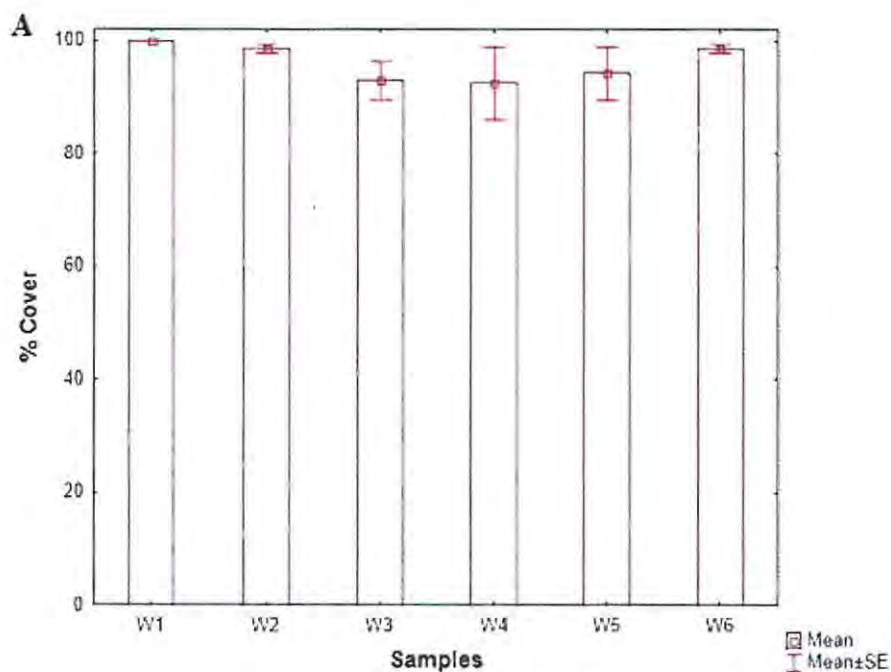


Figure 5.3 Percentage of the macro-invertebrates sampled in three open pools (O) after six weeks in the second step of the experiment.

5.4.3 Effect of biological control and herbicide application on percentage cover (% cover) of water lettuce mats during the study period (Step 3)

Using weevils and herbicide as controls reduced the percentage cover (% cover) of water lettuce in the pools. In the pools with water lettuce (W) and with no control, only a slight reduction of water lettuce was observed during the study period, probably due to seasonality (Figure 5.4 A). No significant difference in the mean of percentage cover of water lettuce treatment (W) was observed during the study period (KW-H(5, 18)=6.375, $p>0.271$). The weevils reduced the water lettuce mats by an average of 30% (Figure 5.4 B) and this was significant (KW-H(5,18)=14.709, $p< 0.01$).

The herbicide treatment had a significant impact on the percentage cover of water lettuce. Cover was reduced by 55% by the first sampling event (six weeks after herbicide application) and by 100% by the fourth sampling event (Figure 5.4 C). This difference was significant (KW-H (5,18)=16.284, $p<0.006$).



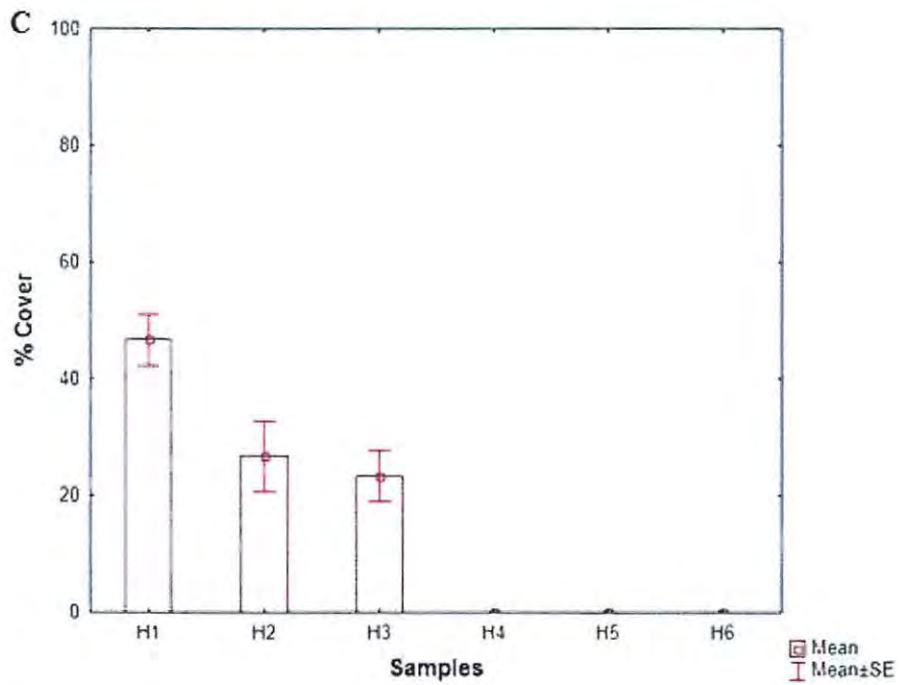
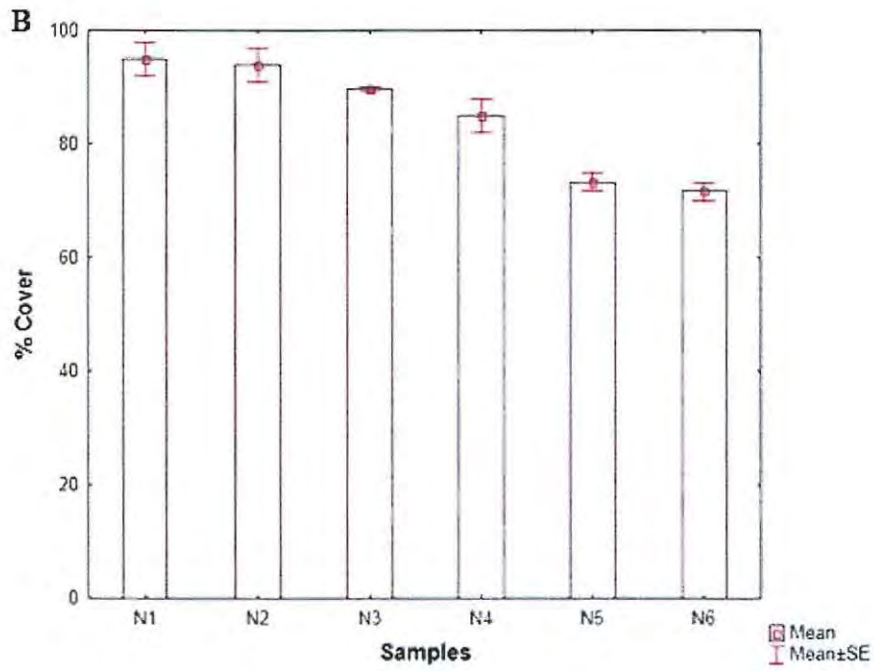


Figure 5.4 A. B and **C** Mean percentage cover of water lettuce mats in water lettuce pools (W); water lettuce controlled by *Neohydronomus affinis* (N) and water lettuce mats controlled by herbicide (H) during the six sampling occasions.

5.4.4 Effect of water lettuce mats in dissolved oxygen (DO) level in different treatments during the study period (Step 3)

A slight decrease in the percentage cover of water lettuce mats (W) without control did not decrease the dissolved oxygen amount measured in this treatment (W (KW-H(2,9)=4.502,p>0.105) (Figure 5.5). In the open water pools, a slight variation in dissolved oxygen concentration was observed but no significant differences were observed during the study period (KW-H(2,9) = 0.371,p>0.8307) (Figure 5.5).

During the study period, a significant decrease in the amount of dissolved oxygen in the water lettuce mats controlled by *Neohydronomus affinis* was observed, (KW-H(2,9)=7.2, p<0.0273). The water lettuce mats controlled by herbicide showed an increase in dissolved oxygen over time (KW-H(2,9)=7.2, p=0.0273) as the mat initially decayed and was then replaced with open water (Figure 5.5).

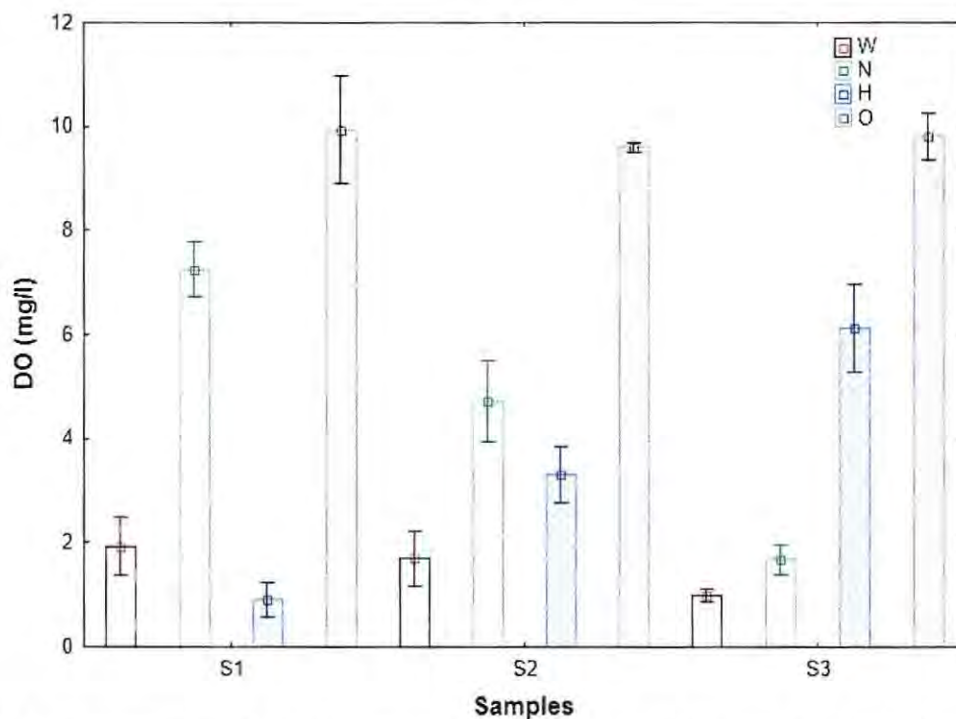


Figure 5.5 Measurement of the dissolved oxygen in the water lettuce mats in water lettuce pools (W), water lettuce controlled by *Neohydronomus affinis* (N), water lettuce mats controlled by herbicide (H) and in open pools (O) on the three sampling occasions.

5.4.5 Nitrate, phosphate, and temperature measurement during the study period in the water lettuce mats in water lettuce pools (W), water lettuce controlled by *Neohydronommus affins* (N), water lettuce mats controlled by herbicide (H) and in open pools (O) on three sampling occasions (Step 3)

There were no significant differences in nitrate and phosphate during the study period in the different treatments. Water temperature followed a similar pattern in all treatments (Figure 5.6): the temperature was higher on the first sampling occasion (between 18 °C and 20 °C in February), decreasing in temperature to the third sampling occasion in July (winter) 8 °C to 9 °C and increasing by September, (spring) 14 °C to 16°C.

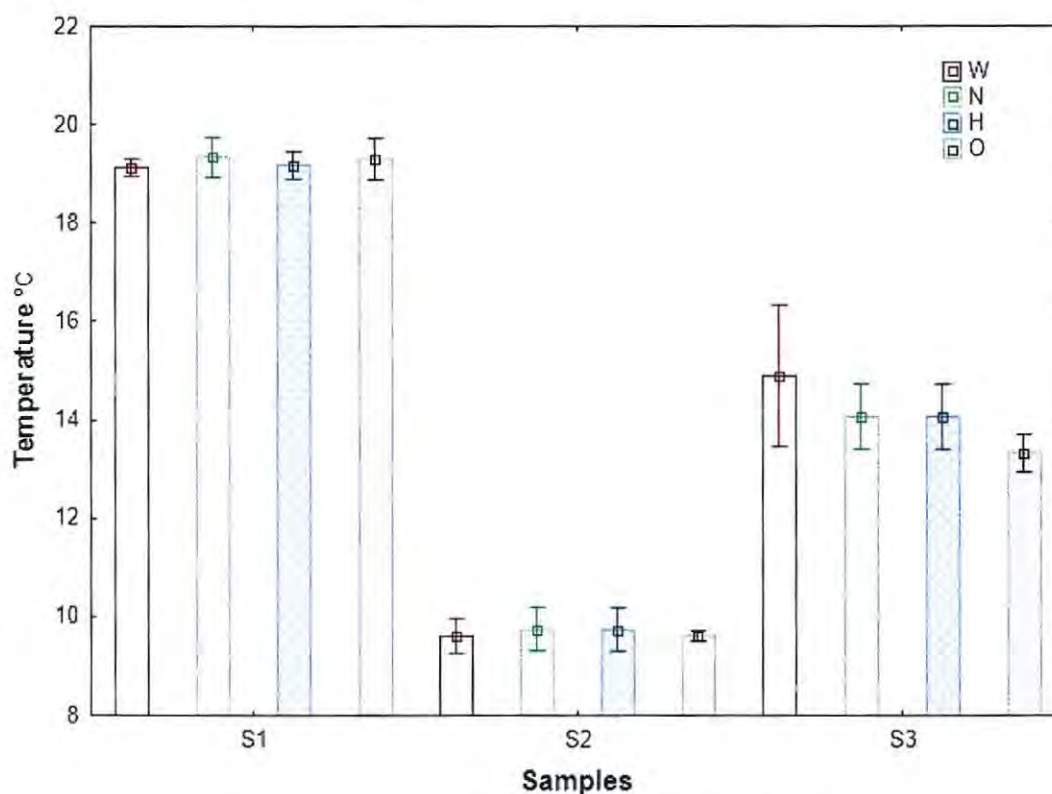


Figure 5.6 Measurement of water temperature in the water lettuce mats in water lettuce pools (W), water lettuce controlled by *Neohydronommus affins* (N), water lettuce controlled by herbicide (H) and in open pools (O) in three sampling occasions.

5.4.6 Comparison of number of taxon between water lettuce mats (W), water lettuce mats controlled by biological control weevils *Neohydronomus affinis* (N), water lettuce mats controlled by herbicide (H) and open water (O) sites during six sampling occasions (Step 3)

A total of 16 taxa comprising 14 415 individuals were recorded during a period of 36 weeks from April 2011 to December 2011. Of the individuals collected, 245 were collected from water lettuce mat pools (W), 1 005 collected from water lettuce mats controlled by the biological control agent *Neohydronomus affinis* (N), 4 145 collected from water lettuce mats sprayed with herbicide (H), and 9 020 collected from the open water (O). More taxa were collected from open water (16) and fewer taxa were collected in the water lettuce mats (6). In water lettuce within *N. affinis* and water lettuce with herbicide, 15 taxa were collected in each treatment.

During the study period, the mean number of individuals (Figure 5.7 A) and mean number of taxon (Figure 5.7 B) per pool were not distributed uniformly. There was no significant difference in the mean number of individual macro-invertebrates in the in open water pools (O): (KW-H(5,18) = 6.6435, $p > 0.248$) and water lettuce pools controlled by herbicide (H): (KW-H(5,18) = 9.2339, $p > 0.100$) were observed. Significant differences were observed only in the mean number of water lettuce pools, without control (W): (KW-H(5,18) = 12.428, $p < 0.02$) and water lettuce pools controlled by weevils (N): KW-H(5,18) = 14.029, $p < 0.01$).

The mean number of individuals was higher in the water lettuce controlled by weevils (N) and open water pools (O) during the three first sampling periods, when compared to water lettuce without control (W) and water lettuce controlled by herbicide (H). A possible explanation is that, at that time, the dissolved oxygen was higher in these pools (N and O) when compared to the other treatments (W and H) (Figure 5.5).

In the water lettuce mats controlled by weevils (N), the mean number of individuals decreased after the third sampling occasion (Figure 5.7 A). This could be explained by a decrease in dissolved oxygen. The water lettuce mats controlled by herbicide showed an increase in the mean of macro-invertebrate individuals and family after the third sampling event (Figure 5.7 A and B) coupled to an increase in dissolved oxygen (Figure 5.5) as the pools were free from water lettuce

mats because of the herbicide treatment (Figure 5.8 C). One danger with herbicide is oxygen depletion after the treatment (herbicide application) caused by the decomposition of the dead plant material. Oxygen depletions probably killed the macro-invertebrates in the pools. In the water lettuce pools without control (W), the dissolved oxygen levels remained low and as a result these pools showed low macro-invertebrate recruitment (Figure 5.5). In the open water, the mean number of macro-invertebrate individuals and mean number of families was much higher when compared to the other treatments, namely water lettuce with no control (W), water lettuce controlled by weevils (N) and water lettuce controlled by herbicide (H). The mean number of macro-invertebrate taxon was lower in the water lettuce mats without control (W) compared to the other treatments (O, N and H) (Figure 5.4 A. B). This means that the recruitment of individuals and macro-invertebrate taxon was influenced by the area covered by water lettuce (% cover) (Figure 5.8 A.B and C).

Figure 5.7 B shows that during the study period, there was some variation in the mean number of families in the different treatments (W, N, H and O) but this was not significant (O): (KW-H(5,18) = 4.845, $p > 0.4350$); (H): (KW-H(5,18) = 10.6859, $p > 0.491$); (W): (KW-H(5,18) = 8.7723, $p > 0.1185$) and (N): (KW-H(5,18) = 4.6131, $p > 0.449$) most probably due to the high variability within samples.

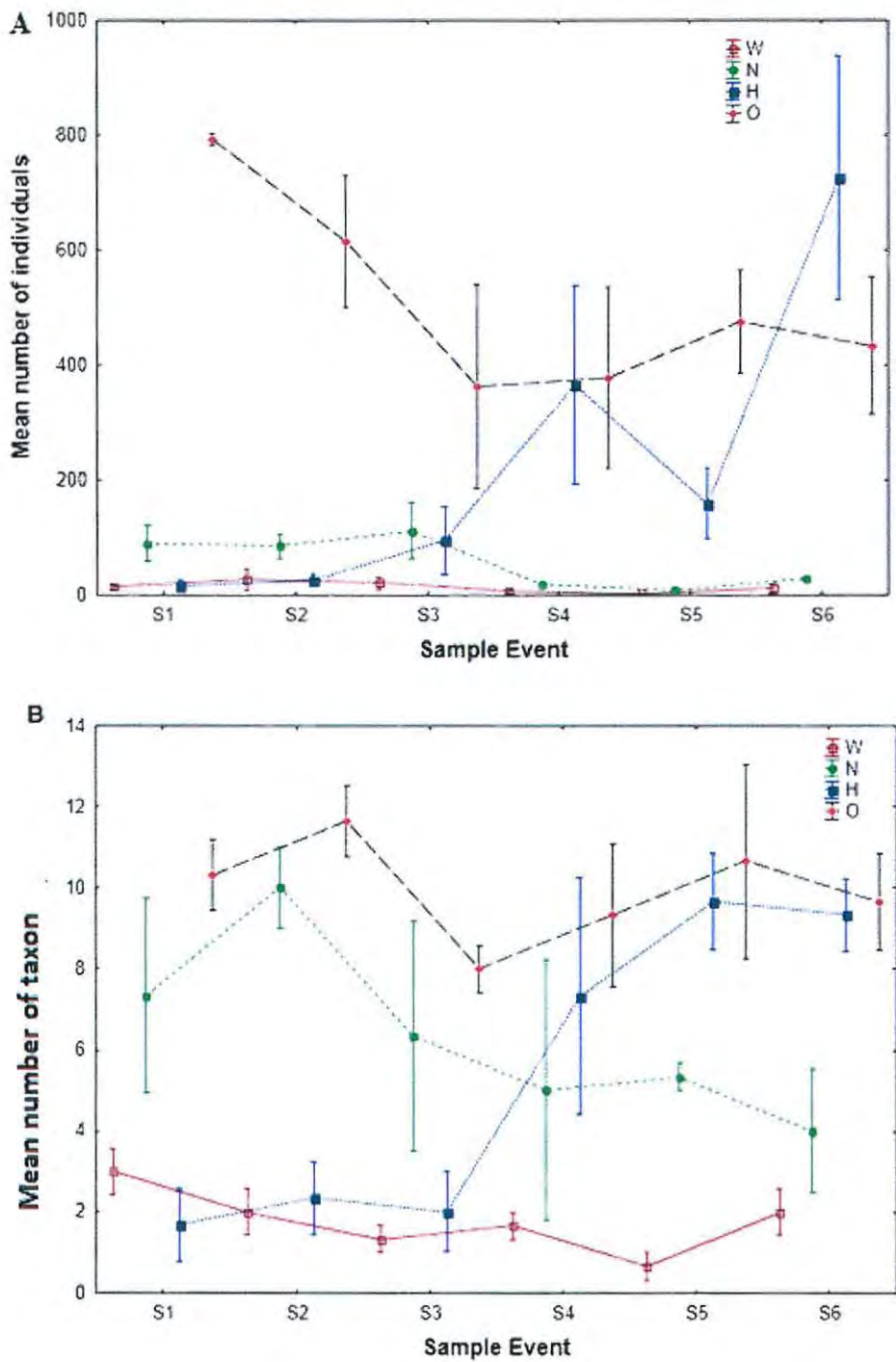
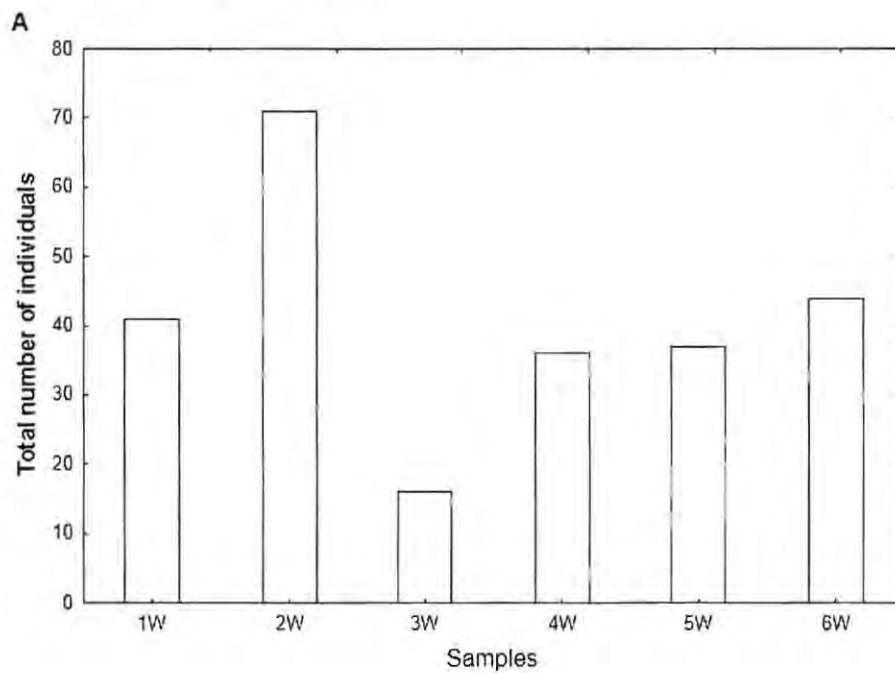
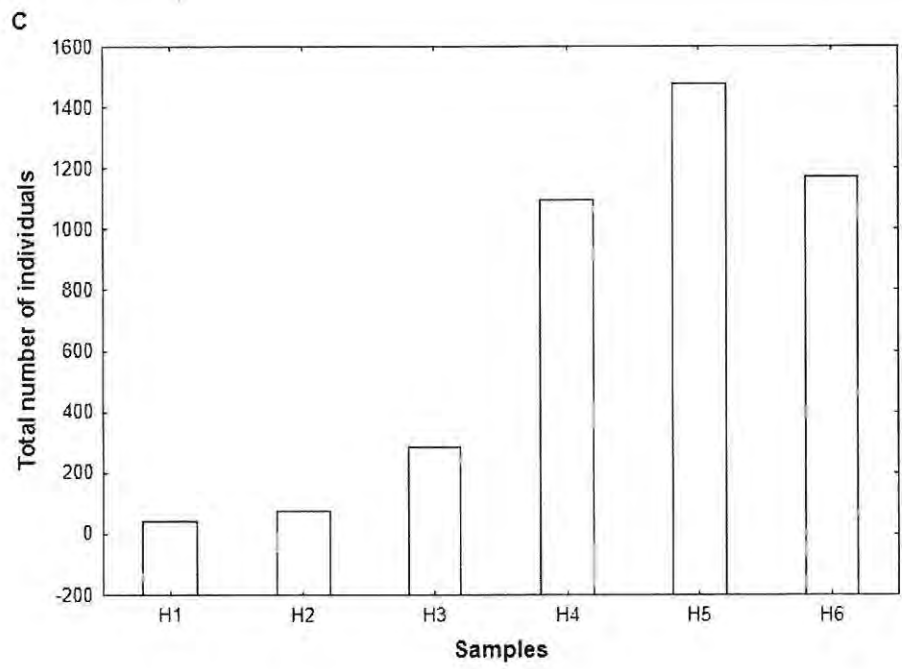
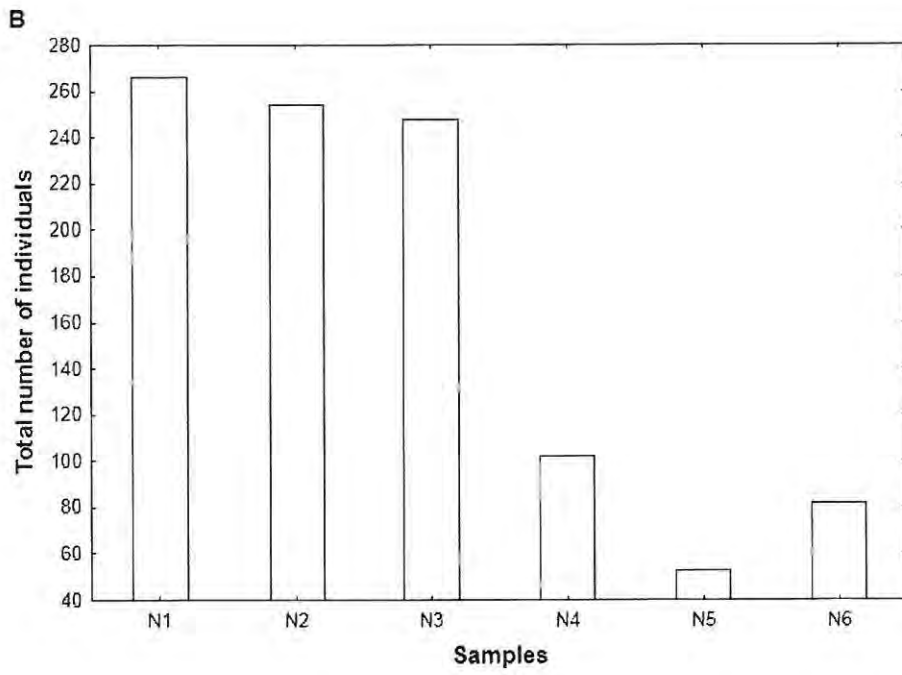


Figure 5.7 A and B Distribution of mean number of individuals (A) and mean number of taxa (B) during study period in the artificial substrates under water lettuce mats (W), in water lettuce mats controlled by *Neohydronomus affinis* (N), in water lettuce mats controlled by herbicide (H) and open water (O).

The removal of the water lettuce mats by weevils and by herbicide resulted in differing recruitment of the number of individuals (macro-invertebrates) in the treatments (Figure 5.8 B and C). The number of macro-invertebrates was lower under water lettuce mats (W), followed by sites where water lettuce was controlled by *Neohydronomus affinis* (N) (Figure 5.8 A and B).

During the study period, the total numbers of macro-invertebrate individuals under water lettuce mats (W) was less than 72 individuals per sampled occasion during the study period (Figure 5.8 A), while the number of individuals underneath water lettuce mats controlled by weevils *Neohydronomus affinis* was around 280 (Figure 5.8 B), 1476 for the herbicide treatment and 2 427 for open (Figure 5.8 C and D).





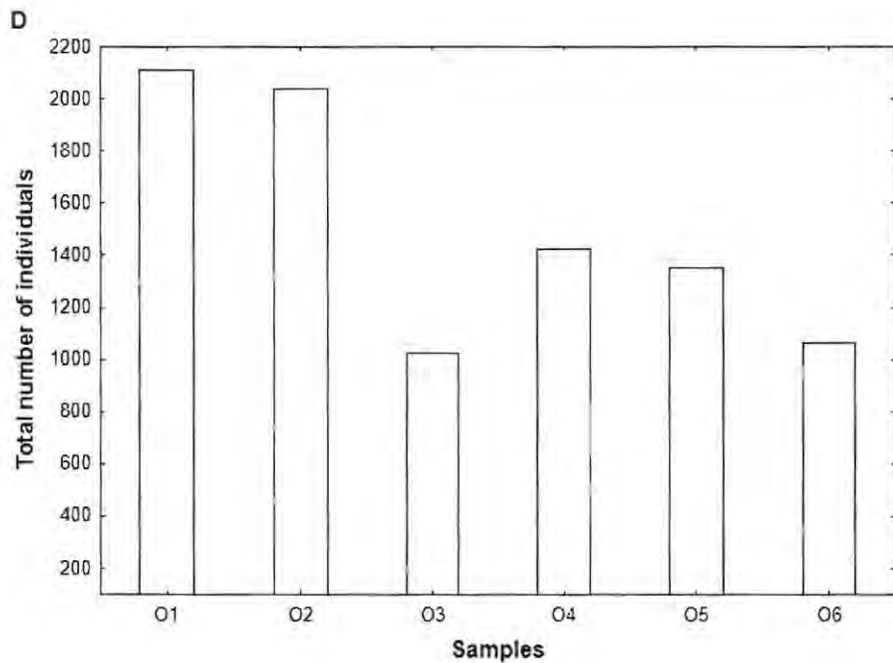


Figure 5.8 A. B. C and D Comparison in number of individuals collected in water lettuce mats in water lettuce pools (A), water lettuce controlled by *Neohydronommus affins* (B), water lettuce mats controlled by herbicide (C) and in open pools (D) during six sampling occasions.

The low colonization of artificial substrate by the macro-invertebrates in the sampling sites, namely those covered by water lettuce mats, could be explained by low levels of dissolved oxygen in the pools containing water lettuce mats (Figure 5.9), because the taxa represented those tolerant of polluted waters namely, Physidae, Chironomidae, Class Annelida represented by Oligochaeta, Hirudinae, and class Crustacea represented by Ostracoda. Because the highest numbers of total taxa were recorded in the open water (O) on all sampling occasions, it is clear that the open-water sites (O) were more productive than the remaining sites, namely water lettuce mats without control (W), water lettuce mats treated with weevils, *Neohydronommus affins* (N), and water lettuce mats treated with herbicide (H) (Figure 5.9). During the study period, 16 taxa were recorded, namely, Chironomidae, Ceratopogonidae, Baetidae, Caenidae, Coenagrionidae, Dytiscidae, Dryopidae, Corixidae, Pleidae, Libellulidae, Hydracarinidae, Physidae, Ostracoda, Hirudinea and Oligochaeta and Hydracarinidae. It was observed that the Oligochaeta, Hirudinae, Ostracoda and Physidae taxa were the last to recover in sampling sites (4O, 5O, 6O).

Under the water lettuce mats controlled by *Neohydronomus affinis* (N) and water lettuce mats controlled by herbicide (H), the number of taxa (S) was higher only when compared to those under the water lettuce mats (W). Under the water lettuce mats controlled by weevils (N), a higher number of taxa was recorded during the first and second sampling occasions (1N 2N) (Figure 5.9). This could be explained by higher levels of dissolved oxygen which were measured during this period and also because the *Neohydronomus affinis* weevils had reduced the water lettuce mats. By contrast, the majority of taxa (S) under the water lettuce mats controlled by herbicide (H) were recorded after the third sampling occasion (only since 3H) (Figure 5.9), which could be explained by the effect of herbicide applied on the water lettuce mats at the beginning of the trials and also the low levels of dissolved oxygen measured. In both sites N and H (water lettuce mats controlled by *Neohydronomus affinis* and water lettuce mats controlled by herbicide), 15 taxa were recorded. These were the same macro-invertebrates recorded in open water, with the exception of the Hydracarinidae family.

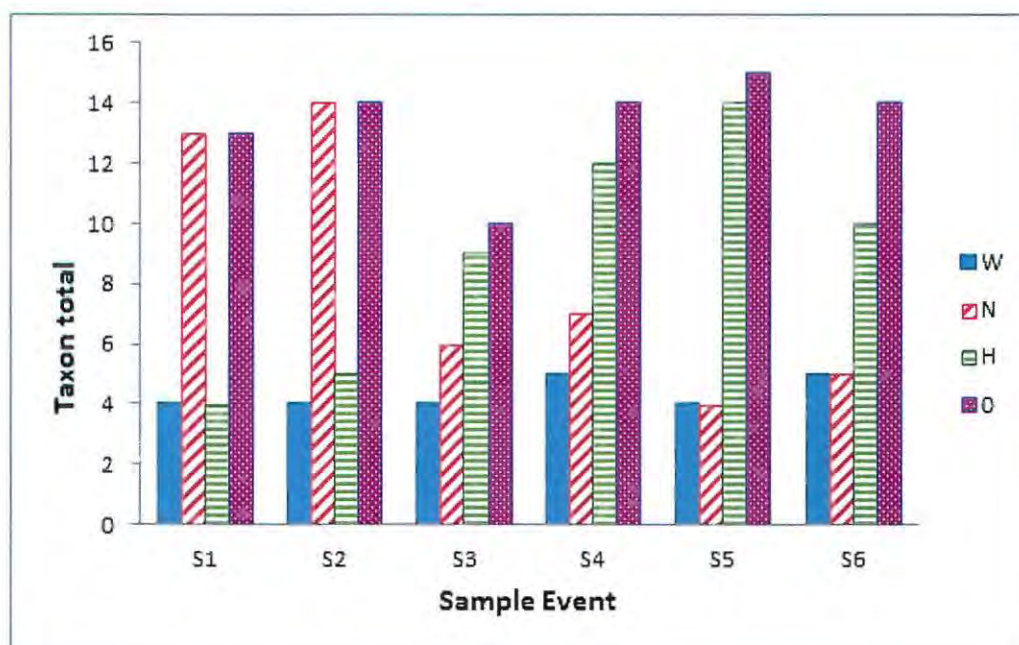


Figure 5.9 Comparison of total number of taxa collected from water lettuce mats (W), water lettuce mats controlled by biological control weevils *Neohydronomus affinis* (N), water lettuce mats controlled by herbicide (H) and open water (O) sites during six sampling occasions.

Analysis of the richness (d) during the study period showed that the highest richness of families was observed underneath water lettuce mats controlled by *Neohydronomus affinis*. On the first and second sampling occasions (1N 2N), richness values were 2.149 and 2.348 respectively (Figure 5.10). In the *Neohydronomus affinis* pools, the water lettuce plants sank slowly, so it was only after the third sampling event that there was a decrease in dissolved oxygen and a decrease in richness (Figure 5.10), while the pools treated with herbicide only recorded a compensable richness value (2.080) by the fifth sampling occasion (Figure 5.10). These results demonstrate that the total recovery of biodiversity in water lettuce mats controlled by herbicide (H) happened later in comparison to the water lettuce controlled by weevils (N). In the herbicide pools, the water lettuce crashed quickly, so it was only after the third sampling event that there was an increase in dissolved oxygen and an increase in richness (Figure 5.10). In the (O) open water, the richness (d) was more constant, varying between 1.398 and 1.945. The highest rate of richness (d) was expected to be recorded in the open water (O), but this was not seen in this study. The lowest (d) richness was found in the water lettuce mats (W), varying from 0.6603 to 1.303 (Figure 5.10). Water lettuce provided some substrate for macro-invertebrates because richness was higher than open water.

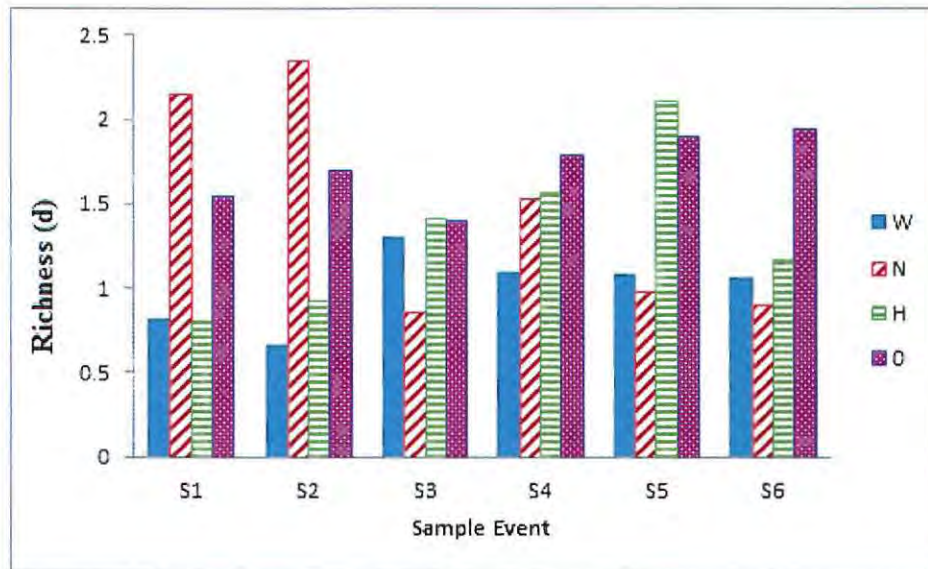


Figure 5.10 Comparison richness (d) of samples from water lettuce mats (W), water lettuce mats controlled by biological control weevils, *Neohydronomus affinis* (N), water lettuce mats controlled by herbicide (H), and open water (O) sites during six sampling occasions.

The Shannon-Wiener (H) index takes into account the number of taxa and the evenness of the taxa. It was expected that in the open-water sites, the Shannon-Wiener index would be higher compared to the other sites, but this was not the case, possibly because the dissolved oxygen levels were higher in the first and second sampling occasions in the pools where water lettuce mats were controlled by *Neohydronomus affinis* (1N 2N) due the effect of the weevils on the % cover of the water lettuce mats. In the pools where the water lettuce mat was controlled by herbicide, an increase in the dissolved oxygen (DO) was recorded on the fifth sampling occasion (5H).

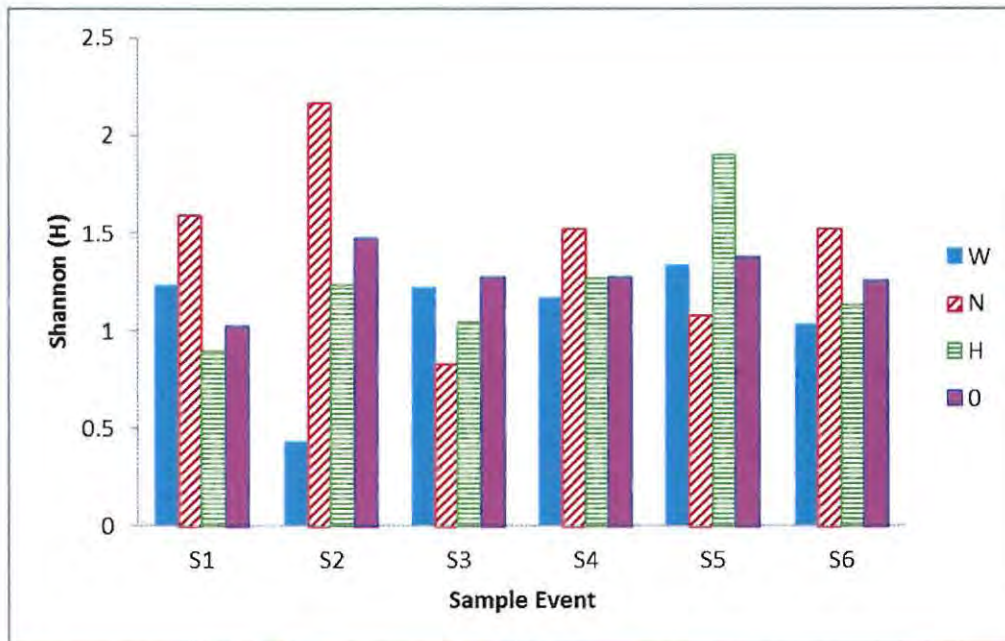


Figure 5.11 Comparison of degree of evenness and abundance, using Shannon-Weiner (H) index, of samples from water lettuce mats (W), water lettuce mats controlled by biological control weevils *Neohydronumus affinis* (N), water lettuce mats controlled by herbicide (H), and open water (O) sites during six sampling occasions

The Shannon evenness index takes into account the degree of evenness in taxa, but also, in this case, family abundance. Maximum diversity could be expected in a situation where all taxa had equal abundances. The number of observed diversity to maximum diversity can be used to measure evenness (J') (Figure 5.12). Unlike the previous observation related to S (number of taxa), N (number of individuals), d (richness), it seems that there is more evenness (J') underneath water lettuce mats (W). This is due to fewer families found underneath water lettuce mats (W) compared to the other sampling sites (O, N, H), and more individuals occurring in the open (O), (N) and (H).

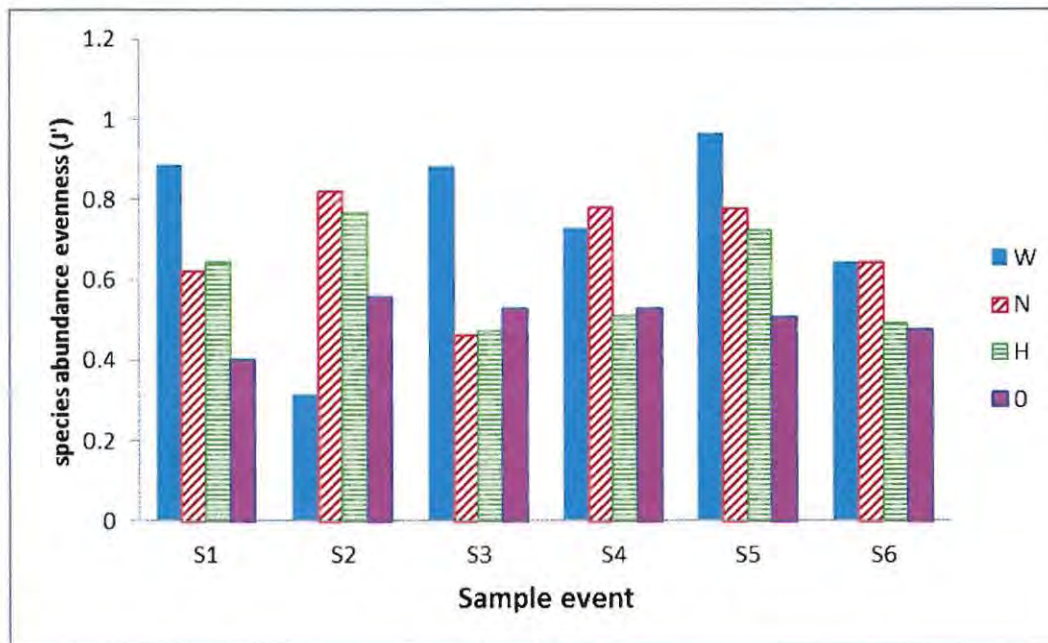


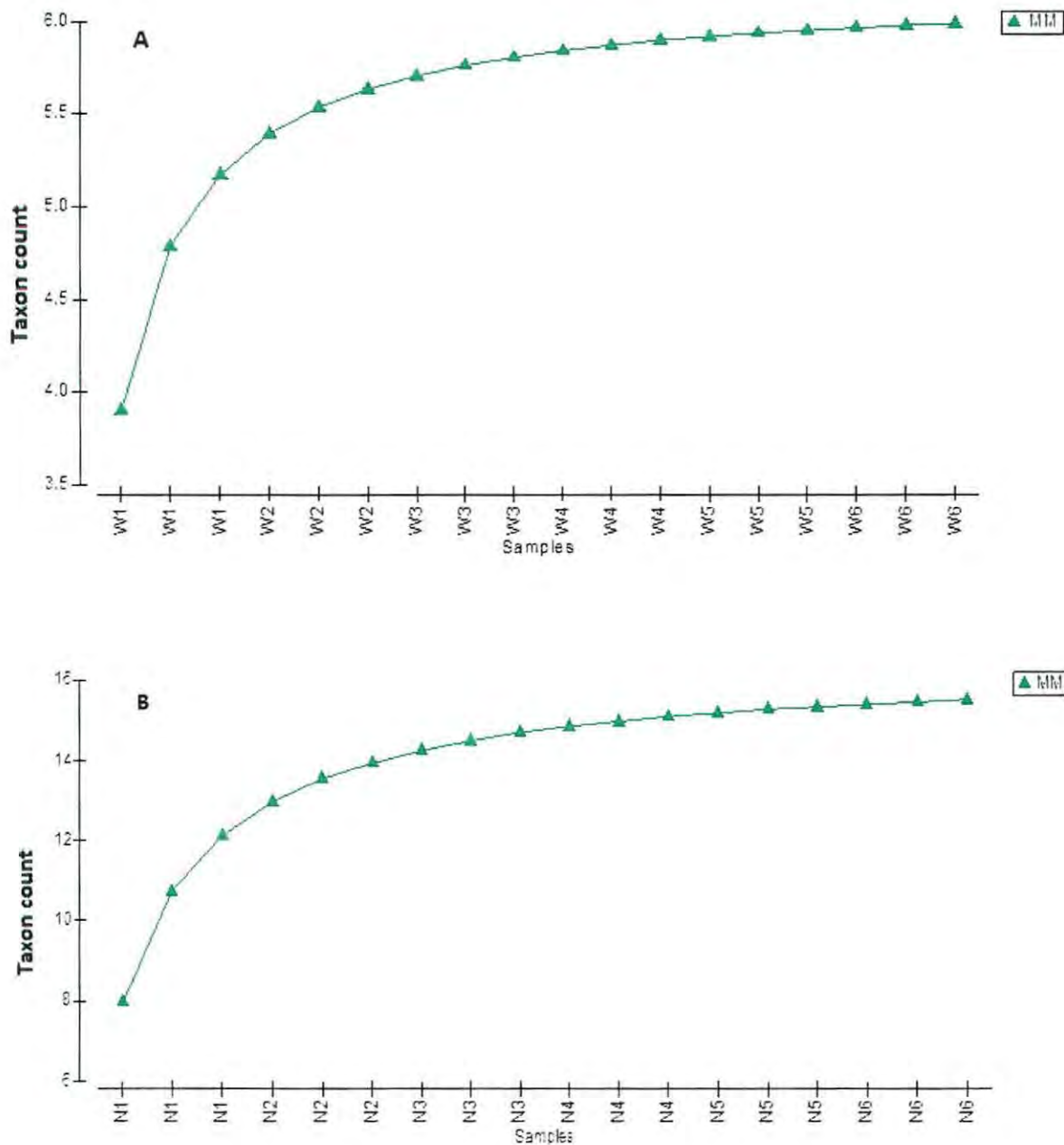
Figure 5.12 Comparison of evenness of samples from water lettuce mats (W), water lettuce mats controlled by biological control weevils *Neohydronomus affinis* (N), water lettuce mats controlled by herbicide (H) and open water (O) sites during six sampling occasions.

At the four sampling sites, seasonal differences in macro-invertebrate composition and abundance were shown. Observed seasonal differences could be attributed to changes in abiotic factors, such as temperature decrease during winter, when the number of individuals decreased (at sampling site 3 (S3), for example), fewer taxa of macro-invertebrates were recorded and richness declined in all four treatments.

5.4.7 Duration of study and accumulation curves

Accumulation curves are used to illustrate the rate at which new taxa are found (richness), but unless sampling has been exhaustive these curves do not indicate total richness (Magurran, 2004). Figure 5.13 A and D show the accumulation curve levels for water lettuce (W) and open water (O). Because all representative macro-invertebrates were collected at maximum effort, the family accumulation curve levels plateau. Figure 5.13 B shows that in the water lettuce mats controlled by *Neohydronomus affinis* (N) sites, all representative taxa were collected at

maximum effort. However, Figure 5.13 C shows that the accumulation curve for water lettuce controlled by herbicide (H) sites did not level off, indicating that all representative taxa were probably not collected at maximum effort.



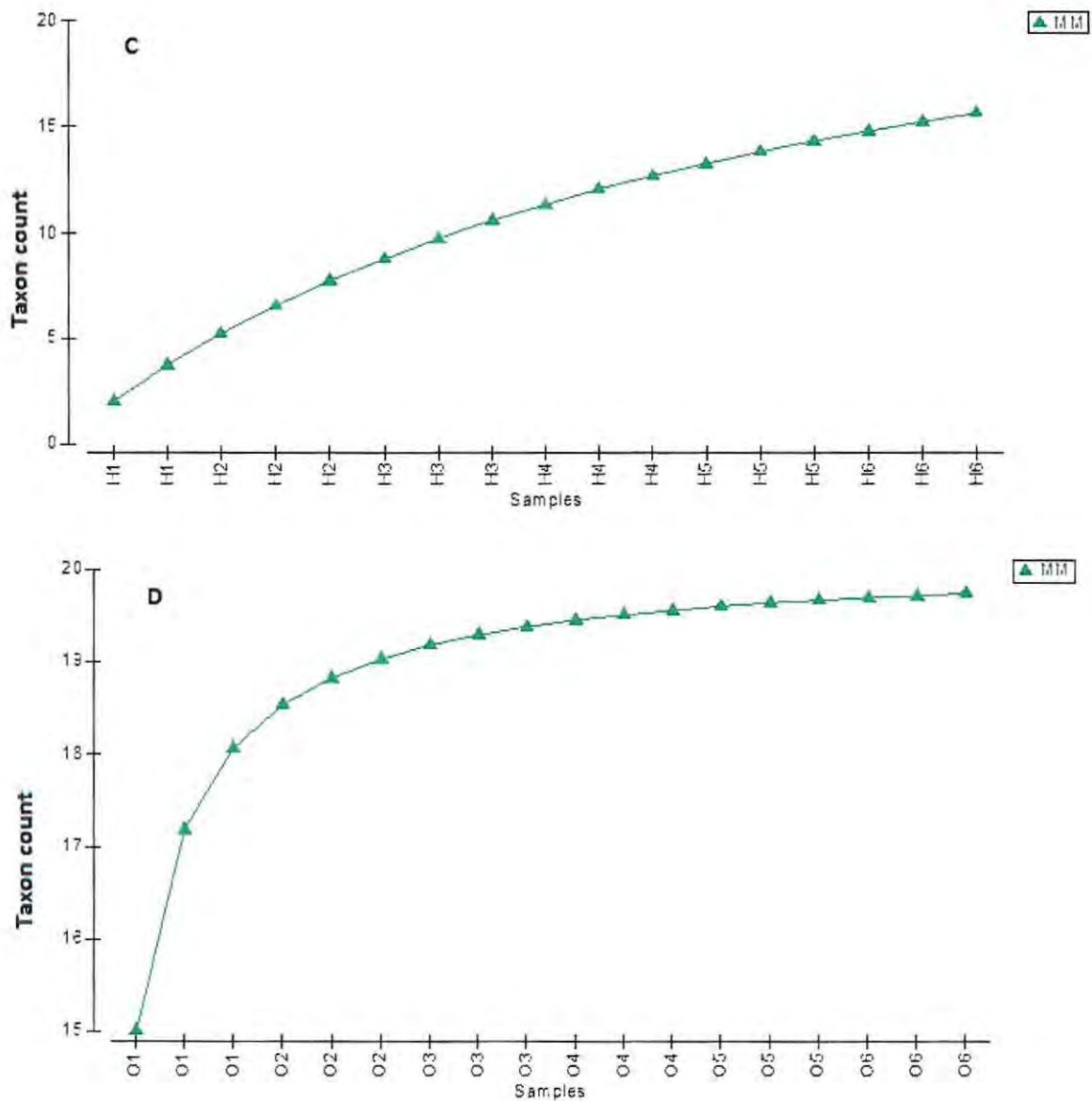
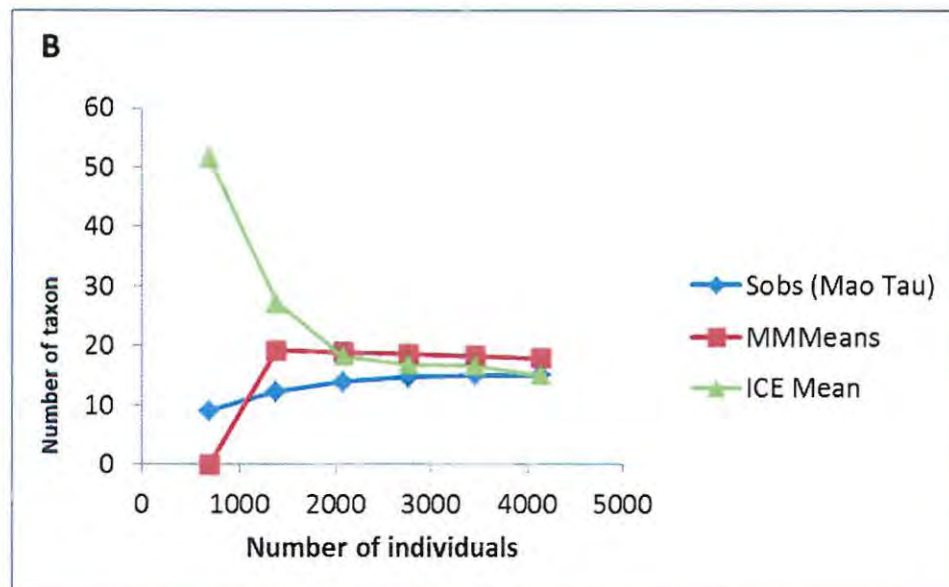
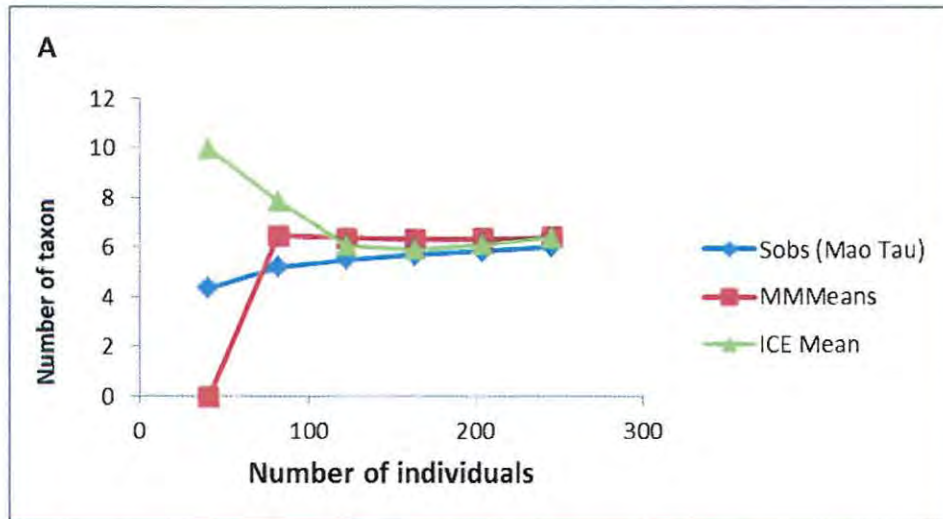


Figure 5.13 A. B. C and D Accumulation curves of taxa sampled in water lettuce mats (W), water lettuce controlled by *Neohydronomus affinis* (N), water lettuce controlled by herbicide (H) and open water (O).

Observed taxon richness (S_{obs}) converged closely with the two richness estimators (Figure 5.14), MMMean and ICE, for open water samples, indicating that this community was sampled completely (Figure 5.14 D). However results for W (water lettuce mats), N (water lettuce

controlled by *Neohydronomus affinis*) and H (water lettuce controlled by herbicide) did not converge closely with MMMeans and with ICE, and this means that these communities were probably not completely sampled.



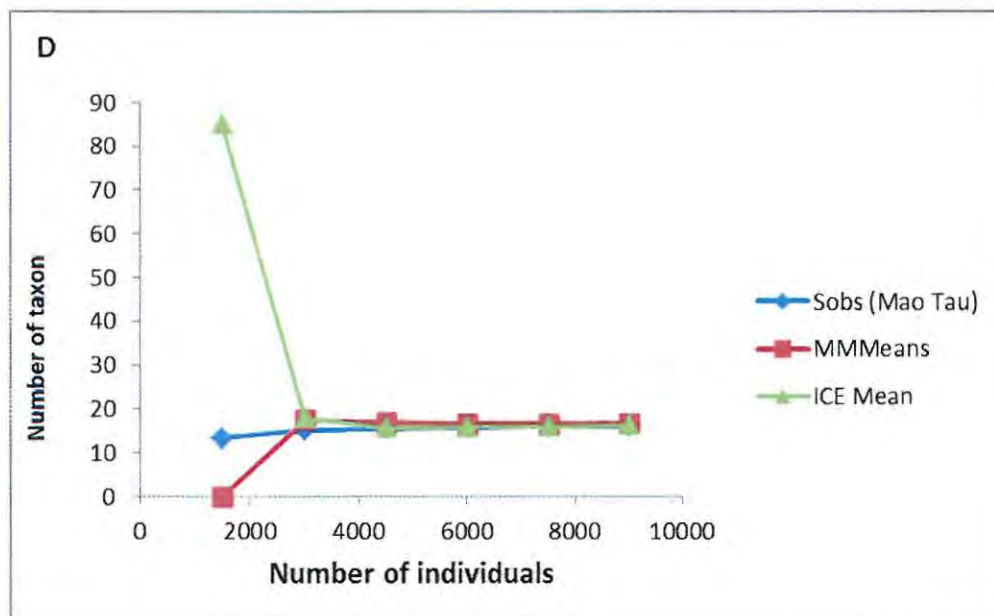
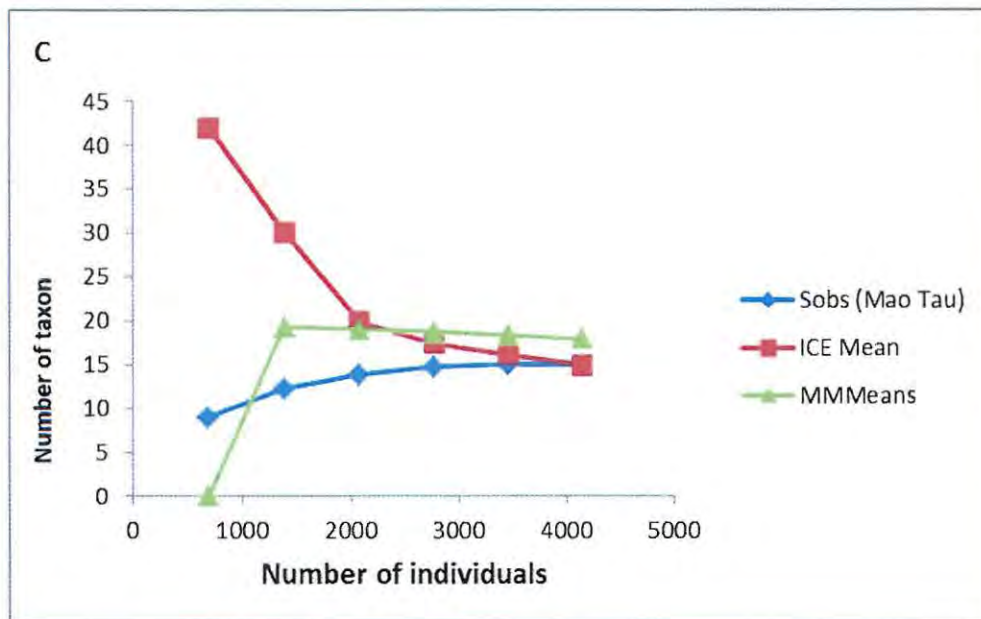


Figure 5.14 A. B. C. and D Individual-based rarefaction curves indicating observed number of species (S_{obs} Mao Tao), Michaelis-Menten Mean (MMMean) richness estimator and incidence-based estimator coverage (ICE) of macro-invertebrates collected from water lettuce mats (A), water lettuce controlled by *Neohydronomus affinis* (B), water lettuce controlled by herbicide (C) and in the open water (D).

5.4.8 Community analyses

Community analysis was carried out using accumulative a data cluster plot and a multi-dimensional scaling plot. The data tested presented very distinct similarities. The stress level indicated in the multi-dimensional scaling plot was similar, indicating a potentially useful two-dimensional picture. Due to the MDS stress level, in this case being at the upper end of the range, a cross-check was carried out using the PRIMER MDS programme, whereby the random number of restarts used was 25, which is in excess of the minimum of five or six suggested by Clark and Warwick (2001). This was done to ensure the correct representation of data.

Results of the Cluster Analyses and MDS indicated the presence of four distinct communities (Figure 5.15 and Figure 5.16). At least at levels of 55% similarities, the Cluster Analysis divided the communities into four groups, where the first community (1st cluster) consisted of samples with 6H 4H 4O 1O 2O 5O 2N 1N 5H, comprising sampling sites with higher species richness; the second community (2nd cluster) consisted of samples with the following sites: 4N 3N 3H 3O; the third community (3rd Cluster) consisted of the following sites: 2H 1W 2W 3W 6N 4W 6W. This cluster consisted mostly of water lettuce mats, with one site of water lettuce mat controlled by herbicide and one controlled by weevils. Finally, the fourth community (4th cluster) consisted of 1H 5W 5N sites.

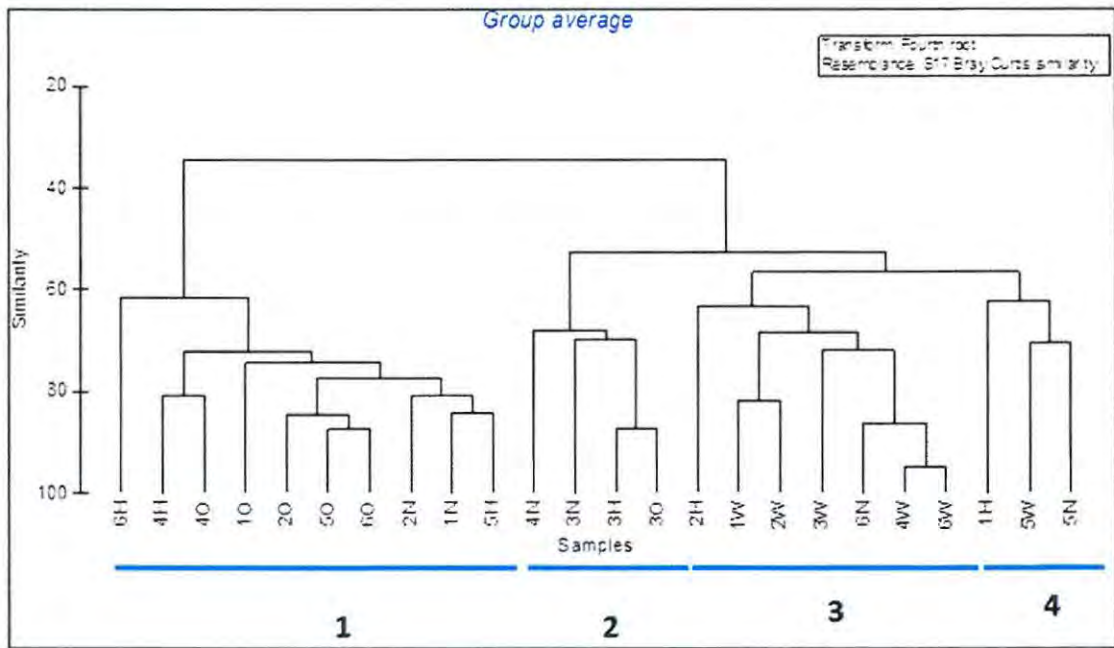


Figure 5.15 Cluster Plot indicating percentage similarity of total samples. Each branch represents sample event (number) and site (W=water lettuce, N=water lettuce mats controlled by *Neohydronomus affinis*, H=water lettuce controlled by herbicide, O=open water).

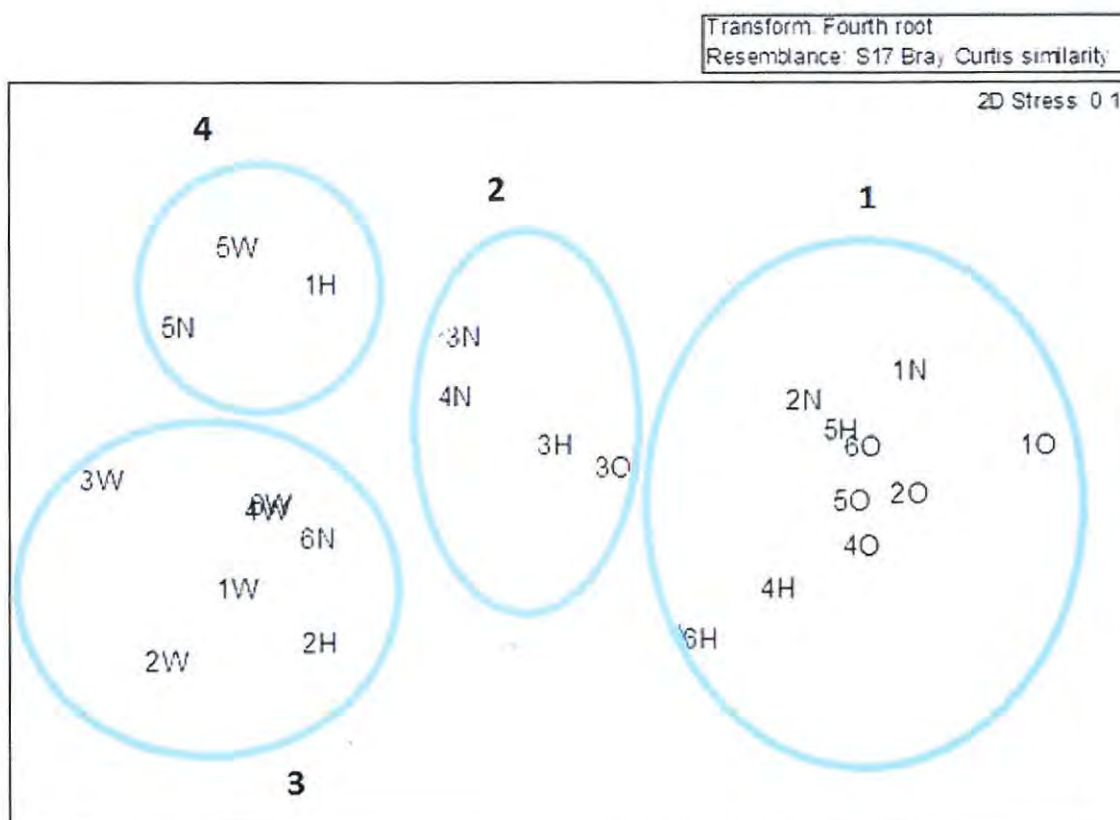


Figure 5.16 Multi-dimensional scaling (MDS) ordination of macro-invertebrate community composition. In the analysis indicating a stress of 0.1, with Cluster Plot overlay, showing four distinct communities and sample event is indicated by number followed by site (W=water lettuce, N=water lettuce mats controlled by *Neohydronomus affinis*, H=water lettuce controlled by herbicide, O=open water).

5.4.9 Analysis of similarity and dissimilarity in macro-invertebrate abundance and composition between sampling sites

Samples that were shown to be similar using both cluster and MDS effort were subjected to SIMPER. Similarity percentage analysis indicated taxa responsible for observed similarities. Four different groups were determined according to SIMPER. Group 1 contained twelve macro-invertebrates; the SIMPER analysis showed that the mean community similarity within group 1 average was 63.57. The taxa that contributed most to the high similarity in group 1 were Chironomidae (18.64%), Ceratopogonidae (14.41%), Ostracoda (13.77%), Libellulidae (7.31%) and Dytiscidae (5.93%), (Table 5.1). Group 2 was represented by six macro-invertebrate taxa; average similarity within this group was 71.20. The taxa Physidae (24.59%), Dytiscidae (22.60%) and Ostracoda (17.11%) contributed to the similarity rate among taxa in this group (Table 5.2). Group 3 consisted of four taxa, namely Oligochaeta, Physidae, Ostracoda and Chironomidae, with an average similarity of 57.75%. Only the taxon Oligochaeta contributed with an average similarity of 40.82% (Table 5.3). Group 4 consisted of only three macro-invertebrate taxa: Oligochaeta, Dytiscidae and Ostracoda. The average similarity was 61.05, with Oligochaeta contributing a percentage similarity of 36.32%.

Table 5.1 Results for one-way ANOSIM comparison of macro-invertebrate species similarity of each group during the study period. Av. Abund. (average abundance); Av. Sim. (average similarity); Sim/SD (measure of variation in contribution to similarity); Contrib. % (percentage contributed to the overall Bray-Curtis similarity between communities at sites from four groups); Cum. % (cumulative percentage).

Group 1		(Average similarity 63.57)			
Taxon	Av. Abund	Av. Sim	Sim/SD	Contrib%	Cum. %
Chironomidae	5.13	11.85	3.88	18.64	18.64
Ceratopogonidae	4.07	9.16	2.81	14.41	33.05
Ostracoda	4.49	8.75	1.4	13.77	46.82
Libellulidae	2.69	4.65	1.24	7.31	54.13
Dytiscidae	2.61	3.77	1.03	5.93	60.06
Baetidae	2.28	3.71	1.14	5.84	65.9
Oligochaeta	1.75	3.65	1.09	5.75	71.65
Pleidae	1.69	3.2	1.73	5.04	76.68
Corixidae	1.45	2.68	1.28	4.22	80.9
Caenidae	1.65	2.59	1.19	4.08	84.98
Dryopidae	1.66	2.52	1.13	3.96	88.94
Gomphidae	1.59	2.39	1.15	3.76	92.7
Group 2		(Average similarity 71.20)			
Taxon	Av. Abund	Av. Sim	Sim/SD	Contrib%	Cum. %
Physidae	4.26	17.51	3.47	24.59	24.59
Dytiscidae	4.24	16.09	3.06	22.60	47.19
Ostracoda	2.76	12.18	8.31	17.11	64.29
Oligochaeta	2.19	9.48	8.45	13.31	77.6
Chironomidae	1.99	6.55	2.18	9.2	86.8
Dryopidae	1.46	4.93	0.89	6.93	93.73
Group 3		(Average similarity 57.76)			
Species	Av. Abund	Av. Sim	Sim/SD	Contrib%	Cum. %
Oligochaeta	2.52	23.58	2.63	40.82	40.82
Physidae	2.24	17.31	1.22	29.97	70.79
Ostracoda	1.57	10.52	1.05	18.21	89
Chironomidae	0.94	6.35	1.32	11	100
Group 4		(Average similarity 61.05)			
Taxon	Av. Abund	Av. Sim	Sim/SD	Contrib%	Cum. %
Oligochaeta	1.6	22.18	13.82	36.32	36.32
Dytiscidae	1.84	20.7	2.41	33.91	70.23
Ostracoda	1.97	18.17	6.8	29.77	100

Overall differences in macro-invertebrate abundance and composition between the four sampling sites during the study period were elucidated by analysis of similarity (ANOSIM) and similarity percentage (SIMPER) analysis, and are presented in Table 5.2. ANOSIM indicated significant difference ($p < 5\%$) between all sampling groups, except groups 3 and 4. SIMPER analysis revealed that significant difference between groups 1 and 2 could be attributed to taxa such as Libellulidae, Caenidae, Gomphidae, Corixidae and Coenagrionidae, which were present in group 1 and absent in group 2. SIMPER analysis also indicated that differences between group 1, and groups 3 and 4 were as a result of Ceratopogonidae, Libellulidae, Baetidae, Pleidae, Caenidae, Dryophidae and Gomphidae and Corixidae, which were absent in groups 3 and 4, but present in group 1. The Corixidae taxon was also absent in group 4, but present in group 3. The absence of Dryophidae and Baetidae in group 3, which were present in group 2, and the abundance of Dytiscidae, Physidae and Oligochaeta in group 2 compared with group 3, contributed to the difference between the two groups. The contributions of taxa such as Physidae, Dytiscidae, Chironomidae, and Ostrocada, which were present in group 2 and absent in group 4, and the absence of Dryophidae, Baetidae and Pleidae in group 4, which were present in group 2 could be a reason for the dissimilarity matrix between groups 2 and 4. Relative abundances were similar between the taxon types found in group 4 and group 3 (Table 5.2). The average dissimilarity was not significant, contributing $p > 5\%$ to the dissimilarity.

Table 5.2 Results of ANOSIM and SIMPER analysis for macro-invertebrate abundance, and comparison between identified groups (Not significant at $P > 5\%$ and Significant at $P < 5\%$).

Groups	Average dissimilarity	Significantly different?	Level (%)
1 and 2	53.25	Yes	0.5
1 and 3	73.63	Yes	0.2
1 and 4	73.35	Yes	0.5
2 and 3	50.63	Yes	4.8
2 and 4	51.12	Yes	2.9
3 and 4	49.13	No	15.5

5.4.10 Relationship between macro-invertebrate communities and water quality

The Canonical Correspondence Analysis ordination plot (CCA) revealed a relationship between macro-invertebrate communities and measured chemical water quality variables (Figure 5.17). According to the CCA plot, dissolved oxygen (DO), nitrates, temperature and water lettuce percentage coverage (% cover) were the variables that impacted on the community structures. The phosphate variable was excluded on the plot because it overlapped with the nitrate variable. CCA revealed that the % cover was positively correlated to the following communities: Dytiscidae, Ostracoda, Physidae, Oligochaeta and Hirudinea. Furthermore, the % cover was associated with the following sampled sites: 1W 2W 3W 4W 5W (mats of water lettuce), and 1H 3H (water lettuce mats controlled by herbicide), and 3N 4N 5N 6N (water lettuce mats controlled by *Neohydronomus affinis*). Physidae, Dytiscidae, Hirudinea, Oligochaeta and Hirudinea communities seemed to be more pollution-tolerant and were correlated to low DO, high nitrate and low temperature.

The CCA ordination plot revealed that DO, nitrate and temperature were positively correlated with the following taxa: Hydracarinae, Libellulidae, Gomphidae, Ceratopogonidae, Caenidae, Corixidae, Baetidae, Dryopidae, Pleidae and Chironomidae, Ceratopogonidae at sites 1O 5O (open water) and 1N 2N (water lettuce mats controlled by *Neohydronomus affinis*) and 5H (water lettuce mats controlled by herbicide (Figure 5.17). These species, as shown on axis 1 of the ordination plot, were abundant in oxygen-rich sites, but their populations were reduced as the oxygen was depleted.

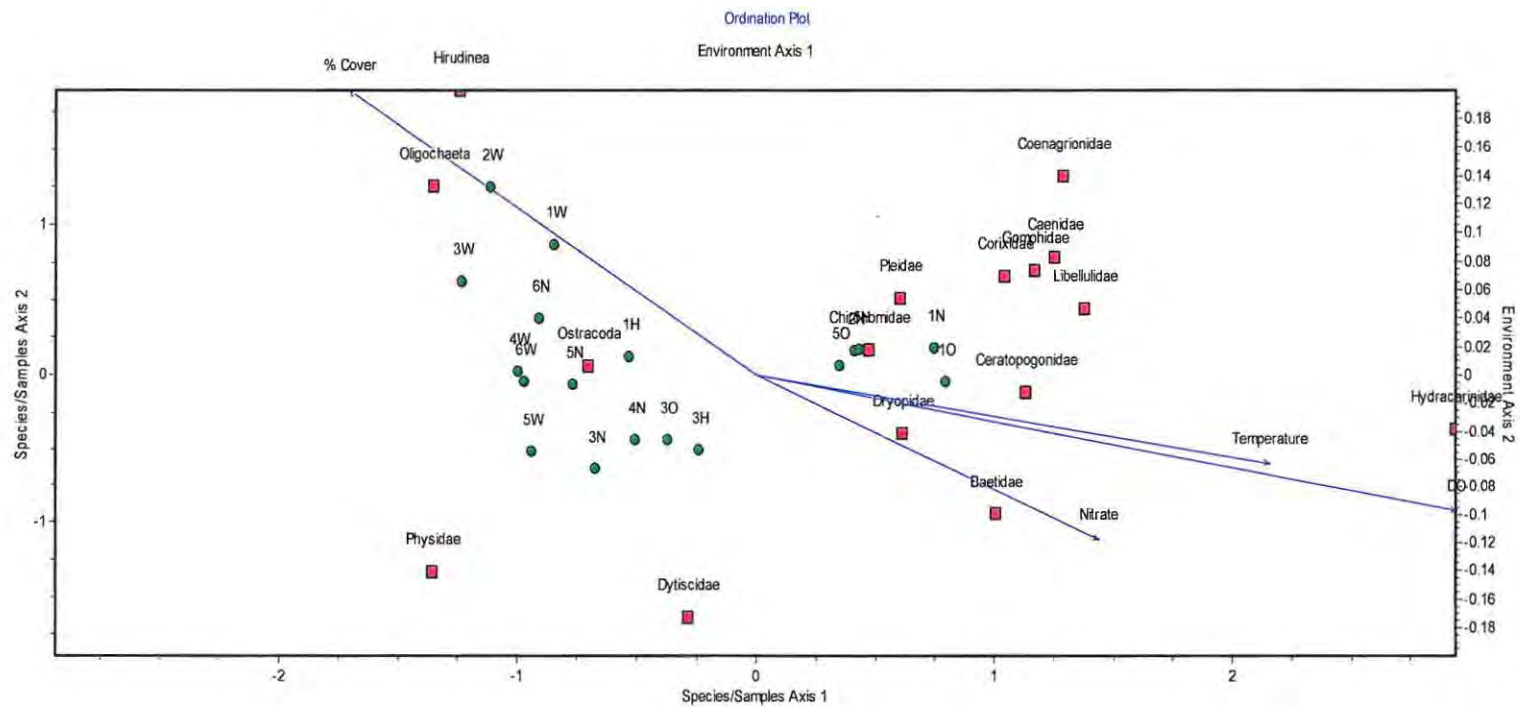


Figure 5.17 CCA ordination tri-plot for macro-invertebrate taxa and water quality variables at the four study sites. Abbreviations: Sample event is indicated by number followed by site (W=water lettuce, N=water lettuce mats controlled by *Neohydrionomus affinis*, H=water lettuce controlled by herbicide, O=open water); DO=dissolved oxygen.

The relative magnitude of Eigen Values for each of the CCA axes is an indication of the relative importance of the axis. CCA axis 1 accounted for 28.38% of total variance of the data set, and in total, the first three axes of the ordination accounted for 39.15% (Table 5.3) of the variance, suggesting low correlation between community data and water quality variables. This could be explained because the water quality parameters were not recorded on all sampling occasions (not collected on second, fourth and sixth occasions). The water quality parameters were recorded on only three sampling occasions during the study period. Pearson's correlation between species and water quality variables displayed positive correlation for all three axes (Table 5.3).

Table 5.3 Properties of the Canonical Correlation Analysis ordination tri-plot.

Canonical Proprieties	Axis		
	1	2	3
Canonical Eigen value	0.23	0.05655	0.03073
% variance explained	28.38	6.97	3.793
Cumulative % variance	28.38	35.36	39.15
Pearson correlation of families and environment scores	0.8385	0.6162	0.7436

5.4.11 Sensitivity to water quality of the taxa sampled

All organisms are sensitive to one form of pollution or another, and in this study the macro-invertebrates are good indicators of the level of pollution in the aquatic environment (Gerber and Gabriel 2002). The SASS5 scoring system (Gerber and Gabriel, 2002) was used to determine the sensitivity of invertebrates sampled from four treatments in this experiment namely, W (water lettuce with no control), N (water lettuce controlled by biological control agent *Neohydronomus affinis*), H (water lettuce controlled by herbicide glyphosate 3%) and O (open water without water lettuce). No macro-invertebrates with very low tolerance to pollution were found in studied pools, probably because of the size of the pools and the fact that they were fertilized to promote water lettuce growth.

Sensitivity scales are recorded on levels 1 to 15 and derived from tolerances to pollution as used in the SASS5 scoring system (Dickens and Graham, 2001), namely: 1-5 highly tolerant to pollution; 6-10 moderately tolerant to pollution; 11-15 very low tolerance to pollution.

Of all taxa collected in the water lettuce mats (W), 100 % were considered highly tolerant of pollution (Table 5. A). In the water lettuce mats controlled by *Neohydronomus affinis* (N), of 15 taxa collected during the study period, 74.5% were highly tolerant to pollution and 25.5% were moderately tolerant to pollution (Table 5.4 B). In the water lettuce mats controlled by herbicide treatment (H), of 15 taxa collected according to SASS5 scoring, 77.4% were considered highly tolerant and 22.6% moderately tolerant to pollution (Table 5.4 C). Finally, in open water treatment (O), of the 16 taxa collected according to SASS5 scoring, 71.1% were considered highly tolerant and 28.9% were considered moderately tolerant to pollution (Table 5.4 D). Taxa with a very low tolerance to pollution were found in none of the treatments. In water lettuce mats (W) the moderately tolerant to pollution taxa were not found (Table 5.4 A, B, C and D). The above indices indicate that the sample area is moderately to highly polluted in one form or another.

Table 5.4 A, B, C and D Sensitivity indication of invertebrates sampled using SASS5 scoring system on the water lettuce (A), water lettuce controlled by weevils *Neohydronomus affinis* (B), water lettuce controlled by herbicide (C) and in the open water without water lettuce (D).

Taxon		Sensitivity level						
		SASS5	1W	2W	3W	4W	5W	6W
Diptera	Ceratopogonidae	5	-	-	-	-	-	-
	Chironomidae	2	2	2	-	2	-	2
Ephemeroptera	Baetidae	6	-	-	-	-	-	-
	Caenidae	6	-	-	-	-	-	-
	Coenagrionidae	4	-	-	-	-	-	-
Odonata	Libellulidae	4	-	-	-	-	-	-
	Gomphidae	6	-	-	-	-	-	-
Coleoptera	Dytiscidae	5	5	-	-	-	5	-
	Dryopidae	8	-	-	-	-	-	-

Hemiptera	Corixidae	3	-	-	-	-	-	-
	Pleidae	4	-	-	-	-	-	-
Annelida	Hirudinea	3	3	3	3	3	-	3
	Oligochaeta	1	1	1	1	1	-	1
Mollusca	Physidae	3	-	-	3	3	3	3
Arachnida	Hydracarinidae	8	-	-	-	-	-	-

B

Taxon		SASS5	1N	2N	3N	4N	5N	6N
Diptera	Ceratopogonidae	5	5	5	-	-	5	-
	Chironomidae	2	2	2	2	2	2	2
Ephemeroptera	Baetidae	6	6	6	6	6	-	-
	Caenidae	6	6	6	6	-	-	-
	Coenagrionidae	4	4	4	-	4	-	-
Odonata	Libellulidae	4	4	4	4	4	-	4
	Gomphidae	6	6	6	6	-	-	-
Coleoptera	Dytiscidae	5	5	5	5	-	5	-
	Dryopidae	8	8	8	-	8	-	-
Hemiptera	Corixidae	3	3	3	-	-	-	-
	Pleidae	4	4	4	4	4	-	-
Annelida	Hirudinea	3	-	3	-	-	3	3
	Oligochaeta	1	1	1	-	1	1	1
Mollusca	Physidae	3	-	-	-	3	3	3
Arachnida	Hydracarinidae	8	-	-	-	-	-	-

C

Taxon		SASS5	1H	2H	3H	4H	5H	6H
Diptera	Ceratopogonidae	5	-	-	-	5	5	5
	Chironomidae	2	2	2	2	2	2	2
Ephemeroptera	Baetidae	6	-	-	-	6	6	6
	Caenidae	6	-	-	-	6	6	6
	Coenagrionidae	4	-	-	-	4	4	4
Odonata	Libellulidae	4	-	-	-	4	4	4
	Gomphidae	6	-	-	-	6	6	6
Coleoptera	Dytiscidae	5	5	5	5	-	5	5
	Dryopidae	8	-	-	8	-	8	8
Hemiptera	Corixidae	3	-	-	-	-	3	3
	Pleidae	4	-	-	4	4	4	4

Annelida	Hirudinea	3	-	3	3	3	3	3
	Oligochaeta	1	1	1	1	1	1	1
Mollusca	Physidae	3	-	3	3	3	3	3
Arachnida	Hydracarinidae	8	-	-	-	-	-	-

D

Taxon		SASS5	10	20	30	40	50	60
Diptera	Ceratopogonidae	5	5	5	5	5	5	5
	Chironomidae	2	2	2	2	2	2	2
Ephemeroptera	Baetidae	6	6	6	6	6	6	6
	Caenidae	6	6	6	-	6	6	4
	Coenagrionidae	4	4	4	-	4	4	4
Odonata	Libellulidae	4	4	4	4	4	4	4
	Gomphidae	6	6	6	-	6	6	6
Coleoptera	Dytiscidae	5	3	5	5	5	5	5
	Dryopidae	8	8	8	8	8	8	8
Hemiptera	Corixidae	3	3	3	-	3	3	3
	Pleidae	4	4	4	4	4	4	4
Annelida	Hirudinea	3	-	-	3	3	3	-
	Oligochaeta	1	1	1	1	-	1	1
Mollusca	Physidae	3	-	3	3	3	3	3
Arachnida	Hydracarinidae	8	8	-	-	-	-	-

5.5 Discussion

This study determined that water lettuce mats have a severe impact on aquatic biodiversity. Similar studies have focused on the impact of water hyacinth on invertebrate assemblage and these are few and contradictory in their conclusions, e.g. Toft *et al.* (2003) concluded that the invasive species had a negative effect on macro-invertebrate assemblage, but Phillips (2008) and Strayer *et al.* (2003) argued that weeds have a positive effect on the density of macro-invertebrates. Cattaneo *et al.* (1998) saw no clear effect of invasive plants on the invertebrate assemblage. Sheppard *et al.* (2006), in their study, stated that the dense vegetation of weeds reduced aquatic biodiversity as well as degrading water quality. Masifwa *et al.* (2001) concluded that the fringe/open water, where it is very well oxygenated, supports diverse and abundant invertebrate communities, but the decline of the invertebrates was verified close to the aquatic weed water hyacinth beds, where the concentration of oxygen was low. Midgley *et al.* (2006)

concluded that the presence of water hyacinth had a negative effect on both abundance and diversity of benthic invertebrates and algal biomass.

Applications of herbicide on the aquatic ecosystems have resulted in negative impacts on both aquatic plants and biodiversity. In their study, Caquet *et al.* (2007) showed the negative effect of applying chemicals on macro-invertebrates. This study showed similar results during the first and second sampling times (1H 2H) in the sites where the water lettuce mats were controlled by herbicide: the herbicide toxicity reduced the water lettuce by 55% (after one weeks) and 75% (after two weeks) respectively, and reduced the dissolved oxygen (DO) in the water, negatively affecting the recovery of aquatic macro-invertebrates. It was also observed that once the water lettuce mats were reduced by 80% or more, *Lemna* plants replaced the water lettuce, and once the effect of the herbicide on the water lettuce mats wore off, namely after the third sampling occasion (from 3H to 6H), the number of individuals and species increased visibly, since the pools were no longer covered by water lettuce and the levels of dissolved oxygen in the water had increased. The delay in macro-invertebrate recovery may be caused by a combination of the long-lasting effect of the herbicide and consequent water eutrophication, which reduces dissolved oxygen.

The chemical water quality variables provide a clear distinction between communities 1, 2, 3 and 4. The main contributors to the low richness index and high organic pollution loading were probably the considerably lower levels of dissolved oxygen (DO) in the water as a result of the full percentage cover of the water lettuce surface area. The low DO was evident in the odour of sulphur dioxide that characterized sites 1H 2H and 5N 6N throughout the sampling periods. This could be the result of anaerobic decomposition of organic matter, resulting in the reduction of the biodiversity recovery in the pools and/or also the consequent reduction of macro-invertebrates. The impact of herbicide on the sites 1H, 2H contributed to eutrophication. This study confirms the results obtained in studies by Dallas and Day (2004) and Nyenje *et al.* (2010) who explained that the poor macro-invertebrate composition in their trials was the result of anaerobic decomposition of organic matter which produced harmful gases, such as methane and hydrogen sulphide. These gases could cause the death of sessile macro-invertebrates and eventually deplete

their populations. Herbicide initially had a negative impact due to the rotting water lettuce mats and consequent low level of dissolved oxygen, but the macro-invertebrates recovered quickly.

Furthermore, on the first, second and third (1N 2N 3N) sampling occasions, it was observed that, in water lettuce pools controlled by in the weevil *Neohydronomus affinis*, the coverage of water lettuce mats had been reduced by 10%, 20% and 30% respectively, consequently increasing the sunlight and oxygen content of the water. The reduction of the mats by weevils resulted in recruitment of a higher number of individuals, a higher number of taxa and also higher richness. On later sampling occasions (fifth and sixth), water eutrophication had occurred at sites where water lettuce had been controlled by *Neohydronomus affinis*, and more than 30% of water lettuce had been eliminated (4N to 6N). On these sampling occasions, the number of individuals, of species, and the species richness was also reduced, possibly due to reduced oxygen in the water as the mat sank. On those occasions (fifth and sixth), the decomposed litter of water lettuce plants formed dense dark mats on the bottom of the ponds. Results of this study are similar to those found by Poi de Neiff and Carignan (1997), who positively correlated macro-invertebrate densities in the roots of the aquatic weed, *Eichhornia crassipes*, with dissolved oxygen concentration. Biological control agents worked slowly, but the small reduction in surface area covered resulted in a large increase in biodiversity. However, as biocontrol continued, and the mat started to sink rapidly, the dissolved oxygen was reduced and the biodiversity decreased. So, in this case, one year is too short in a temperate climate to measure the effect of biocontrol.

Macro-invertebrates are known to exhibit varying degrees of sensitivity to environmental water quality deterioration (Bonada *et al.*, 2006; Arimoro and Muller, 2010; Fouche and Vlok, 2010). Thus, their presence is considered a reflection of the water quality status and aquatic health of the environment in which they live. For instance, when taxa of aquatic macro-invertebrates perceived to be sensitive to water quality deterioration are found at a site, it is assumed that such a site is of good quality, at least from an environmental water quality point of view. In this study, macro-invertebrate replicate samples taken from communities 3 and 4 were often closely associated, while communities 1 and 2 were quite distinct. The distinctiveness of community 1 is due to the presence of macro-invertebrate taxa such as Libellulidae, Baetidae, Caenidae, Gomphidae and Corixidae. These taxa indicate good water quality. The close association

between macro-invertebrate communities at sites 3 and 4 during the study period could be attributed to the presence of taxa of macro-invertebrates such as Oligochaeta and Ostracoda that characterized samples from these sites. These taxa are highly tolerant and can thrive in polluted environments. Of particular interest is the high abundance of Oligochaeta and Ostracoda at communities 3 and 4 respectively. Oligochaeta is regarded as a highly tolerant taxon among aquatic macro-invertebrates because of their ability to survive in oxygen-depleted environments (Fouche and Vlok, 2010). This characteristic could have contributed to their dominance at the two sites with high organic loads and less dissolved oxygen.

Generally, results of this study revealed that the dipterans represented by the taxon Chironomidae, and coleopterans represented by the taxon Dytiscidae were the most ubiquitous groups of macro-invertebrates throughout the sampling times. They were recorded in all the sampling sites. Most taxa within these orders, such as Dytiscidae, Dryopidae, Ceratopogonidae and Chironomidae are air-breathers and are thus capable of replenishing their oxygen supply directly from the atmosphere and are, therefore, less affected by depleted oxygen levels in water as they rise to the water surface to breathe and come down with air bubbles. Chironomids, on the other hand, are benthic organisms which undergo cutaneous respiration, which is aided by the presence of hemoglobin in their bodies during the larval stage. This is probably the most plausible explanation for their continuous presence in most of the sites. Results of this study showed that the Cereatopogonidae and Chironomidae represented the taxa Diptera with Chironomidae being one of the most dominant taxa (30.2%). It was found in all studied sites and at most of the most sampling times. These species were found in the open water treatment, with higher DO concentrations, but also in eutrophic areas with low dissolved oxygen concentrations and in sites with a full cover of surface area. This means that the Chironomidae can be found in unpolluted water but yet tolerate environmental pollution. The CCA revealed that the Chironomidae is positively correlated to sites near nitrate, temperature and DO. Results of this corroborate studies by Rossaro *et al.* (2007), who noticed that *Chironomus plumosus* (Linnaeus, 1758) from the taxa Chironomidae was highly tolerant of nutrient concentrations, and studies by Fouche and Vlok (2010) who concluded that chironomids are regarded as highly tolerant taxa among aquatic macro-invertebrates because of their ability to survive in oxygen-depleted environments. Furthermore, Arimoro (2009) and Dickens and Graham (1998) noted that

Chironomidae (chironomids species) are opportunistic and possess the ability to thrive in areas of low competition. Apart from poor oxygen levels, relatively high water weeds (water hyacinth) can also contribute to the poor macro-invertebrate assemblages.

According to the CCA plot in this study, the taxa Annelida (Hirudinea and Oligochaeta), Crustacea (Ostracoda), Mollusca (Physidae) and Coleoptera (Dytiscidae and Dryopidae) were observed aligned with the water lettuce % cover vector. These taxa are regarded as highly tolerant taxa among aquatic macro-invertebrates because of their ability to survive in oxygen-depleted environments. These results corroborate those of Mandaville (2002), Boyle and Fraleigh (2003) and Fouche and Vlok, (2010), who observed that the taxa Annelida in particular, and Oligochaeta are known to tolerate oxygen stress.

The Ephemeroptera (Baetidae, Caenidae, and Coenagrionidae) and the Odonata (Libellulidae and Gomphydae) were found in different quantities and were not found under water lettuce mats or in the polluted sites with low DO and high eutrophication. The CCA plot related these families positively to DO. This study confirms results from Gupta and Paliwal (2010), who showed that Odonata insects are found in freshwater habitats rich in oxygen. Studies by Legesse (2001) and Kedebe *et al.* (2010) also testify that Ephemeroptera taxa abound in rich, oxygenated water; in fact, they are used in Ethiopia as a water quality monitoring index.

Results obtained by the SASS5 scoring system showed that in the water lettuce mats controlled by *N. affinis*, the number of moderately tolerant to pollution macro-invertebrates taxa were high in the first second and third sampling occasions compared to the fifth and sixth sampling occasions; this could be explained because the water quality was enriched with dissolved oxygen at the beginning of the experiment. In contrast to the water lettuce mats controlled by herbicide, the moderately tolerant to pollution macro-invertebrates families only started to colonize the artificial substrate in the third sampling occasion, probably because at that time it was observed that the dissolved oxygen increased. In the open water, the moderately tolerant to pollution families were found on most of the sampling occasions. In the water lettuce mats without control, no moderately tolerant to pollution taxa were found. The single case of a moderately

tolerant to pollution taxon found on five sampling occasions was not significant. There were no samples of very low tolerant to pollution macro-invertebrates taxa.

5.5 Conclusion

The study clearly demonstrated that water lettuce had a significant impact on the recruitment of macro-invertebrates to the artificial substrates, and that water lettuce contributed to the reduction of oxygen in the water and consequent reduction of macro-invertebrate abundance and diversity. The recruitment of macro-invertebrates was less in water lettuce pools compared to the pools that contained water lettuce controlled by *N. affinis*, water lettuce controlled by herbicide, or in the open water. The biodiversity recovered in the pools containing water lettuce controlled by *N. affinis* and water lettuce controlled by herbicide, but richness and diversity of macro-invertebrates was higher in the water lettuce controlled by *N. affinis* during the first sampling occasion compared to the water lettuce in pools controlled by herbicide, which increased only when DO levels recovered after water lettuce mat decay. Basically herbicide gave a quick fix and but probably needs to be applied regularly. Biocontrol caused a small reduction in % cover that resulted in quick recovery, but as biocontrol increased, the mat sank and biodiversity was reduced, but it is expected that over a longer period of time, biodiversity would make a full recovery.

General Discussion

6.1 Introduction

The overall goal of this research study was to strengthen our understanding of aquatic invasive plants and how they interact with important aspects, such as water quality, control methods and biodiversity recovery. This thesis synthesized the results of several field studies conducted over the study period and discussed them in an ecosystem context. The objectives, methods, and description of the results are presented in greater detail in preceding chapters. This chapter focuses on the big picture of aquatic invasive plants, sums up the most relevant results, discusses the interconnectivity of biological communities, and highlights the implications of this research in the context of invasive aquatic plants, water quality, the socio-economic impact of weeds and how biodiversity recovers after the removal of weeds.

The first chapter synthesized prior studies pertaining to aquatic invasive plant dynamics worldwide. There are several take-home messages from this chapter: the effects of aquatic invasive plants are directly related to their density or extent of coverage; once established, their density appears to be influenced by available nutrients from neighboring farms and industries along the rivers.

This first component of this study (Chapter 2) was to document the distribution of aquatic weeds and compare them to the indigenous flora. This study clearly indicated that the examined macrophytes consisted of aquatic invasive plants (weeds) and native plants (opportunistic plants) and weeds in some regions in the southern part of Mozambique. The most troublesome weeds found were the water hyacinth (*Eichhornia crassipes*), water red fern (*Azolla microphylla*), water lettuce (*Pistia stratiotes*) and salvinia (*Salvinia molesta*). It is therefore necessary to monitor the weeds along the southern Mozambique rivers and to implement the correct control management for all of them. It will be important to extend this research to the central and northern rivers in Mozambique to identify the weeds and map their distribution and abundance.

The survey and consultations on the impact of aquatic weeds in the Incomati Basin River (Chapter 3) indicate that, currently, aquatic weed infestations are increasing all the time. Communities living along the rivers are well aware of the range of socio-economic problems caused by the weed. However, quantitative data for each weed have to be carefully studied to give an idea of the real implications and impacts on the communities. Quantifying impacts and thus defining the real problems caused by the aquatic weeds presents a challenge. Aquatic weeds have a serious impact on humans, increasing some diseases such as malaria, bilharzia and cholera and creating economic impacts since it is necessary to pay for weed control.

A comprehensive strategy needs to be carried out to address the socio-economic concerns associated with water weeds. Further, a co-ordinating mechanism to manage water hyacinth and other invasive weeds needs to be put in place to ensure that a common approach is adopted, not only in one river (Incomati Basin River) but in the all the Mozambique rivers basin. For the future, it is recommended that a common approach be implemented to manage water hyacinth, water lettuce and water red fern in order to enhance understanding and alleviate some of the impacts associated with infestation by these weeds.

Since a lack of appropriate tools and systems for monitoring makes it impossible to know the precise areas of coverage of each weed, it is necessary to coordinate activities properly throughout the river.

6.1.1 Evaluation of biological control programme

The benefits of the biological control of weeds and evaluation of the success of biological control are essential to justify the continued use of biological control for conservation (Van Driesche *et al.*, 2010; Morin *et al.*, 2009). In the Mozambique rivers, it is recommended that the impact of weevils on water hyacinth is monitored and evaluated periodically; that weevils are redistributed to areas with low weevil populations and that new infestations of water weeds are investigated. At this level, it is recommended that the responsible organizations such as MICOA (Ministry of Coordination and Environmental Affairs), DNA (National Directorate of Water) and the Ministry of Agriculture facilitate the importation of weevils from neighbouring countries such as South Africa. In order to minimize the impact of water hyacinth, which grows

aggressively, it is necessary to release the weevils *Neochetina eichhorniae* and *N. bruchi* as well as *Eccritotarsus caterinensis* and possibly other host-specific species on floating mats *Eichhornia crassipes* and to assist in their redistribution and spread to non-release sites.

Concerning the other weeds, such as water lettuce, red water fern and salvinia, low numbers of biological control agents, namely *Neohydronomus affinis*, *Cyrtobagous salvinae* and *Stenopelmus rufinasus*, were found along the southern Mozambique rivers. This study indicated lower densities of insects in Mozambique. It is recommended that the number of biological agents be increased in the Mozambique rivers or be released in the rivers where no biological control was found.

This study (Chapter 4) has clearly shown that of the four floating water weeds, water hyacinth had the greatest and quickest negative impact on the environment and people and, although the study found the weevils *Neochetina eichhorniae* and *N. bruchi* were effective biological control agents, their impact is too gradual compared to the aggressive proliferation of water hyacinth. Thus additional agents are required to better control the weed, and sources of pollution must be addressed.

6.1.2 Identification and knowledge of invasive species with the greatest impact on biodiversity

In Mozambique, there are different policies, regulations, strategies and institutional arrangements concerning Invasive Alien Species. The effective implementation of the strategy and action plan is based firstly on attributing responsibilities to various institutions, at national, provincial and local level, signifying that coordination between the different levels is indispensable. It is also important for its success that the different sectors of Mozambican society are taken into consideration and included during its application, namely the private sector, NGOs and civil society in general. The Ministry for the Coordination of Environmental Action (MICOA) must oversee coordination of implementation and related activities and ensure the integration of the various sectors via the National Biodiversity Unit.

The main objectives of MICOA organization are to measure and prevent the introduction of weeds, to control or eradicate alien species, and to arouse public awareness on the risks of introducing alien invasive species, all of which are currently being undertaken.

A reduction in weed densities will not necessarily result in an increase in biodiversity, but because protecting biodiversity is the aim of the biological control of environmental weeds, it is native biodiversity that should be measured when evaluating success (Chapter 5). Many alien species have been introduced into Mozambique for different purposes, namely commercial (*Eucalyptus* plantations) agriculture, livestock, agro-froresty (*Leucaena leucocephala* (Lam.) *Azadirachta indica* (Neem)), ornamental landscaping, and even for conservation (*Casuarina* sp.) plantations along the coast line. Some have invaded river basins as in the Incomati River (*Salvinia molesta* and *Eichhornia crassipes*) reducing water availability, which is serious problem in Mozambique. In Mozambique, measures and strategies were established to eradicate the main invasive species, reduce the introduction of new species and adopt tariff and non-tariff borders that inhibit/limit importing invasive species, but the impact of these IAS on biodiversity is poorly understood, and recovery after control has not been studied at all.

This study (Chapter 5) has shown that environmentally negative effects have been associated with the presence of water lettuce on biodiversity recovery in pools during a one-year trial. However, this does not prove that water lettuce does alter the ecosystem. It is possible that the observations reflect the cumulative impact of intermittent water lettuce infestations rather than the initial ecological response to water lettuce's presence. It is difficult to know with certainty if water lettuce is the sole driver of the observed results, but by taking an ecosystem approach, it was possible to cross-validate the results of this study (Chapter 5) and look beyond the direct effects commonly studied. Thus it can be concluded that water weeds such as water lettuce have a negative effect on biodiversity. It may be that the initial introduction and establishment of water weeds in this system caused the system to shift away from such conditions to resemble what we see today. Such alterations can be permanent, even if water lettuce were to be eradicated. Several management recommendations can be made, based on the results of this study, since most countries give more weight to IAS issues in their biodiversity strategy and action plans than their national environmental action plans and policies.

6.1.3 Recommendations for long-term management of the invasive aquatic plants in Mozambique

Greater connectivity within the modern world has resulted in globalization (IPCC, 2007; Bright, 1999), and this has increased the threat posed by invasive species, such as aquatic invasive weeds (Thieme *et al.*, 2010; Vörösmarty *et al.*, 2010; Scheffer *et al.*, 1993). Managing invasive aquatic plants results in minimizing the socio-economic damage caused by these plants. However, in some countries, the reality is that most invasive plants are nearly impossible to control, or to eradicate once established, unless significant capital expenditure is invested. In many cases, the ecosystem structures, such as food webs and energy pathways, are changed once the non-native plants become invasive (Scheffer *et al.*, 1993). In such cases, managers are faced with a difficult choice of how to allocate limited resources to combat invasive species threats. They give priority to control efforts, especially in aquatic systems where changes can drastically affect human well-being. Unfortunately, invasive species management is mostly reactive and rarely practical, and management is often initiated in the absence of adequate understanding. Quick responses to invasive species issues that lack the support of strong ecological understanding can lead to inadequate allocation of time and resources, and in some cases, can further complicate the problem.

Mozambique faces heightened invasion pressures as a result of increasing globalization, increased movement of people across borders, food insecurity (and the resultant aid shipments), and climate change effects, (including more frequent, more severe droughts and floods). At a human management level, the major challenges faced are a widespread lack of knowledge and awareness of the aquatic invasive plant problem and inadequate human resources available to manage these invasions. This capacity problem is exacerbated by the effects of diseases like malaria, bilharzia and diarrhea.

The three major institutions currently addressing Invasive Alien Species (IAS), including aquatic invasive weeds problem within Mozambique, are the Ministry of Environment, the Ministry of Agriculture, and the Eduardo Mondlane University of Mozambique. The main mechanisms for addressing the problem within the country should be public awareness such as posters, newsletters, radio and TV advertisements, and community mobilisation both through

formal training programmes and awareness workshops, strengthening research and updating information on invasive aquatic weeds in the country and the initiation of research into sustainable management strategies. Enhanced networking between the ministries of Environment Affairs, Agricultural Research, Fisheries, Water Resources, Forestry, Energy and Justice, and Investment Partners and NGOs is essential. The motivation to improve the prevention and management of aquatic weeds in Mozambique should come from the combined efforts of the three leading institutions: the IUCN in Mozambique, the Faculty of Agriculture and the Environmental Affairs Department within the Ministry of Natural Resources, and Environmental Affairs.

The institution proposed to deal with the challenges should consist of three sectors: MICOA, the scientific community and the private and industrial sectors. The government, represented by MICOA, in coordination with other institutions would be responsible for integrating the proposed activities into the development plans and for suggesting necessary alterations in accordance with each situation. This Institution (MICOA) should:

- create greater capacity and provide additional funding to carry out invasive species activities;
- lead regional and international co-operation and develop sub-regional invasive species management plans;
- establish and participate in public education and awareness-raising campaigns linked to invasive species;
- develop sustainable management plans for natural resources under the most pressure;
- ensure that communities participate in managing invasive alien species, including waterweeds;
- ensure that considerations on biodiversity are integrated into land use plans, both for rural and urban areas;
- ensure that the community and stakeholders benefit from involvement in the management of invasive species in the country by providing financial and technical support and assisting them to develop the necessary human resources to manage invasive alien species effectively;

- update existing laws of the country and those of the African Phytosanitary Council of the Inter-African Union.

The role of the scientific community, via government research, museums, NGOs and other research bodies, is fundamental in order to implement the strategy due to the major lack of scientifically-grounded and up-to-date information.

The main objective of the scientific community should be:

- To provide the scientific evidence about sustainable use and management and measures to mitigate damage to the conservation of biodiversity as a result of the various business developments in order to achieve the objectives laid down in this strategy. These should be closely related to government organs in the aim of directing research towards relevant areas and in accordance with national priorities.

The private and industrial sectors also have to contribute.

- The role of the private and industrial sector should be centred on the commitment to implement the environmental prescriptions and regulations proposed by the government, the acceptance of social and environmental responsibility through voluntarily adopting measures to minimize impacts, and the development of economic activities that support sustainable conservation and the use of national biodiversity.

6.1.4 Importance of Aquatic ecosystem in Mozambique

Rivers in Mozambique have enormous economic and aesthetic value and are largely responsible for maintaining and supporting overall environmental health. Local populations along the southern Mozambique rivers depend on aquatic resources for food, medicines, and collecting building materials, as well as for recreational and commercial purposes such as fishing and transport. Aquatic organisms also rely upon the great diversity of aquatic habitats and resources for food, materials, and breeding grounds. Factors including the introduction of exotic species, pollution from urban, industrial, and agricultural areas, as well as habitat loss and alteration through damming and water diversion all contribute to the declining levels of aquatic biodiversity in freshwater environments. As a result, valuable aquatic resources are becoming

increasingly susceptible to both natural and artificial environmental changes. Thus, conservation strategies to protect and conserve aquatic life are necessary to maintain the balance of nature and support the availability of resources for future generations.

References

Aguilar J.A, Camarena, O.M., Center, T.D. and Bojorquez, G. 2003. Biological control of waterhyacinth in Sinaloa, Mexico with the weevils *Neochetina eichhorniae* and *N. bruchi*. *Biocontrol* **48**:595-608.

Ajuonu, O. and Neuenschwander, P. 2003. Release, establishment, spread and impact of the weevil *Neohydronomus affinis* (Coleoptera: Curculionidae) on water lettuce (*Pistia stratiotes*) in Benin, West Africa. *African Entomology* **11**:205-211.

Ajuonu, O., Byrne, M.J., Hill, M.P., Neuenschwander, P. and Korie, S. 2009. The effect of two biological control agents, the weevil *Neochetina eichhorniae* and the mired *Eccritotarsus catarinensis* on water hyacinth, *Eichhornia crassipes*, grown in culture with water lettuce, *Pistia stratiotes*. *Biocontrol* **54**:155-162.

Ajuonu, O., Schade, V., Veltman, B., Sedjro, K. and Neuenschwander, P. 2003. Impact of the weevils *Neochetina eichhorniae* and *N. bruchi* (Coleoptera: Curculionidae) on water hyacinth, *Eichhornia crassipes* (Pontederiaceae), in Bénin, West Africa. *African Entomology* **11**:153-161.

Albano Pérez, E., Coetzee, J.A., Ruiz Téllez, T. and Hill, M.P. 2011. A first report of water hyacinth (*Eichhornia crassipes*) soil seed banks in South Africa. *South African Journal of Botany* **77**:795-800.

Anesio, A.M., Abreu, P.C. and Biddanda, B.A. 2003. The role of free and attached microorganisms in the decomposition of estuarine macrophyte detritus. *Estuarine, Coastal and Shelf Science* **56** (2):197-201.

Anon Mozambique. 2006. Mozambique National Summary Report On Land-Based Activities, Sources of Pollution And Pollutant Levels In Water And Sediment. Draft report submitted to WIO-Lab PMU, Nairobi, Kenya.

ARC-Plant Protection Research Institute (ARC-PPRI). 2010. Focus on invasive aquatic plants. Sapia News Southern African Plant Invaders Atlas 19, pp:1-7.

Arimoro, F.O. 2009. Impact of rubber effluent discharges on the water quality and macroinvertebrate community assemblages in a forest stream in the Niger Delta. *Chemosphere* **77**:440-449.

Arimoro, F.O. and Muller, W.J. 2010. Mayfly (Insecta:Ephemeroptera) community structure as an indicator of the ecological status of a stream in the Niger Delta area of Nigeria. *Environmental Monitoring and Assessment* **166**:581-594.

Ashton, P.J. and Walmsley, R.D. 1984. The taxonomy and distribution of *Azolla* species in Southern Africa. *Botanical Journal of Linnean Society*. **89**:239-247.

Ashton, P.J., Scott, W.E., Steyn, D.J. and Wells, R.J. 1979. The Chemical Control Programme Against the Water Hyacinth *Eichhornia crassipes* (Mart.) Solms on Hartebeespoort Dam: Historical and Practical Aspects. *South African Journal of Science* **75**:303-306.

Atonga, A.S. 2001. "Selectivity of Gillnets on Nile Perch, *Lates Niloticus* Population in Lake Victoria, Kenya," (M.Phil thesis, Moi University, 2001).

Axelsen, S. and Julien, C. 1988. Weed control in small dams. Part II. Control of salvinia, azolla and water hyacinth. *Queensland Agricultural Journal*, pp: 291-298.

Baloi, P., Santana-Afonso, P., Premegi N., Volstad, J.H. 2007. Metodologia e Processamento de Dados de Captura e Esforço de Pesca em Moçambique. *Revista de Investigação Pesqueira* N^o 25. Instituto Nacional de Investigação Pesqueira, Moçambique, pp: 29

Bartram, J., Carmichael, W.W., Chorus, I., Jones, G., and Skulberg, O. 1999. Introduction. In: Chorus, I., Bartram, J. (eds). Toxic Cyanobacteria in Water. A Guide to Their Public Health Consequences, Monitoring and Management, New York: E and FN, pp: 1-14.

Beilfuss, R., Moore, D., Dutton, P. and Bento, C. 2001. Patterns of vegetation change in the Zambezi Delta, Mozambique. Working papers of the Program for the Sustainable Management of Cahora Bassa Dam and Lower Zambezi Valley. Working paper 3, pp: 78.

Bennett, F. D. 1966. Investigations on the insects attacking the aquatic ferns, *Salvinia* spp. in Trinidad and northern South America. *Proceedings of the Southern Weed Conference* 19:497-504.

Bickel, T.O. and Closs, G.P. 2008. Fish distribution and diet in relation to the invasive macrophyte *Lagarosiphon major* in the littoral zone of Lake Dunstan, New Zealand. *Ecology of Freshwater Fish* 17(1):10-19.

Bonada, N., Prat, N., Resh, V.H. and Statzner, B. 2006. Development in aquatic insect biomonitoring: A comparative analysis of recent approaches. *Annual Review of Entomology* 51:495-523.

Bond, W.J. and Roberts, M.G. 1978. The colonization of Cabora Bassa, Mocambique, a new man-made lake, by floating African macrophytes. *Hydrobiologia* 60:243-259.

Bowes, G., Rao, S.K., Estavillo, G.M., and Reiskind, J.B. 2002. C4 mechanism in aquatic angiosperms: comparisons with terrestrial C4 systems. *Functional Plant Biology* 29:379-392.

Boyle, T.P. and Fraleigh, H.D. Jr. 2003. Natural and anthropogenic factors affecting the structure of the benthic macroinvertebrate community in an effluent-dominated reach of the Santa Cruz River, Arizona. *Ecological Indicators* 3:93-117.

Bright, C. 1999. Invasive species: Pathogens of globalization. *Foreign Policy*, **116**:50-60, 62-64.

Brito, R., Famba, S., Munguambe, P., Ibraimo, N. and Julaia, C. 2009. Profile of the Limpopo Basin in Mozambique, a contribution to the Challenge Program on Water and Food Project 17 “Integrated Water Resource Management for Improved Rural Livelihoods: Managing risk, mitigating drought and improving water productivity in the water scarce Limpopo Basin”. *WaterNet Working Paper 11*. WaterNet, Harare.

Burrows, J. E. 1999. Two new taxa of Ophioglossum from Tropical Africa. *Bothalia* **29**: 109-112.

[Cal-IPC] California Invasive Plant Council. 2007. California Invasive Plant Inventory. Cal-IPC Publication 2006-02. Berkeley, California: California Invasive Plant Council, pp: 39 <http://www.cal-ipc.org/ip/>.

Camargo, A. F. M., Pezzato, M. M. and Henry-Silva, G. G. 2003. Factores limitantes ao crescimento de macrófitas aquáticas. In: Thomaz, S. M. and L. M. Bini (eds). *Ecologia e Manejo de Macrófitas Aquáticas*. Maringá: Eduem, pp: 59-83.

Caquet, C., Hanson, M., Roucaute, M., Graham, D. and Lagadi, L. 2007. Influence of isolation on the recovery of pond mesocosms from the application of an insecticide. II Benthic macroinvertebrate responses. *Environmental Toxicology and Chemistry* **26**:1280-1290.

Carmo Vaz, A.C. 2000. Coping with floods – the experience of Mozambique. In: 1st WARFSA/WaterNet Symposium: Sustainable Use of Water Resources. Maputo, 1–2 November.

Carmo Vaz, A. and Lopes Pereira, A. 2000. The Incomati and Limpopo International River Basins, a View from Downstream. *Water Policy*. Vol. 2, Nos 1–2, pp: 99-112.

Carmo Vaz, A. and Van der Zaag, P. 2003. Sharing the Incomati Waters: co-operation and competition in the balance, from potential conflict to co-operation potential. Maputo and

Harare, Mozambique and Zimbabwe: 11 December 2002, 2002. (SC-2003/WS/46) UNESCO-IHE/IHP/WWAP. PCCP report 14 SC-20.

Cattaneo, A., Galanti, G., Gentinetta, S. and Susana, A. 1998. Epiphytic algae and macroinvertebrates on submerged and floating-leaved macrophytes in an Italian lake. *Freshwater Biology* 39: 725-740.

Center, T.D. 1994. Biological control of water weeds: water hyacinth and water lettuce. *In: Rosen, D., Bennett, F.D. and Capinera, J.L. (eds.). Pest Management in the Subtropics – A Florida Perspective. Intercept Ltd., Andover, pp: 481-521.*

Center, T.D., Hill, M.P., Cordo, H. and Julien, M.H. 2002. Water hyacinth *In: Van Driesche, R., et al., 2002. Biological Control of Invasive Plants in the Eastern United States, USDA Forest Service Publication FHTET, pp: 41-64.*

Center, T.D.; Dray, A.F.; Jubinsky, G.P. and Grodowitz, M.J. 1999. Biological control of water hyacinth under conditions of maintenance management: can herbicides and insects be integrated? *Environmental Management* 23: 241-256.

Chadwell, T.B. and Engelhardt, A.M. 2008. Effects of pre-existing submersed vegetation and propagule pressure on the invasion success of *Hydrilla verticillata*. *Journal of Applied Ecology* 45: 515-523.

Chao, A. 2005. Species richness estimation. *In: Balakrishnan N, Read CB, Vidakovic B (eds). Encyclopedia of statistical sciences. Wiley, New York, pp: 7909-7916.*

Charudattan, R., 2001. Biological control of weeds by means of plant pathogens: significance for integrated weed management in modern agro-ecology. *BioControl* 46: 229–260.

Chazdon, R.L.; Colwell, R.K.; Denslow, J.S. and Guariguata, M. R. 1998. Statistical methods for estimating species richness of woody regeneration in primary and secondary rain

forests of NE Costa Rica. *In*: Dallmeier, F. and Comiskey, J.A. (eds). Forest biodiversity research, monitoring and modeling: conceptual background and Old World case studies. Paris, Parthenon Publishing, pp: 285-309.

Chiconela, T. 2009. Personal communication*

Chiconela, T., Santos, L. and Cugala, D. 2002. Plantas Aquáticas das zonas Centro e Sul de Moçambique. Relatório de Pesquisa, Maputo. UEM, pp: 25.

Chikwenhere, G.P. and Keswani, C.L. 1997. Economics of biological control of Kariba weed (*Salvinia molesta* Mitchell) at Tengwe in north-western Zimbabwe. A case study. *Int. Journal Pest Management* **43**: 109-112.

Chikwenhere, G.P. and Forno, I.W. 1991. Introduction of *Neohydronomus affinis* for the biological control of *Pistia stratiotes* in Zimbabwe. *Journal of Aquatic Plant Management* **29**:53-55.

Chikwenhere, G.P., Keswani, C.L. and Liddel, C. 1999. Control of water hyacinth and its environmental and economic impacts at Gache Gache in the eastern reaches of Lake Kariba, Zimbabwe. *In*: Hill, M.P., Julien, M.H. and Center, T.D. (eds). Biological and Integrated control of water hyacinth, *Eichhornia crassipes*. Proceedings of the 1st Meeting of the Global Working Group for the Biological and Integrated Control of water hyacinth, Harare, Zimbabwe, 16-19 November 1998. Plant Protection Research Institute, Pretoria, South Africa, pp: 30-38.

Cilliers, C.J. 1991. Biological control of water hyacinth, *Eichhornia crassipes* (Pontederiaceae) in South Africa. *Agriculture, Ecosystems and Environment* **37**:207-217.

Cilliers, C. J. 1987. First attempts at and early results on the biological control of *Pistia stratiotes* L. in South Africa. *Koedoe* **30**:35-40. Pretoria ISSN-0075-6458.

Cilliers, C.J., Hill, M.P., Ogwang, J.A. and Ajuonu, O. 2003. Aquatic weeds in Africa and their control. *In: Neuenschwander, P., Borgemeister, C. and Langewald, J. (eds). Biological control in IPM systems in Africa.* CAB International, pp: 161-178.

Clarke, K. R. 1993. Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology* **18**:117-143.

Clarke, K.R. and Gorley, R.N. 2006. Primer v6: user manual/tutorial. PRIMER-E, Plymouth.

Clarke, K.R. and Warwick, R.M. 2001. Change in marine communities: an approach to statistical analyses and interpretation, 2nd edn. PRIMER-E, Plymouth.

Clarke, K.R. and Warwick, R.M. 1994. Change in Marine Communities. An approach to Statistical Analysis and Interpretation. Published-Plymouth Marine Laboratory, Natural Environment Research Council, United Kingdom, pp: 5(1)-5(12); 8(1).

Clavero, M. and García-Berthou, E. 2005. Invasive species are a leading cause of animal extinctions. *Trends in Ecology and Evolution* **20**:110. doi:10.1016/j.tree.2005.01.003.

Clay, K. 2003. Parasites lost. *Nature* **421**: 585-586.

Coetzee J.A., Byrne M.J. and Hill, M.P 2007. Impact of nutrients and herbivory by *Eccritotarsus catarinensis* on the biological control of water hyacinth, *Eichhornia crassipes*. *Aquatic Botany* **86**:179-186.

Coetzee, J.A., Hill, M.P., Byrne, M.J. and Bownes, A. 2011. A review of the biological control programmes on *Eichhornia crassipes* (C. Mart.) Solms (Pontederiaceae), *Salvinia molesta* D.S. Mitch. (Salviniaceae), *Pistia stratiotes* L. (Araceae), *Myriophyllum aquaticum* (Vell.) Verdc. (Haloragaceae) and *Azolla filiculoides* lam. (Azollaceae) in South Africa. *African Entomology* **19** (2):451-468.

Coetzee, J.A., Hill, M.P., Julien, M.H., Center, T.D. and Cordo, H.A., 2009. *Eichhornia crassipes* (Mart.) Solms-Laub. (Pontederiaceae). In: Muniappan, R., Reddy, G.V., Raman, A. (eds). *Biological Control of Tropical Weeds using Arthropods*. Cambridge University Press, New York, NY, pp: 183-210.

Colwell, R.K. 2005. *Estimates: Statistical estimation of species richness and shared species from samples*. Version 7.5. User's Guide and application published at: <http://purl.oclc.org/estimates>.

Consultec 1998. *Country Situation Report: Water Resources* (Final draft) Vol I, II and III. DNA. Maputo, Mozambique.

Cook, C.D.K. 2004. *Aquatic and wetland plants of southern Africa*. Leiden, Backhuys Publishers. Hill, M.P. and Coetzee, J.A. 2008. Integrated control of water hyacinth in Africa. (a ten-step plan). *OEPP/EPPO Bulletin* **38**:452–457.

Corbin, J.D. and D'Antonio, C.M. 2004. Competition between native perennial and exotic annual grasses: implications for an historical invasion. *Ecology* **85**:1273-1283.

Cordo, H. and Sosa, A. 2000. The weevils *Argentinorhynchus breyeri*, *A. bruchi* and *A. squamosus* (Coleoptera: Curculionidae), candidates for the biological control of waterlettuce (*Pistia stratiotes*). In *Proceedings of the X International Symposium on Biological Control of Weeds* (N.R.Spencer,ed.),pp:325-335.<http://www.invasive.org/publications/xsymposium/Session5.html>.

Cossa, N. E. 2009. *Distribuição e possíveis factores de proliferação das plantas aquáticas invasivas na Bacia do Rio Incomati*. Trabalho de licenciatura, Universidade Pedagógica. Maputo. Moçambique.

Cronk, J.K. and Fennessy, M.S. 2001. *Wetland Plants. Biology and Ecology*. Lewis Publishers, Boca Raton, Florida.

Crow, G.E. 1993. Species diversity in aquatic angiosperms: latitudinal patterns. *Aquatic Botany* **44**:229–258.

Cugala, D. 2009. Personal communication**

Cugala, D. 2006. Espécies Invasivas em Moçambique. MICOA: Nível de Conhecimento, necessidades de treinamento e potenciais centros de excelência em Moçambique. Maputo, pp: 50.

Cugala, D. 2004. *Relatório sobre espécies invasivas*. MICOA. Moçambique.

Dallas, H.F. and Day, J.A. 2004. The effect of water quality variables on aquatic ecosystems. A review. Water Research Commission. Report No. TT 22/04.

Daubermire, J. (1957). *Cover Scale or Classe Methods in Bonham*. Canada, pp: 54.

Davies, B. R., Hall, A. and Jackson, P. N. B. 1975. Some ecological aspects of the Cabora Bassa Dam. *Biological Conservation* **8**:189-201.

De Groote, H., Ajuonu, O., Attignon, S., Djessou, R. and Neuenschwander, P. 2003. Economic impact of biological control of water hyacinth in Southern Bénin. *Ecological Economics* **45**:105-117.

Den Hartog, C. and Segal, S. 1964. A new classification of the water plant communities. *Acta botanica Neerlandica* **13**: 367–393.

Den Hollander, N. G., Diouf, S., Schenk, I., Bastiaans, L., Kropff, M. J. and Pieterse A. H. 1998. Crowding enhances flowering of *Pistia stratiotes*. In: Monterio A, Vasconcelos T, Catarion L (eds), Management and ecology of aquatic plants. Proceedings, 10th European Weed Research Society International Symposium on Aquatic Weeds, Lisbon, 21–25 September 1998, pp: 71-74.

Dickens, C. W. S. and Graham, P. M. 1998. Biomonitoring for effective management of wastewater discharges and the health of the river environment. *Aquatic Ecosystem Health and Management*, **1(2)**:199 -217.

Dickens, C.W.S. and Graham, P.M. 2002. The South African Scoring System (SASS) Version 5 Rapid Bioassessment Method for Rivers. *African Journal of Aquatic Science* **27**:1-10.

Diop, O. and Hill, M.P. 2009. Quantitative post-release evaluation of biological control of floating fern, *Salvinia molesta* D.S. Mitchell (Salviniaceae), with *Cyrtobagous salviniae* Calder and Sands (Coleoptera: Curculionidae) on the Senegal River and Senegal River Delta. *African Entomology* **17**:64–71.

DNA (National Directorate of Water) 2011. Environmental and Social Impact Assessment (ESIA) for the construction of Ressano Garcia Weir. Volume1. Biophysical Environment, pp: 18.

DNA (National Directorate of Water) 2008. Boletim de Análise de Água. Laboratório Nacional de Higiene de Alimentos e Águas. Ministério da Saúde. Maputo, Moçambique.

DNA (National Directorate of Water) 1999. Water Resources of Mozambique, Synopsis 1999: Instituto da Agua e Direccao Nacional de Aguas. Edition supported by the Cooperation Portugal-Mozambique.

DNA (National Directorate of Water) 1996. Monografia hidrográfica da bacia do rio Limpopo. Texto. Direcção Nacional de Águas-Ministério de Obras Públicas e Habitação. Maputo.

DNA (National Directorate of Water) 1994. Participação da DNA no Seminário sobre o Impacto das Práticas agrícolas na albufeira dos Pequenos Libombos (16-17 Novembro de 1993). Maputo, Moçambique, pp: 8.

Dray, F.A. and Center, T.D. 2002. Water lettuce. *In*: Van Driesche R, Blossey B, Hoddle M, Lyon S, Reardon R (eds). *Biological control of invasive plants in the eastern United States*. Publication FHTET-2002-04, USDA Forest Service, pp: 65-78.

Dray, F. A., Center, T. D. and Habeck, D. H. 1993. Phytophagous insects associated with *Pistia stratiotes* in Florida. *Environmental Entomology* **22**:1146-1155.

Duelli, P. and Obrist, M. K. 2003. Biodiversity indicators: the choice of values and measures. *Agriculture, Ecosystems and Environment* **98**:87-98.

Evans, H.C. and Reeder, R.H. 2001. Fungi Associated with *Eichhorina Crassipes* (Water Hyacinth) in the Upper Amazon Basin and Prospects for Their Use in Biological Control. International Organization for Biological Control, Second Global Working Group Meeting for Biological and Integrated Control of Waterhyacinth, 9-12 October 2000, Beijing, China, pp: 62–70.

Facon, B., Genton, B.J., Shykoff, J., Jarne, P., Estoup, A. and David, P. 2006. A general ecoevolutionary framework for understanding bioinvasions. *Trends in Ecology and Evolution* **21**:130-133.

FAO-SAFR 2004. Drought impact mitigation and prevention in the Limpopo River Basin. A situation analysis Sub-regional office for Southern-Africa/ Harare, Rome.

Feikin, D.R., Tabu, C.W. and Gichuki, J. 2010. Does water hyacinth on East African lakes promote cholera outbreaks? *American Journal of Tropical Medicine and Hygiene* **83**:370-373. doi:10.4269/ajtmh.2010.09-0645.

Ferreira, M.T., Catarino, L. and Moreira, I. 1998: Aquatic weed assemblages in an Iberian drainage channel system and related environmental factors. *Weed research* **38** (4):291-300.

Forno, I.W., and Julien, M.H., 2000. Success in biological control of aquatic weeds by arthropods. *In*: Gurr, G. and Wratten, S. (eds). *Biological Control: Measures of Success*. Kluwer Academic Publishers. The Netherlands, pp: 159-187.

Fouche, P.S.O. and Vlok, W. 2010. Water quality impacts on in stream biota of the Shingwedzi River, South Africa. *African Journal of Aquatic Science* **35** (1):1-11.

Gerber, A. and Gabriel, M. J. M. 2002. *Aquatic Invertebrates of South African Rivers: Field Guide*. Institute For Water Quality Services, Department of Water Affairs and Forestry, Pretoria.

GIIBS (Grupo Inter-Institucional sobre Bio-Segurança) 2005. Proposta do quadro legal e institucional sobre biosegurança em Moçambique, Ministerio de Agricultura. Maputo, Mozambique.

GISP (Global Invasive Species Programme) 2003. *Prevention and Management of Invasive Alien Species*. Proceedings of Workshop on Forging Cooperation throughout Southern Africa. *In*: Macdonald, I.A.W., J.K. Reaser, C. Bright, L.E. Neville, G.W. Howard, S.J. Murphy and G. Preston (eds). *Invasive alien species in southern Africa: national reports and directory of resources*. Global Invasive Species Programme, Cape Town, South Africa.

Gorgens, A.H.M. and Wilgen, B.W. 2004. Invasive alien plants and water resources in South Africa: current understanding, predictive ability and research challenges. *South African Journal of Science* **100**: 27-33.

Gotelli, N. J. and Colwell, R.K. 2001. Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. *Ecology Letters* **4**:379–391.

Gratwicke, B. and Marshall, B. E. 2001. The impact of *Azolla filiculoides* Lam. on animal biodiversity in streams in Zimbabwe. *African Journal of Ecology* **39**(2): 216-218.

Greathead, J. D. 2003. Aquatic weeds in Africa and their control. *In*: P. Neuenschwander, P., Borgemeister, C. and Langewald, J. (eds). Biological Control in IPM Systems in Africa. CABI Publishing, Wallingford, U.K, pp: 1-26.

Greenfield, B. K., Blankinship, M. and McNabb, T.P. 2006. Control costs, operation, and permitting issues for non-chemical plant control: case studies in the San Francisco Bay-Delta Region, California. *Journal Aquatic Plant Manage* **44**:40-49.

Grobler, H., Vermeulen, J. and Van Zyl, K. 2000. *A guide to the use of herbicides. 17th edition*. National Department of Agriculture, RSA. Directorate: Agricultural Production inputs.

Gupta, M. and Paliwal, A. 2010. Role of aquatic insects of water quality in related to Physico-chemical parametres in Yamuna River at District Firozabad (UP) *Advances in Bio research* **1 (1)**:71-74.

Gustafsson, A. and Johansson, M. 2006. An investigation of nutrient levels along the Mbuluzi River. A background for sustainable water resources management. A Minor Field Study (MFS) conducted in Mozambique and Swaziland Master of Science Thesis in Environmental Engineering Department of Water Resources Engineering Faculty of Engineering Lund University Report 9, pp:130.

Gutiérrez, E., Arreguín, F., Huerto, R. & Saldaña, P. 1994. Aquatic weed control. *Int. J. Water Resources Development* **10**: 291-312.

Harley, K.L.S. 1990. The role of biocontrol control in the management of water hyacinth, *Eichhornia crassipes*. *Biocontrol News and Information* **11(1)**: 11-22.

Harley, K.L.S., R.C. Kassulke, D.P.A. Sands, and M.D. Day. 1990. Biological control of water lettuce *Pistia stratiotes* (Araceae) by *Neohydronomus affinis* (Coleoptera: Curculionidae). *In*: Hassan, R., Schole, R. and Ash, N. (eds.) (2005), Ecosystems and human well-being: current state and trends. Vol. 1 Island press, Washington, pp: 917. <http://www.millenniumassessment.org/en/Condition.aspx#download> Accessed: 25August, 2010.

Hatton, J., Couto, M. and Oglethorpe, J. 2001. Biodiversity and war: a case study of Mozambique. Washington, DC: WWF Biodiversity Support Program.

Havel J.E., Lee C.E. and Vander Zanden, M.J. 2005. Do reservoirs facilitate invasions into landscapes? *BioScience* **55**:518-25.

Heard, T.A. and Winterton, S. L. 2000. Interactions between nutrient status and weevil herbivory in the biological control of water hyacinth. *Journal of Applied Ecology* **37**:117-127.

Henderson, L. 2001. Alien Weeds and Invasive Plants. Agricultural Research Council, Plant Protection Research Institute, pp: 21.

Henderson, L. and Cilliers, C. 2002. Invasive aquatic plants. A guide to the identification of most important and potentially dangerous invasive aquatic and wetland plants in South Africa. Agricultural Research Council, Pretoria, pp: 88.

Henderson, L. and Cilliers, C. 1991. Water lettuce. Weeds A.33. Farming in South Africa. Published by the Department of Agricultural Development and obtainable from the Directorate of Agricultural Information, Private Bag X144, Pretoria 0001. Gutenberg Book Printers, Pretoria.

Henry-Silva, G. G. and Camargo, A. F. M. 2000. Impacto do lançamento de efluentes urbanos sobre ecossistemas aquáticos do município de Rio Claro-SP. *Revista Ciências Biológicas e do Ambiente* **3**:317-330.

Hill, M.P. 2003. Impact and Control of alien aquatic vegetation in South African aquatic ecosystems. *African Journal of Aquatic Science* **28** (1):19-24.

Hill, M.P. 2001. Summary of session 6 (Integrated management). In: Julien, M.H., Hill, M.P., Center, T.D. and Ding Jianqing (eds). Biological and Integrated control of water hyacinth,

Eichhornia crassipes. Proceedings of the 2nd Meeting of the Global Working Group for the Biological and Integrated Control of water hyacinth, Beijing, China, 9-12 October 2000. Australian Centre for International Agricultural Research, Canberra, Australia. pp: 151-152.

Hill, M.P. 2000. More agents for South Africa. *Water Hyacinth News* **1**: 7. A-AQUATIC MACROPHYTE, MANAGEMENT, BIOCONTROL, EICHHORNIA.

Hill, M.P. 1999. Biological control of red water fern, *Azolla filiculoides* Lamarck (Pteridophyta: Azollaceae) in South Africa. In: Olckers, T., Hill, M.P. (eds). Biological Control of Weeds in South Africa (1990–1998), *African Entomology Memoir* **1**: 119-124.

Hill, M. P. 1998. Life history and laboratory host range of *Stenopelmus rufinasus*, a natural enemy for *Azolla filiculoides* in South Africa. *BioControl* **43**:215–224.

Hill, M. P. 1997. The potential for the biological control of the floating aquatic fern, *Azolla filiculoides* Lamarck (red water fern/rooiwatervaring) in South Africa. *WRC Report N° KV 100/97*, pp: 31.

Hill, M.P. and Cilliers, C.J. 1999. A review of the arthropod natural enemies, and factors that influence their efficacy, in the biological control of the water hyacinth, *Eichhornia crassipes* (Mart.) Solms-Laubach (Pontederiaceae), in South Africa. In: Olckers, T. and Hill, M.P (eds). *Biological control of weeds in South Africa (1990-1998)*. *African Entomology Memoir* 1. The Entomological Society of South Africa, Pretoria, pp:103-112.

Hill, M.P. and Cilliers, C.J. 1999. *Azolla filiculoides* Lamarck (Pteridophyta: Azollaceae), its status in South Africa and control. *Hydrobiologia* **415**:203-206.

Hill, M.P. and Coetzee, J.A. 2008. Integrated control of water hyacinth in Africa. OEPP/EPPO, *Bulletin OEPP/EPPO, Bulletin* **38**:452-457.

Hill, M.P. and Julien, M.H. 2004. The transfer of appropriate technology; key to the successful biological control of five aquatic weeds in Africa. In: *Proceedings of the XIth International Symposium on Biological control of Weeds*. In: Cullen, J.M., Briese, D.T., Kriticos, D.J., Lonsdale, W.M., Morin, L. and Scott, J.K. (eds). CSIRO Entomology, Canberra, Australia, pp: 370-374

Hill, M.P. and Madeira, P. 2011. *Stenopelmus rufinasus* proves to be an excellent *Azolla* taxonomist. *13th International Symposium on Biological Control of Weeds*. 11th to 16th September 2011, Waikoloa, Hawaii.

Hill, M.P. and McConnachie, A. J. 2009. *Azolla filiculoides*. In: Muniappan, R., Reddy, G.V.P., Raman, A., Gandhi, V.P. (eds). *Weed Biological Control with Arthropods in the Tropics*. Cambridge University Press, Cambridge, UK, pp: 74-87.

Hill, M.P. and Olckers, T. 2001. Biological control initiatives against water hyacinth in South Africa : constraining factors, success and new courses of action. In: Julien, M., Hill, M.P., Center, T. and Ding, J. (eds). *Proceedings of the Meeting of the Global Working Group for the Biological Control and Integrated Control of Water Hyacinth, Beijing, China, 9-12 October 2000*. Australian Centre for International Agricultural Research. Canberra, Australia, pp: 33-38.

Hill, M.P., Cilliers, C.J. and Neser, S. (1999) Life history and laboratory host range of *Eccritotarsus catarinensis* (Carvalho) (Heteroptera: Miridae), a new natural enemy released on water hyacinth (*Eichhornia crassipes* (Mart.) Solms-Laub.) (Pontederiaceae) in South Africa. *Biological Control* **14**:127-133.

Hill, M.P., Coetzee J.A. and Ueckermann, C. 2012. Toxic effect of herbicides used for water hyacinth control on two insects released for its biological control in South Africa *Biocontrol Science and Technology* **22 (11)**:1321-1333.

Holl, K. D. and Howarth, R. B. 2000. Paying for restoration. *Restoration Ecology* **8**: 260-267.

Holm, L. G., Plucknett, D. L., Pancho J. V. and Herberger, J. P. 1991. The world's worst weeds; Distribution and biology. Krieger Publishing Company, Malabar, FL, pp: 609.

Houlahan, J.E. and Findlay, C.S. 2004. Effect of invasive plant species on temperate wetland plant diversity. *Conservation Biology* **18**:1132-1138.

Howard, G.W. and Harley, K.L.S. 1998. How do floating aquatic weeds affect wetland conservation and development? How can these effects be minimised? *Wetlands Ecology and Management* **5**: 215-225.

Hussner, A. and Lösch, R. 2005. Alien aquatic plants in a thermally abnormal river and their assembly to neophyte-dominated macrophyte stands (River Erft, Northrhine-Westphalia) *Limnologica* **35**:18-30.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: Synthesis Report*. Intergovernmental Panel on Climate Change, Geneva, Switzerland. www.ipcc.ch/pdf/assessmentreport/ar4/syr/ar4_syr.pdf.

IUCN. 2000. Guidelines for the prevention of biodiversity loss due to biological invasion. IUCN–The World Conservation Union, Gland, Switzerland.

Jacot Guillarmod, A. 1979. Water weeds in southern Africa. *Aquatic Botany* **6**:377-391.

Jacob Guillarmod, A. and Allanson, B.R., 1978. Eradication of water hyacinth. *South African Journal of Science* **74**: 122.

Jacobs, M.J. and Macisaac, H.J., 2009. Modelling spread of the invasive macrophyte *Cabomba caroliniana*. *Freshwater Biology* **54**:296-305.

Jacono, C. and Pitman, B. 2001. “*Salvinia molesta*: Around the world in 70 years,” *Aquatic Nuisance Species Digest* **4**:13-16.

Jafari, N., Senobari, Z. and Pathak, R. K. 2010. Biotechnological potential of *Azolla filiculoides*, *Azolla microphylla* and *Azolla pinnata* for biosorption of Pb(II), Mn(II), Cu (II) and Zn(II). *Ecology, Environment and Conservation* **16**:443–449.

Jafari, N. G., Gunale, V.R., Mahajan, D.M. and Shirke, D.R. 2006. Effects of Environmental Factors on Ecology and Distribution of Aquatic Macrophytes. *Asian Journal of Plant Sciences* **5**:871-880.

James, C.S., Easton, J.W. and Hardwick, K. 1999. Competition between three submerged macrophytes, *Elodea canadensis* Michx, *Elodea nuttallii* (Planch) St. John and *Lagarosiphon major* (Ridl.) Moss. *Hydrobiologia* **415**:35-40.

Jayaweera, M.W. and Kasturiarachchi, J.C. 2004. Removal of nitrogen and phosphorus from industrial wastewaters by phytoremediation using water hyacinth (*Eichhornia crassipes* (Mart.) Solms). *Water Science Technology* **50**:217-225.

Jones, R. 2009. The impact on biodiversity, and integrated control, of water hyacinth, *Eichhornia crassipes* (Martius) Solms-Laubach (Pontederiaceae) on the Lake Nsezi – Nseleni River System. Masters dissertation, Department of Zoology and Entomology, Rhodes University, Grahamstown, South Africa, pp: 49.

Julien M.H, 2001. Biological control of water hyacinth with arthropods: a review to 2000. In: Julien, M.H., Hill, M.P., Center, T.D., Jianqing, D. (eds). *Biological and Integrated Control of Water Hyacinth*, *Eichhornia crassipes*. *Proceedings of the Second Meeting of the Global Working Group for the Biological and Integrated Control of Water Hyacinth, 2000*. Canberra, Australia: Australian Centre for International Agricultural Research: ACIAR Proceedings No. **102**, pp: 8-20.

Julien, M. H., Griffiths, M. W. and Stanley, J. N. 2001. *Biological control of water hyacinth. The moths Niphograptus albiguttalis and Xubida infusellus: biologies, host ranges, and rearing, releasing and monitoring techniques for biological control of Eichhornia crassipes*.

Monograph No. 79. Australian Centre for International Agricultural Research (ACIAR), Canberra, pp: 79

Julien, M.H. and Griffiths, M.W. 1998. Biological control of weeds. A world catalogue of agents and their target weeds, 4th ed. Wallingford, UK, CAB International, pp: 223.

Julien, M.H., Hill, M.P. and Tipping, P.W. 2009. *Salvinia molesta* D.S. Mitchell (Salviniaceae). In: Muniappan, R., Reddy, G.V.P., Raman, A., Gandhi, V.P. (eds). Weed Biological Control with Arthropods in the Tropics. Cambridge University Press, Cambridge, pp: 378-407.

Julien, M.H., Griffiths, M.W. and Wright, A.D. 1999. Biological control of water hyacinth: the weevils *Neochetina bruchi* and *N. eichhorniae*, biologies, host ranges and rearing, releasing and monitoring techniques for biological control of *Eichhornia crassipes*. Canberra, Australian Centre for International Agricultural Research, ACIAR Monograph No. 60, pp: 87

Kateregga, E. and Sterner, T. 2009. Lake Victoria fish stocks and the effects of water hyacinth. *The Journal of Environment and Development* **18**:62-78.

Keane, R.M. and Crawley, M.J. 2002. Exotic plant invasions and the enemy release hypothesis. *Trends in Ecology and Evolution* **17**:164-170.

Kebede, Y., Kebede, T., Assefa, F. and Amsalu, A. 2010. Environmental impact of coffee processing effluent on the ecological integrity of rivers found in Gomma woreda of Jimma zone, Ethiopia. *Ecohydrology and Hydrobiology* **10(2)**: 259-270.

Kent, A. and Coker, P. 1992. Vegetation Description and Analysis – A Practical Approach. John Wiley and Sons, New York.

Kent, M. and Coker, P. 1994. Vegetation description and analysis – a practical approach. John Wiley and Sons Chichester, New York.

Kimura, M. 2005. Populations, community composition and biomass of aquatic organism in the floodwater of rice fields and effects of field management. *Soil Science and Plant Nutrition* **51** (2):159-181.

Kiorboe, T. and Saiz, E. 1995. Planktivorous feeding in calm and turbulent environments, with emphasis on copepods. *Marine Ecology-Progress Series* **122**, pp: 135-145.

Kitoh, S., Shiomi, N. and Uheda, E. 1993. The growth and nitrogen fixation of *Azolla filiculoides* Lam. in polluted water. *Aquatic Botany* **46**:129-139.

Kolar, C.S. and Lodge, D.M. 2000. Freshwater non-indigenous species: interactions with other global changes. In *Invasive Species*, pp: 3-30.

Lake, J. C. and Leishman, M. R. 2004. Invasion success of exotic plants in natural ecosystems: the role of disturbance, plant attributes and freedom from herbivores. *Biological Conservation* **117**:215-226.

Legesse, W. 2001. *Sensitivity of biotic indices to natural disturbances*. PhD thesis, Department of Zoology and Animal Ecology, University College Cork, Republic of Ireland.

Leitner, W. and Turner W.R. 2001. Measurement and analysis of biodiversity. In: Levin SA (ed). *Encyclopedia of biodiversity*. Academic Press, Princeton, Vol 4 pp: 123-144.

Lindgren, C.J., Corrigan, J. and De Clerck-Floate, R.A. 2002. *Lythrum salicaria* L. purple Loosestrife (Lythraceae). In: Mason, P.G., Huber, J.T. (eds). *Biological Control Programs in Canada, 1981–2000*. CABI Publishing, New York, pp: 383-390.

Longepierre, S., Robert, A., Levi, F. and Francour, P. 2005. How an invasive alga species (*Caulerpa taxifolia*) induces changes in foraging strategies of the benthivorous fish *Mullus surmuletus* in coastal Mediterranean ecosystems. *Biodiversity and Conservation* **14** (2): 365-376.

Lu, J.B., Wu, J.G., Fu, Z.H. and Zhu, L. 2007. Water hyacinth in China: A sustainability science based Management framework. *Environmental Management* **40**: 823-830.

Lugo, A.E. 1994. Maintaining an open mind on exotic species. *In*: Principles of conservation biology. Meffe, G.k. and Carroll C.R. (eds). Sinauer Associates, Massachusetts, pp: 18-20.

Lumpkin, T. A. and Plucknett, D. L. 1982. *Azolla* as a green manure: Use and Management in crop production. Westview Tropical Agriculture Series No. 5. Westview Press, Boulder, Colorado, pp: 230.

Macedo, J. M. A. 1974. Vegetação aquática em Cabora Bassa: alguns problemas futuros Lourenço Marques: Inst. de Investigação Agronómica de Moçambique, pp: 86.

Maceina, M.J., Cichra, M., Betsill, R. and Bettoli, P. 1992. Limnological changes in a large reservoir following vegetation removal by grass carp. *Journal of Freshwater Ecology* **7**:81–93.

Mack, R.N. and Smith, M.C. 2011. Invasive plants as catalysts for the spread of human parasites. *NeoBiota* **9**:13-29. doi: 10.3897/neobiota.9.1156

Mack, R.N., Simberloff, D., Lonsdale, W.M., Evans, H., Clout, M. and Bazzaz, F.A. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. *Ecological Applications* **10**:689-710.

Madsen, J. D. 2000. Advantages and disadvantages of aquatic plant management techniques. ERDC/EL MP-00-1, Environmental Laboratory, U.S. Army Corps of Engineers

Madsen, T.V. and Maberly, S.C. 1991. Diurnal variation in light and carbon limitation of photosynthesis by two species of submerged freshwater macrophyte with a differential ability to use bicarbonate. *Freshwater Biology* **26**:175-187.

Magurran, A.E. 2004. *Measuring Biological Diversity*. Blackwell Science Ltd. Blackwell Publishing 9600 Garsington Road, Oxford, United Kingdom.

Mailu, A. M. 2001. Preliminary assessment of the social, economic and environmental impacts of water hyacinth in the Lake Victoria basin and the status of control. In *Proceedings of the 2nd Meeting of the Global Working Group for the Biological and Integrated Control of Waterhyacinth, Beijing, China, 9-12 October 2000*. In: Julien, M. H, Hill, M.P., Center, T.D. and Ding, J. (eds). Australian Centre for International Agricultural Research, Canberra, Australia, pp: 130-139.

Maki, K., and Galatowitsch, S. 2004. Movement of invasive aquatic plants into Minnesota (USA) through horticultural trade. *Biological Conservation* **118**: 389–396.

Mallya, G.A. 1999. Water hyacinth in Tanzania. In: Hill, M.P., Julien, M.H. and Center, T.D. (eds.) Biological and Integrated control of water hyacinth, *Eichhornia crassipes*. Proceedings of the 1st Meeting of the Global Working Group for the Biological and Integrated Control of water hyacinth, Harare, Zimbabwe, 16-19 November 1998. Plant Protection Research Institute, Pretoria, South Africa, pp: 25-29.

Mandaville, S. M. 2002. Benthic macroinvertebrates in freshwaters: Taxa tolerance values, metrics, and protocols. Project H-1, Soil and Water Conservation Society of Metro Halifax. xviii, <http://chebucto.ca/Science/SWCS/SWCS.html>. Soil and Water Conservation Society of Metro Halifax, Nova Scotia Canada. 48 p, Appendices A–B, pp: 120.

Mangas-Ramirez, E. and Elias-Gutierrez, M. 2004. Effect of mechanical removal of water hyacinth (*Eichhornia crassipes*) on the water quality and biological communities in a Mexican reservoir. *Journal of Aquatic Health and Management* **7**:161-168.

Martin, G. D. and Coetzee, J. A. 2011. Pet stores, aquarists and the internet trade as modes of introduction and spread of invasive macrophytes in South Africa. *Water SA* [online] **37(3)**:371-380. ISSN 1816-7950.

Martinez Jimenez, M and Gomez Balandra, M.A .2007. Integrated control of *Eichhornia crassipes* by using insects and plant pathogens in Mexico. *Crop Protection* **26**:1234-1238.

Masifwa, W.F., Twongo, T. and Denny, P. 2001. The impact of water hyacinth, *Eichhornia crassipes* (Mart) Solms on the abundance and diversity of aquatic macroinvertebrates along the shores of northern Lake Victoria, Uganda. *Hydrobiologia* **451**:79-88.

Mbati, G. and Neuenschwander, P. 2005. Biological control of three floating water seeds, *Eichhornia crassipes*, *Pistia stratiotes*, and *Salvinia molesta* in the Republic of Congo. *BioControl* **50**:635-645.

McConnachie, A.J., Hill, M.P. and Byrne, M.J. 2004. Field assessment of a frond-feeding weevil, a successful biological control agent of red water fern, *Azolla filiculoides*, in southern Africa. *Biological Control* **29**:326-331.

McConnachie, A.J., de Wit, M.P., Hill, M.P. and Byrne, M.J. 2003. Economic evaluation of the successful biological control of *Azolla filiculoides* in South Africa. *Biological Control* **28**: 25-32.

Meerhoff, M., Fosalba, C., Bruzzone, C., Mazzeo, N., Noordoven, W. and Jeppesen, E. 2006. An experimental study of habitat choice by *Daphnia*: plants signal danger more than refuge in subtropical lakes. *Freshwater Biology* **51**:1320-1330.

Mehra, A., Farago, M. E., Banerjee, D. K. and Cordes, K. B. 1999. The water hyacinth: An environmental friend or pest? A review. *Resource Environmental Biotechnology* **2**:225-281

Michelan, T.S., Thomaz, S. M., Mormul, R.P. and Carvalho, P. 2010. Effects of an exotic-invasive macrophyte (tropical signalgrass) on native plant community composition, species richness and functional diversity. *Freshwater Biology* **55**:1315-1326. doi:10.1111/j.1365-2427.2009.02355.x

Middelboe, A.L. and Markager, S. 1997. Depth limits and minimum light requirements of freshwater macrophytes. *Freshwater Biology* **37**:553-568.

Midgley, J.M., Hill, M.P. and Villet, M. H. 2006. The effect of water hyacinth, *Eichhornia crassipes* (Martius) Solms-Laubach (Pontederiaceae), on benthic biodiversity in two impoundments on the New Year's River, South Africa. *African Journal of Aquatic Science* **31**:25-30.

Ministério Para a Coordenação da Acção Ambiental (MICOA) 2007. Estratégia Ambiental Para o Desenvolvimento Sustentável de Moçambique.

Miretzky, P., Sarelegui, A. and Cirelli, F. 2006. Simultaneous heavy metal removal mechanism by dead macrophytes. *Chemosphere* **62**:247-254.

Mironga J.M., 2004. Geographic information systems (GIS) and remote sensing in the management of shallow tropical lakes. *Applied Ecology and Environmental Research* **2**:83-103.

Mironga, J. M., Mathooko, J. M., Onywere, S. M. 2011. The Effect of Water Hyacinth (*Eichhornia Crassipes*) Infestation on Phytoplankton Productivity in Lake Naivasha and the Status of Control. *Journal of Environmental Science and Engineering* **5(10)** 1252-1261.

Mitchell, C.E. and Power, A.G. 2003. Release of invasive plants from fungal and viral pathogens. *Nature* **421**:625-626.

Mitchell, D.S. 1969. The ecology of vascular hydrophytes on Lake Kariba. *Hydrobiologia* **34**:448-64

Mitchell, D.S. 1972. Aquatic weeds. *Rhodesia Science News* **6**:105-106.

Mooney, H.A. 2005. Invasive alien species: The nature of the problem. In: *Invasive Alien Species*, H.A. Mooney, R.N. Mack, J.A. McNeely, L.E. Neville, P.J. Sheia, and J.K. Waage (eds.), Island Press, Washington, DC, pp: 1-15.

Moozhiyil, M. and Pallauf, J. 1986. Chemical composition of the water fern, *Salvinia molesta*, and its potential as feed source for ruminants. *Economic Botany* **40**:375-383.

Morin, L., Reid, A.M., Sims-Chilton, N.M., Buckley, Y.M., Dhileepan, K., Hastwell, G.T., Nordblom, T.L., Raghu, S. 2009. Review of approaches to evaluate the effectiveness of weed biological control agents. *Biological Control* **51**, 1–15.

Nagasaka, M., Yoshizawa, K. Ariizumi, K and Hirabayashi, K. 2002. Temporal changes and vertical distribution of macrophytes in Lake Kawaguchi. *Oecologia* **3**:107-114

Navarro, L.A. and Phiri, G. 2001. Water hyacinth in Africa survey of problems and solutions. International Development Research Center, pp: 140.

Navarro, L. and Phiri, G. 2000. *Water hyacinth in Africa and the Middle East. A survey of problems and solutions*. International Development Research Centre, Ottawa, Canada, pp: 140.

Neuenschwander, P., Julien, M.H., Center, T.D. and Hill, M.P. 2009. *Pistia stratiotes* L. (Araceae). In: Muniappan, R., Reddy, G.V., Raman, A. (eds). *Biological Control of Tropical Weeds Using Arthropods*. Cambridge University Press, New York, NY, pp: 332-352.

Nyenje, P.M., Foppen, J.W., Uhlenbrook, S., Kulabako, R and Muwanga, A. 2010. Eutrophication and nutrient release in urban areas of sub-Saharan Africa – A review. *Science of the Total Environment* **408**:447-455.

O'Brien, C.E. and Jones, R.L. 2003. Early and Middle Pleistocene vegetation of the Médoc region, southwest France. *Journal of Quaternary Science* **18 (6)**:557-579.

O'Hara, R. B. 2005. Species richness estimators: how many species can dance on the head of a pin? *Journal Animal Ecology* **74**:375-386.

Obot, E.A. and Ayeni, J.S.O.1987. *A handbook of common aquatic plants of the Kainji Lake Basin, Nigeria*. Kainji Lake Research Institute/Saolog Printing Production, Ilorin.

Odjegba, V.J., and Fasidi, I.O. 2004. Accumulation of trace elements by *Pistia stratiotes*: Implications for phytoremediation. *Ecotoxicology* **13**:637-646.

Ogwang, J.A. and Molo, R., 2003. 'Water hyacinth, *Eichhornia crassipes*: A case of successful Biological Control in Lakes Kyoga and Victoria. *Uganda Journal of Agricultural Sciences* **8**:245-252.

Oliveira, J. S. 1972. 'Zimofolia' Um novo alimento levedurizada. Instituto superior de Agronomia. Lisboa **32**:21-36.

Oliver, J. D. 1993. "A review of the biology of giant salvinia (*Salvinia molesta* Mitchell)," *Journal of Aquatic Plant Management* **31**:227-231.

Oosthuizen, G. J. and Walters, M. M. 1961. Control of water fern with diesoline. *Farming in South Africa* **37**:35-37.

Opande, G.O. 2002. Distribution of the water hyacinth (*Eichhornia crassipes* (MART.) SOLNS), its carpet characteristics, some of its diseases and their causative agents in the Winam gulf (Lake Victoria). In: PhD thesis October 2002. Maseno University, Maseno, Kenya.

Opande, G.O., Onyango, J.C., Wagai, S.O. 2004. Lake Victoria: The water hyacinth (*Eichhornia crassipes* [Mart.] Solms), its socio-economic effects, control measures and resurgence in the Winam gulf. *Limnologica* **34**:105-109.

Oudhia P.1999a. Medicinal weeds in rice fields of Chhattisgarh (India). *Int Rice Res Notes* **24**:40.

Oudhia, P. 1999b. Studies on allelopathy and medicinal weeds in chickpea fields. *Int Chickpea Pigeonpea Newsl* **6**:29-33

Padilla, D. K and Williams, S. L 2004. Beyond ballast water: aquarium and ornamental trades as sources of invasive species in aquatic ecosystems. *Frontiers in Ecology and the Environment* **2**:131-138.

Palumbi, S.R. 2001: Humans as the world's greatest evolutionary force. *Science* **293**:1786-1790.

Parker M., Simberloff D., Lonsdale W.M., Goodell K., Wonham M., Kareiva P.M., Williamson, M.H., Holle B.V., Moyle P.B., Byers J.E. and Goldwasser L. 1999. Impact: Toward a framework for understanding the ecological effects of invaders. *Biological Invasions* **1**:3-19.

Pearson, D. E 2009. Invasive plant architecture alters trophic interactions by changing predator abundance and behavior. *Oecologia* **159**:549-558.

Parsons, W.T. and Cuthbertson, E.G., 2001. Soursob. In: Parson, W.T., Cuthbertson, E.G. (Eds.), *Noxious Weeds of Australia*. Csiro Publishing, Australia, pp: 529-534.

Perna, C. and Burrows, D. 2005. Improved dissolved oxygen status following removal of exoticweed mats in important fish habitat lagoons of the tropical Burdekin River floodplain, Australia. *Marine Pollution Bulletin*, **51**:138-148.

Perrings, C., Williamson, M., Dalmazzone, S. (eds). (2000). *The Economics of Biological Invasions*. Edward Elgar, Northampton, MA.

Phiri, G. (ed). 1997. *Water Hyacinth Newsletter (African)*, No.6, International Institute of Biological Control, Nairobi Office.

Pielou, E. C. 1975. *Ecological Diversity*. Wiley, New York, New York, USA.

Pieterse, A.H., Kettunen, M., Diouf, S., Ndao, I., Sarr, K., Tarvainen, A., Kloff, S., Hellsten, S. 2003. Effective biological control of *Salvinia molesta* in the Senegal River by means of the weevil *Cyrtobagous salviniae*. *Ambio* **32**:458-462.

Pieterse, A.H., Hellsten, S.K., Janauer, G.A., Dieme, C., Diouf, S. and Exler, N. 2002. Management of aquatic vegetation in the lower Senegal River basin. *Verhandlungen der Internationalen Verein Limnologie* **28**:549-555.

Pillips, E.C. 2008. Invertebrate colonization of native and invasive aquatic macrophytes in Presque Isle Bay, Lake Erie. *Journal of Freshwater Ecology* **23**:451–458.

Pimentel, D., Lach, L., Zuniga, R. and Morrison, D. 2000. Environmental and economic costs of nonindigenous species in the United States. *BioScience* **50**:53-64.

Pisces Conservation Ltd., 2000. ECOM: Environmental Community Analysis, Version 1.27. www.irchouse.demon.co.uk.

Poi de Neiff, A. and Carignan, R. 1997. Macroinvertebrates on *Eichhornia crassipes* roots in two lakes of the Paraná River floodplain. *Hydrobiologia* **345 (2)-(3)**:185-196.

Pushpa, G.S. and John, C.V. 2010. Does water hyacinth (*Eichhornia crassipes*) compensate for simulated defoliation? Implications for effective biocontrol. *Biocontrol* **54**:35-40.

Raju, R. A. and Gangwar, B. 2004. Utilization of potassium-rich green-leaf manures for rice (*Oryza sativa*) nursery and their effect on crop productivity. *Indian Journal of Agronomy* **49**: 244-247.

Reddy, K.R., Kadlec, R.H., Flaig, E. and Gale, P.M. 1999. Phosphorus retention in streams and wetlands: a review. *Critical Reviews in Environmental Science and Technology* **29**:83-146.

Relyea, R.A. 2005. The Impact of Insecticides and Herbicides on the Biodiversity and Productivity of Aquatic Communities. *Ecological Applications* **15** (2):618- 627, ISBN 1051-0761.

Reyes, O.S. and Fermin, A. C. 2003. Terrestrial leaf meals or freshwater aquatic fern as potential feed ingredients for farmed abalone *Haliotis asinina* (Linnaeus 1758). *Aquaculture Research* **34**:593-599

Ricciardi, A. and Cohen, J. 2007. The invasiveness of an introduced species does not predict its impact. *Biological Invasions* **9**:309-315.

Richards, D.I., Small J. and Osborne, J. 1985. Response of zooplankton to the reduction and elimination of submerged vegetation by grass carp and herbicides in four Florida lakes. *Hydrobiologia* **123**:97-108.

Richardson, D.M. and Van Wilgen, B.W. 2004. Invasive alien plants in South Africa: How well do we understand the ecological impacts? *South African Journal of Science* **100**: 45-52.

Richardson, D.M., Pyšek, P., Rejmánek, M., Barbour, M.G., Panetta, F.D. and West, C.J. 2000. Naturalization and invasion of alien plants: concepts and definitions. *Diversity and Distributions* **6**: 93-107.

Ripley, B.S., Muller. E., Behenna, N., Whittington-Jones, G. M. and Hill, M.P. 2006. Biomass and photosynthetic productivity of water hyacinth (*Eichhornia crassipes*) as affected by nutrient supply and mirid (*Eccritotarus catarinensis*) biocontrol. *Biological Control* **39**:392-400.

Robelas, R. 1984 Qualidade de água na albufeira dos Pequenos Libombos, aspectos de saúde relacionados a construção e empreendimento e projectos de regadio acompanhantes. DNA. Maputo, Moçambique, pp:14.

Rodolfo, A. 2007 Avaliação preliminary do Impacto da Infestação por jacinto-de-água, *Eichhornia crassipes* (Mart.) Solm. (Liliales: Ponteriaceae) e fauna associada na Bacia do Rio Incomati - Trabalho de Licenciatura, UEM, Maputo, Moçambique.

Rolon, A.S., and Maltchik, L. 2006. Environmental factors as predictors of aquatic macrophyte richness and composition in wetlands of Southern Brazil. *Hydrobiologia* **556** (1): 221-231.

Rommens, W., Maes, J., Dekeza, N., Inghelbrecht, P., Nhiwatiwa, T., Holsters, E., Ollevier, F., Marshall, B. and Brendonck, L. 2003. The impact of water hyacinth (*Eichhornia crassipes*) in a eutrophic subtropical impoundment (Lake Chivero, Zimbabwe). I. Water quality. *Archiv Fur Hydrobiologie*, **158**:373-388.

Room, P.M., 1990. Ecology of a simple plant-herbivore system: biological control of salvinia. *Trends in Ecology and Evolution* 5:74-79.

Room, P. M. 1986a. "Salvinia molesta - a floating weed and its biological control." *The ecology of exotic animals and plants*. R. L. Kitching, ed., John Wiley, Brisbane, Queensland, Australia, pp: 164-186.

Room, P.M. and Julien, M.H. 1995. *Salvinia molesta*. In: Groves, R.H., Shepherd, R.C.H. and Richardson, R.G. (eds). *The Biology of Australian Weeds*. R.G. and F.J. Richardson, Melbourne, pp: 217-230.

Room, P. M., Harley, K. L. S. Forno, I. W. and Sands, D. P. A. 1981. Successful biological control of the floating weed salvinia. *Nature* **294** (5836):78-80.

Room, P. M., Julien, M. H. and Forno, I. W. 1989. Vigorous plants suffer most from herbivores: latitude, nitrogen and biological control of the weed *Salvinia molesta*. *Oikos*. **54**:92-100.

Rossaro, B., Marziali, L., Cardoso, C. A., Solimini, A., Free, G. and Giacchini, R. 2007. A biotic index using benthic macroinvertebrates for Italian lakes. *Ecological Indicators* 7:412-429.

Sands, D. P. A. 1983. Identity of *Cyrtobagous* sp. (Coleoptera: Curculionidae) introduced into Australia for biological control of salvinia. *Journal of the Australian Entomological Society* 22:200.

Santos, L., Chiconela, T. and Cugala, D. 2002. *Stenopelmus rufinasus* Gyllenhal (Curculionidae) como agente de biocontrole da *Azolla filiculoides* Lamarck (Azollaceae). Relatório de pesquisa. Faculdade de Agronomia e Engenharia Florestal, Departamento de Produção Vegetal, Universidade Eduardo Mondlane, pp:13.

Scheffer, M., Hosper, S.H., Meijer M.L., Moss, B. and Jeppesen, E. 1993. Alternative equilibria in shallow lakes. *Trends in Ecology and Evolution* 8:275-279.

Schelpe, E.A.C.L.E., 1961. The ecology of *Salvinia auriculata* and associated vegetation on Kariba Lake. *South African Journal of Botany* 27: 181-187.

Schelpe, E.A.C.L.E., 1969. A revised check list of the Pteridophyta of Southern Africa. *South African Journal of Botany* 35:127-140.

Schelpe, E.A.C.L.E., 1977. Pteridophyta. In: Fernandes, R.B., Launert, E. and Mendes, E.J. (eds). *Conspectus Florae Angolensis*. Junta de Investigações Científicas do Ultramar, Lisbon, pp: 1-197.

Schooler, S.S., Williams, D.G., Stokes, K. and Julien, M. 2005. Invasive Plants: Impacts and Management in Rivers and Catchments. River symposium. <http://www.riversymposium.com>. Entomology, Long Pocket Laboratories, Indooroopilly QLD, Australia, pp: 13.

Sculthorpe, C.D., 1967. The biology of aquatic vascular plants. Edward Arnold, London.

Sheppard, A.W., Shaw, R.H. and Sforza, R. 2006. Top 20 environmental weeds for classical biological control in Europe: a review of opportunities, regulations and other barriers to adoption. *Weed Research* **46**:93–117.

Smith, R. L. and Smith, T. M. 2001. Ecology and field biology, 6th ed. An imprint of Addison Wesley Longman, Inc. USA.

Stets, E.G. and Cotner, J.B. 2008. Littoral zones as sources of biodegradable dissolved organic carbon in lakes. *Canadian Journal of fisheries and Aquatic Science* **65 (11)**:2454-2460.

Storrs, M. J. and Julien, M. H. 1996. *Salvinia: A handbook for the integrated control of Salvinia molesta in Kakadu National Park*. Australian Nature Conservation Agency, Darwin.

Strayer D.L., Lutz, C, Malcom, H.M., Munger, K., and Shaw, W.H. 2003 Invertebrate communities associated with a native (*Vallisneria americana*) and an alien (*Trapa natans*) macrophyte in a large river. *Freshwater Biology* **48**:1938–1949.

Stuckey, R.L. and Les, D.H. 1984. *Pistia stratiotes* Recorded from Florida in Bartram's Travels. *Aquaphyte*, **4(6)**:1765-1774.

Tamele, C. (2002). *Contribuição para o Estudo dos Macrofitos Aquáticos nas Principais Bacias do Hidrográficas da Província de Maputo*. Tese de Licenciatura. 81pp. Maputo. Universidade Eduardo Mondlane.

Tembe, J. and Baloi, A. 2001. Water Access, Policies and Irrigation Schemes Management in Mozambique A Case Study of Umbeluzi river. University of Wisconsin-Madison, pp:1-15.

Ter Braak, C.J.F., Verdonschot, P.F.M., 1995. Canonical correspondence analysis and related multivariate methods in aquatic ecology. *Aquatic Ecology* **57 (3)**, 255–289.

Thieme, M.L., Turak, E., McIntyre, P., Darwall, W., Tockner, K., Cordeiro, J. and Butchart, S.H.M. 2010. Freshwater ecosystems under threat: the ultimate hotspot. *In: Mittermeier, R.A., Farrell, T., Harrison, I.J., Uppgren, A.J. and Brooks, T. (eds). 2010. Fresh Water The Essence of Life. Cemex Conservation Book Series: 18. Conservation International, Arlington, USA, pp: 299.*

Thirion, C. 2000. A new biomonitoring protocol to determine the ecological health of impoundments, using artificial substrates. *African Journal of Aquatic Science* **25**: 123- 133.

Thomas, P.A. and Room, P.M. 1986. Taxonomy and control of *Salvinia molesta*, *Nature* **320**: 581-584.

Thomaz, S.M. and Cunha, E.R. 2010. The role of macrophytes in habitat structuring in aquatic ecosystems: methods of measurement, causes and consequences on animal assemblages' composition and biodiversity. *Acta Limnologica Brasiliensia* **22(2)**:218-236. doi: 10.4322/actalb.02202011.

Thompson, C.R. and D.H. Habeck. 1989. Host specificity and biology of the weevil *Neohydronomus pulchellus*, a biological control agent of waterlettuce (*Pistia stratiotes*). *Entomophaga* **34**: 299-306.

Thomson, S., Enala, T.M. and Mick, M. 2002. Control of aquatic weeds through pollutant reduction and weed utilization: a weed management approach in the lower Kafue River of Zambia. *Physics and Chemistry of the Earth* **27**: 983-991.

Tipping, P.W., Martin, M.R., Center, T.D. and Davern, T.M. 2008. Suppression of *Salvinia molesta* Mitchell in Texas and Louisiana by *Cyrtobagous salviniae* Calder and Sands. *Aquatic Botany* **88**:196-202.

Tiwari S., Dixit, S. and Verma, N. 2007. An effective means of biofiltration of heavy metal contaminated water bodies using aquatic weed *Eichhornia crassipes*. *Environmental Monitoring and Assessment* **129**:253-256.

Toft, D.J., Simenstad, C.A., Cordell, J.R. and Grimaldo, L.F. 2003. The Effects of Introduced Water Hyacinth on Habitat Structure, Invertebrate Assemblages, and Fish Diets. *Estuaries* **26**:746-758.

Tomas, S.M. and Cunha E.R. 2010. The role of macrophytes in habitat structuring in aquatic ecosystems: methods of measurement, causes and consequences on animal assemblages' composition and biodiversity. *Acta Limnologica Brasiliensia* **22(2)**:218-236.

Torchin , M.E. , Lafferty , K.D. , Dobson , A.P. , McKenzie , V.J. and Kuris , A.M . 2003. Introduced species and their missing parasites. *Nature* **421**:628-630.

Toti, S.D., Coyle, F.A. and Miller, J.A. 2000. A structured inventory of Appalachian grass bald and heath bald spider assemblages and a test of species richness estimator performance. *The Journal of Arachnology* **28**:329-345.

Twongo, T. and Balirwa, J. 1995. The water hyacinth problem and the biological control option in the highland lake region of the upper Nile Basin-Uganda's experience. Unpublished paper presented at The Nile 2002 Conference. Comprehensive Water Resources Development of the Nile Basin, held 13–17 February 1995 Arusha, Tanzania.

Twongo, T. and Howard, G. 1998. Ways with weeds. *New Scientist* **159**: 57-57.

Ueckermann, C. and Hill, M.P. 2001. Impact of herbicides used in water hyacinth control on the natural enemies released against the weed for biological control. Report to the Water Research Commission No. 915/1/01. South Africa, pp: 81.

UNEP/Nairobi Convention Secretariat and WIOMSA 2009. An assessment of hydrological and land use characteristics affecting river-coast interactions in the West.

Uqueio, O.V. 2008. Diversidade das Macrófitas Aquáticas Invasivas ao longo da Bacia do rio Umbelúzi- Trabalho de licenciatura, Universidade Pedagógica. Maputo. Moçambique.

Uveges, J.L., Corbett, A.L., and Mal, T.K. 2002. Effects of Pb contamination on the growth of *Lythrum salicaria*. *Environmental Pollution* **120**: 319-323.

Van Driesche, R.G., Carruthers, R.I., Center, T., Hoddle, M.S., Hough-Goldstein, J., Morin, L., Smith, L., Wagner, D.L., et al., 2010. Classical biological control for the protection of natural ecosystems. *Biological Control Supplement 1*: 2–33.

Van Wyk, E and Van Wilgen, B.W. 2002. The cost of water hyacinth control in South Vermeulen, J.B., Grobler, H. and van Zyl, K. 1998. A guide to the Use of Herbicides. Victoria and its control. In: Proceedings of the 1st IOBC Global.

Villamagna, A. M. and Murphy, B.R. 2010. Ecological and socioeconomic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. *Freshwater Biology* **55**:282-298, doi:10.1111/j.1365-2427.2009.02294.

Vörösmarty, C., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Reidy Liermann, C. and Davies, P.M. 2010. Global threats to human water security and river biodiversity. *Nature* **467**:555–561.

West, R.G. 1953. The occurrence of *Azolla* in British interglacial deposits. *New Phytologist* **52**: 267–272.

Willoughby, N., Watson, I.G., Lauer, S., and Grant, I. F. 1993. An Investigation into the Effect of Water Hyacinth on the Biodiversity and Abundance of Fish and Invertebrates in Lake Victoria, Uganda. NRI Project Report 10066 Ao32g, Natural Resources Institute, Chathan, UK.

Wilson, L.M., Fehrer, J., Bräutigam, S. and Grosskopf, G. 2006. A new invasive hawkweed, *Hieracium glomeratum* (Lactuceae, Asteraceae), in the Pacific Northwest. *Canadian Journal of Botany* **84**:133-142.

World Bank. 2000. The inspection panel investigation report. Kenya: Lake Victoria Environmental Management Project (IDA Credit. 2907-KE and GEF TF 23819).

Wright, A.D. and Center, T.D. 1984. Predicting population intensity of adult *Neochetina eichhorniae* (Coleoptera: Curculionidae) from incidence of feeding on leaves of waterhyacinth, *Eichhornia crassipes*. *Environmental Entomology* **13**(6):1478-1482.

WWF (World Wildlife Fund). 2008. WWF Freshwater Work in Mozambique. Lake Niassa Reserve and Lake Chiuta - Amaramba. MA-Millennium Assessment-(2005). Ecosystems and Human Well-being: Biodiversity Synthesis.

Xie, X.J, Ran, W, Shen, Q.R., Yang, C.Y., Yang, J.J. and Cao, Z.H. 2004. Field studies on ³²P movement and P leaching from flooded paddy soils in the region of Taihu Lake, China. *Environ Geochem Health* **26**:237-243.

Yang, B. L. 2004. Study on the chemical components in alfalfa seed. *Grassland and Turf* **3**: 33-35.

* Tomás Chiconela Lecturer and researcher at Eduardo Mondlane University, Av. J.Nyerere, Campus Universitário, Maputo, Mozambique

** Domingos Cugala (Lecturer and researcher) Crop Protection Faculty of Agronomy and forestry Engineering, Eduardo Mondlane University, Av. J. Nyerere, Campus Universitario I, Maputo, Mozambique.