ECONOMIC EVALUATION OF CHEMICAL AND BIOLOGICAL CONTROL METHODS ON FOUR AQUATIC WEEDS IN SOUTH AFRICA.

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ABSTRACT

Invasive alien plants (IAPs) of various kinds pose a threat to ecosystems, biodiversity, conservation and overall economy. In a world experiencing exponential increase in IAPs – this issue has become endemic, especially for developing countries such as South Africa. South Africa is a water scarce country and IAPs increase water stress. Thus, South Africa must invest in a more realistic, environmentally and economically inclusive policy outlook on the management of IAPs including aquatic weeds. This is especially urgent when considering the changing global climate, which is predicted to further reduce the quantity and quality of potable water. The Working for Water Programme (WfW) in South Africa aimed at addressing the issue of IAPs in a way that protects the environment as well as produces maximum return to society through poverty alleviation. As such, the aquatic weeds management strategy put in place for four of South Africa's aquatic weeds *Pista stratiotes*, *Salvinia molesta*, *Azolla filiculoides* and *Myriophyllum aquaticum* - should be one that is cost-effective, efficient and sustainable; yielding the best possible return on investment. Since these four weeds are already under complete biological control, in the absence of biological agents, the WfW programme would have used herbicides to control these weeds. As such, this thesis conducted a retrospective analysis of the relative herbicide cost-saving associated with the use of biological control.

To do this, due to existing limitations, *E. crassipes* was used as a surrogate weed and its herbicide control costs were used as proxy for the herbicide control cost estimates of the four selected weeds; with reasonable conversion factors applied to cater for the biological difference of the five weeds. Using the cost benefit analysis (CBA) framework, the net present cost (NPC) of each control method was calculated to which the relative cost-saving was considered to represent the avoided cost of using biological control instead of chemical control on these weeds. The avoided cost was used as the main benefit component when deriving the relative benefit cost ratios (BCR). Two scenarios were used, one assuming no follow-up requirement and the other assuming one follow-up requirement for chemical control.

Using an 8% discount rate, the study found that the estimated cost of the biological control method on all four aquatic weeds was about R7,843,205 while for chemical control the estimated costs would have costed R149,580,142, R268,264,838 and R881,711,738 for application by means of a boat, bakkie and knapsack. Chemical control cost estimates would have increased to about R164,538,052, R295,216,120 and R1,008,761,000 for boat, bakkie and knapsack approach respectively when including a possible follow-up programme. These would have led to positive BCRs of 90.24:1, 164.97:1 and 557.99:1 across the three chemical control approaches without a follow-up (with BCR of about 99.67:1, 182.00:1 and 631.56:1 for the boat, bakkie and knapsack approach respectively with the accepted follow-up programme). When running a sensitivity test with varying discount rates of 5% and 10%, these results remained robust.

As such, failing to reject the dominant hypothesis in literature, the main conclusion of the study is that biological control is indeed the more cost-effective management option compared to chemical control with respect to herbicide cost-saving. Further, biological control is most-likely to produce more environmental cost-saving and water-saving over chemical control. The study recommends the continued use of the biological control investment on the four aquatic weeds under study as well as on emerging aquatic weeds such as *Iris pseudacorus*, *Nymphaea mexicana* and *Sagittaria platyphylla* in South Africa.

Keywords: invasive alien plants, aquatic weeds, biological control, chemical control, herbicides, cost benefit analysis, cost-effectiveness, herbicide cost-saving, working for water

DECLARATION

This thesis has not been submitted to a university other than Rhodes University, Grahamstown, South Africa. The work presented here is that of the author, unless otherwise stated and all references have been accurately recorded.

Signed: *Maluleke Mary* Date: 26 November 2019

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IAPs – Invasive Alien Plants	**DEFF** – Department of Environment, Fishery and Forestry
ISSA – Invasive Species South Africa	**WfW** – Working for Water
ISR – Invasive Species Regulation	**NRMP**- Natural Resource Management programme
SANBI – South African National Biodiversity Institute	**DWAF** – Department of Water Affairs and Forestry
SAPIA – South African Plant Invaders Atlas	**CBC** – Centre for Biological control
NEMBA – National Environmental Management: Biodiversity Act (no 10 of 2004)	**CBA** – Cost Benefit Analysis
CARA – Conservation of Agricultural Resource	**BCR** – Benefit Cost Ratio
GSDG – Global Sustainable Development Goal	**NPC** – Net Present Cost
CFR – Cape Floristic Region	**GDP** – Gross Domestic Product
SA – South Africa	**CPI** – Consumer Price Index
SANParks – South African National Parks	**PPI** – Producer Price Index

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CHAPTER ONE: INTRODUCTION

1.1 INVASIVE ALIEN PLANT MANAGEMENT IN SOUTH AFRICA

The Department of Environment, Forestry and Fishery (DEFF) Working for Water (WfW) programme in South Africa is a poverty alleviation project through the expanded public works programmes that seeks to control invasive alien plants (IAP) thereby increasing water security, and the programme has two key agendas: an environmental agenda as well as an economic agenda. The environmental agenda's main aim is to protect against environmental degradation. The resource and development economic research agenda has two main aims, to indicate the associated project's full economic costs, as well as develop prioritization methods for future projects, which will help maximize returns to society (Turpie, 2004). The WfW programme has undertaken to invest in an effective system of implementation, monitoring and evaluation in order to achieve the economic agenda – serving part of the above dilemma. The objective of this undertaking is to help determine the best returns on projects, as well as to help establish which of the available control management approaches for invasive alien plants used by the WfW provides the most cost-effective results and a relatively higher cost-saving. Although this undertaking and objective exists, the programme has since, its inception, been unable to adequately address questions relating to the efficiency and effectiveness of its control efforts as well as address how cost-effective and cost-efficient these methods are in achieving desired control levels.

Established in 1995, the WfW programme is South Africa's longest running conservation project (Hosking and du Preez, 2004; van Wilgen *et al*., 2012). The programme has used the globally practiced control methods to reduce IAPs to acceptable levels. All these methods have the same goal but differ with respect to the procedures of achieving tolerable densities. For example, they differ with respect to factors such as time, ease, safety, effectiveness, labour requirement, maintenance and sustainability – amongst others (McFadyen, 1997; Cilliers *et al*., 2003; van Wilgen *et al*., 2004 and Kraehmer *et al*., 2014). The WfW programme has historically relied heavily on mechanical and herbicide control to meet its mandate, with some use of biological control. Although only a small component in terms of budget allocation initially, biological control has, over time, played an important role in the reduction of IAPs populations and their spread (van Wilgen, 2012).

1.2 AQUATIC WEEDS IN SOUTH AFRICA

The WfW programme in South Africa has targeted five aquatic weed invasions known as The Big Bad Five aquatic weeds. They are *Pistia stratiotes (*water lettuce*)*, *Salvinia molesta (*salvinia*)*, *Azolla filiculoides (*red water fern*)*, *Myriophyllum aquaticum (*parrot's feather*)* and *Eichhornia crassipes* (water hyacinth). These weeds are free floating except for *Myriophyllum aquaticum* (parrot's feather) that is rooted. They all originate in South America and have a NEMBA category rating of 1B. This category means that the IAPs may not be owned/grown/sold/ moved/dumped/imported into South Africa because they are considered major invaders that may need state assistance to remove - hence they are under the WfW management programme sponsored by the state (Invasive Species South Africa, 2018). The current status of the weeds is that four of the five weeds are under complete biological control; they are only controlled by a biological control agent and require no other intervention. The exception is *Eichhornia crassipes* (water hyacinth), which is not yet under complete biological control (Hill, 2003; Cilliers *et al*., 2003; Coetzee *et al*., 2011; Hill and Coetzee, 2017). Historically, both chemical and mechanical control have been used on these weeds, however they failed to bring them to satisfactory levels of control due to reasons of impracticality, unsustainability, inefficiency or cost-ineffectiveness (Cilliers *et al*.,2003).

1.3 METHOD TO BE FOLLOWED

This study seeks to evaluate if the WfW has kept true to its undertaking and objective expressed above in terms of the sustainable control of these four aquatic weeds. To do this, the study will conduct a retrospective analysis on the control of these weeds to evaluate if the current control method used is effective not only in achieving the desired efficacy but in terms of producing return on investment. To draw out this cost-effectiveness, relative evaluation should be done on the alternative control method that would have been otherwise used. This is to conduct a broader perspective on the relative return of the use of biological control investment on these weeds.

There are only a few studies in South Africa that have evaluated this matter on one of the four selected aquatic weeds so far and will serve as guide in the proposed study. McConnachie *et al*. (2003) evaluated the cost-effectiveness of biological control in *Azolla filiculoides* in South Africa and found positive benefit cost ratios. No other South African study has been done on the four aquatic weeds, but Doeleman (1989) (Sri Lanka) and Chikwenhere and Kenswani (1987) (Zimbabwe) have been used as reference studies on *Salvinia molesta* – both of which indicate positive return on the biological control incentives on *S. molesta*. Although these studies are few and dated, they are useful for methodology. The proposed study will also help fill the gap of lack of economic evaluation studies on these weeds as it will provide new South African based results on *Pistia stratiotes*, *Salvinia molesta* and *Myriophyllum aquaticum* as well as provide more recent and updated results on *Azolla filiculoides*.

The main hypothesis of this study based on the literature is that biological control is relatively more cost effective than chemical (herbicide) control, providing a higher cost-saving return (van Wyk and van Wilgen, 2002). Although the WfW has since 1995 used biological control exclusively on these weeds, it has not done a retrospective and relative study of this investment on the weeds to see if biological control is in fact cost-effective and efficient. This may be due to the fact that the alternative method (chemical control) has not been used on these weeds since 1995. However, there is a reasonable expectation that the success of biological control has offered a probable cost-saving in relation to what would have been the alternative method and probable to expect some prevailing avoided costs in this regard. It is for this reason that a comparative retrospective analysis is essential to help estimate this possible cost-saving. This comparative retrospective analysis will use *Eichhornia crassipes* (water hyacinth) herbicide costs as a surrogate weed and the costs will be transformed through an expert informed conversion factor.

1.4 PROBLEM STATEMENT

The Department of Environment, Forestry and Fisheries (DEFF) – Working for Water programme (WfW) in South Africa should be in a position to use a cost-effective approach to decide how to control exotic aquatic weeds. The problem is, the continued use of cost-ineffective control management methods will result in continued waste of scarce financial resources; considering the existing fiscal constraints in funding environmental management programmes. Being in this position, the WfW programme should ensure that every Rand invested on aquatic weed management is spent effectively and efficiently – producing maximum possible ecological and economic return. Currently, *Azolla filiculoides*, *Salvinia molesta*, *Pistia stratiotes*, and, *Myriophyllum aquaticum* – are under complete biological control in South Africa (Hill and Coetzee 2017). In the absence of biological control agents, these selected aquatic weeds would have been controlled using herbicides - the main alternative control method under the WfW programme in South Africa. Although biological control has been proven effective in reducing densities and is generally considered a more cost-effective, efficient and financially sustainable approach; there remains a need to adequately evaluate the relative herbicide cost saving of using the biological control management programme, instead of the chemical control management programme on the four selected aquatic weeds in South Africa from the year when the agents were first released until 2018. This herbicide cost-saving will reflect the net avoided cost of using the biological control programme and the overall findings of this study will help the DEFF make a more informed decision in choosing the best approach towards aquatic weed biological invasion control; which is a cost- effective, cost-efficient and financially sustainable management approach both ecologically and economically. In order to recommend, invest in and encourage the continued use of that method going forward. In cases where the DEFF applies herbicide control on the secondary invasions of these aquatic weeds as suggested by the Water Information Management System (WIMS) records, the results should encourage the discontinuation of herbicide use in order to maximize the possible cost saving both currently and in future.

1.5 GOALS OF RESEARCH

This study has one main goal:

- To determine the relative herbicide cost-saving (avoided costs) of using biological control methods, instead of chemical control methods on *Pistia stratiotes (*Water lettuce*)*, *Salvinia molesta (*Salvinia*)*, *Azolla filiculoides (*Red water fern) and *Myriophyllum aquaticum (*Parrot's feather*)* in South Africa.

Sub -goals:

- To estimate the cost of chemical and biological control on the four selected weeds.
- To estimate the avoided cost of using biological control on the four weeds.
- To calculate the relative benefit cost ratio of using biological control on the four weeds.
- To calculate the Net Present Value (NPC) of both chemical and biological control on the four weeds and make deductions on the cost-effectiveness of each.

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

The conservation of biodiversity philosophy in South Africa has acknowledged the need to deal with the issue of biological invasion as a strategy since the 1970s (van Wilgen *et al*., 1997). At the time, biological invasions and in particular invasive aquatic weeds, were considered a detrimental threat to the water resources of the country. Steps taken to help aid the control of such invasive aquatic weeds in catchment areas, included initially, the passing of the Mountain Catchments Areas Act of 1970 motivated by the prevailing reduction in the water resource supply of South Africa, which was exacerbated by the increase of IAPs in water catchments (van Wilgen *et al*., 1997). Prior to this, the presence of IAPs on water resources was never seen as an issue until water demand overtook water supply (van Wilgen *et al*., 1997). Hence, since 1992 following the UN Summit in Rio de Janeiro, IAPs were regarded as one of the fundamental causes of biodiversity loss which translates into an economic loss (Born *et al*., 2005).

The prevailing nature of this issue led to the launch of the Working for Water (WfW) programme in 1995 (Turpie, 2004). Prior to this, early emphasis was put on the evaluation of the costs and benefits of these IAPs as well as the effects they have on the water yield and supply, with little emphasis on the translation of such effects to overall economic losses (Pratt *et al*., 2017). Thus, upon realization of economic losses, a much broader economic valuation of IAPs was initiated so that these losses could be quantified, and their monetary values adequately estimated.

Due to the prevailing lack of ecological and especially economic evaluation at the time, many of the early economic evaluation attempts failed in their ability to evaluate the total value of water, biodiversity and many other economic and environmental resources lost due to IAPs (van Wilgen *et al*., 1997; Turpie, 2004). For example, in some cases economic benefits of IAPs control programmes were underestimated, while in others, the related costs were overestimated (Turpie, 2004). The gap in the integrated ecological and economic evaluation of costs, impacts and benefits became a hindrance to the development and application of effective IAPs control (Pratt *et al*., 2004). More recently, studies continued to seek to identify, evaluate, quantify and compare IAPs costs and benefits as it relates to both their impacts and control measures (Born *et al*., 2005). As such, different economic analytical approaches (van Wilgen *et al*., 1997) and methodologies (Born *et al*., 2005) have been applied to determine which method is more suitable for such analyses. Most scholars however seem to agree that the Cost Benefit Analysis (CBA) framework is the best approach for such economic evaluation, although it has associated limitations and problems (van Wyk and van Wilgen, 2002; McConnachie *et al*., 2003; Born *et al*., 2005 and McConnachie *et al*., 2012).

This chapter will investigate the relevant literature and theoretical framework, postulating that the core sub-disciplines in economics may be useful in understanding the full economic evaluation of the respective policy decision making under study. Moreover, this section will consider literature of the above issues raised, synthesise what has already been done, what is currently being done and what is recommended for the future understanding in each area raised. It will end with a systematic review, conceptual framework as well as a theoretical framework observed in relevant CBA studies done in literature.

2.2 CAUSES OF INVASIVE ALIEN PLANTS

Biological invasions occur when a non-indigenous species are transported, survive, become established and invade an area that is not its place of origin (Mack *et al*., 2000). Invasive species are a threat to the global ecosystems, have increased in number in recent years and are expected to increase exponentially. They are caused by various factors; some of which are either direct (intentional) or indirect (accidental). For example, ecosystem susceptibility and vulnerability are an inherent cause of IAP existence and dominance. Although inherent to most, if not all ecosystems, the degree of ecosystem susceptibility indicates the need to understand that susceptibility depends on various factors such as, human behaviour, land use, demographic, market and institutional structures and circumstances, as well as on the regulatory frameworks and control strategies available (Perrings, 2001; Perrings *et al*., 2002). As it stands, desert, woodland and tropical dry forest (amongst others) are considered less susceptible to biological invasions; while island and aquatic ecosystems are considered the most susceptible. With respect to vulnerability of an ecosystem, it is often enhanced by the nation’s trade dependence, patterns of trade, structure of the economy, as well as travel (Perrings *et al*., 2002). Hence, when evaluating the vulnerability of an ecosystem, the process requires analysis of the relationship between species composition and trade flows (Dalmazonne, 2000). The relationship between economic activity and the susceptibility and vulnerability of ecosystems is said to be positive (Perrings *et al*., 2001). Meaning that, an increase in economic activity will lead to an increase in both the susceptibility and vulnerability of an ecosystem. Factors such as subsidies, policies around tax, property rights, prices and incomes are also said to be positively related to susceptibility.

The above explains the three hypotheses described by Dalmazzone and Giaccaria (2014) with regards to IAPs and their causes. Two of the hypotheses include that "invasions are most likely to occur where ecosystems are disrupted by economic activities" and that "international trade is a crucial pathway of invasions" (Dalmazzone and Giaccaria, 2014:155). International trade is said to be the lead cause of unintentional biological invasions (Mack *et al*., 2000; Xu *et al*., 2006; Dalmazzone and Giaccaria, 2014; Hulme, 2009 and Pratt *et al*., 2017). At a macro level, Perrings *et al*. (2002) suggested that the openness, trade flow composition and regulatory regimes of a country's economy are important enablers for biological invasions. This is because international trade grants access to imports, migration, globalization and tourism. Hence, Mack *et al*. (2000) argued that the growing human migration and commerce enhance a much faster growth in biological invasions.

Alongside economic activities are socio-economic factors caused by the collaborative effect of economic activities, political interests and human behaviour. These include, the GDP (available resource and capacity) and population density of the country. Human behaviour (especially ignorance of actions that enhance new risk), social customs and norms are said to also play a significant role in biological invasion especially through their production, consumption and movement (Perrings *et al*., 2002). In addition to these, Mack *et al*. (2000) suggested that the facilitation of biological invasions could also be attributed to the cultivation and husbandry of those species transported to habitats. Hence the transportation to and introduction in indigenous habitats is another major cause of invasion. These factors– although not the only causes - are identified as the major causes of biological invasions (Marias *et al*., 2001; Essl *et al*., 2011 and Pratt *et al*., 2017).

2.3 EFFECTS OF INVASIVE ALIEN PLANTS

Often, impacts of IAPs have been categorized as either primary and secondary, direct and indirect, short-term and long-term. Direct impacts or losses are those that directly damage ecosystem goods and services that cause direct declines in revenue experienced by key stakeholders affected; while indirect impacts or losses are usually those that relate to the overall ecosystem function and or services (Xu *et al*., 2006). Although primary and or direct impacts are often easy to quantify, indirect or secondary impacts are often among the hardest to quantify (Born *et al*., 2005).

IAPs are by far the greatest threat to the conservation of biodiversity, changing its structural make-up, organization and genetic diversity which altogether leads to an alteration of the functioning, resilience and productivity of ecosystems (Turpie, 2004; Mooney, 2005 and Xu *et al*., 2006). In addition to these, other effects include the alteration of fundamental ecological processes, the production and sustainability of natural ecosystems, direct destruction of indigenous habitats, devastation / competition with / replacement of native species, enhancement of the pollution effect, the threat to the overall human and animal health and welfare, as well as the reduction in water yield and supply (Hill, 2003; Turpie, 2004; Korsgaard and Schou, 2010; Pratt *et al*., 2017). IAPs can also increase environmental hazards such as droughts, fire and floods (Mack *et al*., 2000).

Often the impacts of IAPs are their association with an impact on the economy (Pratt *et a*l., 2017); expressed through their ability to affect the nation’s economic productivity (Richardson and van Wilgen, 2004; Fraser *et al*., 2016). The two main categories of such economic impacts or costs include: loss in potential economic output and losses related to the cost of combating invasions (Mack *et al*., 2000). For example, the resulting crop production loss, loss in the diversity of outputs, reduction in income for agricultural sectors, loss of genetic resources with potential pharmaceutical value, household utility loss and – more commonly - an increase in the cost of control (Turpie, 2004; Born *et al*., 2005). Additionally, IAPs can also have an impact on livelihoods as well as on food security (Pratt *et al*., 2017). Some of these impacts, although cannot be quantified, cannot be ignored and or excluded as though they do not exist; hence, they are often expressed qualitatively.

The overall effect of IAPs is the impact the have on the biotic integrity of ecosystems, which is defined as "the capacity of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region" (Karr, 1987:249). The impact and interruption of biotic integrity is problematic in that it imposes various social, economic and environmental effects that are and have the potential to be costly if left unaddressed (Richardson and Wilgen, 2004).

The specific impacts of aquatic weeds (the topic of this thesis) often include loss of water due to high evaporation rates, suppression of aquatic vegetation, consumption of significant water quantities, effect on irrigation water and activities, effect on the supply of water by households and or for domestic use, loss of oxygen in water, reduction of and interference with fish stocks to the extent of threat of and or depletion, effect on native vegetation, birds, as well as impact on recreational activities, tourism, property investment in areas around the invaded sites, as well as externalities that are self-perpetuating (van Wyk and van Wilgen, 2002; Hill, 2003; Cilliers *et al*., 2003; Turpie, 2004; Korsgaard and Schou, 2010; Stiers *et al*., 2011; Barbier, 2017; Hill and Coetzee, 2017). Some of the impacts of IAPs have not yet been integrated; they include the value of biodiversity impact, changes in economic values associated with changes in aquatic alteration made to the functioning of downstream aquatic habitats and many others (Turpie, 2004).

2.4 COSTS ASSOCIATED WITH INVASIVE ALIEN PLANTS

Various studies have been devoted towards the economic analyses of economic costs, economic determinants, bioeconomic models and decision-making strategies of IAPs (Dalmazzone and Giaccaria, 2014). Generally - in most countries across the globe – the estimated costs of IAPs impacts are enormous and impose immense costs to the global economy (Born *et al*., 2005; Fraser *et al*., 2016). For example, the global cost of IAPs are estimated to be about US $1.4 trillion (Pimentel *et al*., 2001); prior to which they were estimated to cost about US $138 billion per annum (Pimentel et al., 2000).

Historically, the consideration of economic costs of IAPs began with respect to the value of water losses and saving (Fraser *et al*., 2016; Pratt *et al*., 2017). To do a full economic cost measurement of biological invasions, as many as possible direct and indirect impacts or costs need to be accounted for (Perrings *et al*., 2002). This is because broader consideration and inclusion gives more weight to the results and estimates quantified (Perrings *et al*., 2002). For example, Born *et al*. (2005) suggested *a priori* expectation that costs rise as the extent of the study increases. Thus, when evaluating the costs of IAPs, it is important to note the different contexts in which this can be done. It can be an evaluation of cost of impacts, avoided cost of impacts, cost of control, avoided cost of control as well as cost of related economic implications, such as crop yield loss, water yield loss and total economic cost.

2.4.1 Global account of costs of IAPs impact and clearing and clearing effort

In China, Xu *et al*. (2006), found that the total economic cost of IAPs for the period 2001 and 2003 were about US $14.45 billion, to which, 16.59% was towards direct economic costs and 83.41% towards indirect economic costs (Xu *et al*., 2006). Similarly, Pratt *et al*. (2017) evaluated the cost of IAPs on smallholder livelihoods in six African countries and found that the estimated crop yield loss was an annual economic loss of about US 0.9 billion to about US 1.1 billion which equated to about 1.8% and 2.2% of GDP (Pratt *et al*., 2017). Pratt *et al*. (2017) further found that the prevailing water yield reduction or loss has a cost of about US $165 million and US $205.1 million; to which the use of biological control management produced a related cost-saving of about US $305.7 and US $371.9 over a period of ten years. Pimentel *et al*. (2000) further found that the estimated costs of IAPs control management in the U.S was US $27 billion per annum on agricultural loss and about US $26 billion on potential crop loss. Moreover, Pimentel (2005) found that the estimated cost of control for the annual damage caused by aquatic IAPs were about US $14.2 billion in the US. These are examples of a few studies on the cost of IAPs around the world.

2.4.2 National account of costs of IAPs impact and clearing effort

Like the rest of the world, different studies on the costs of IAPs in South Africa have used different approaches, (Turpie, 2004). Although South Africa is said to have minimal attempts towards the estimation of the total economic costs of IAPs for the overall nation; there are a few studies that have attempted to do so (Turpie, 2004; Born *et al*., 2005). For example, the recent reports from the Convention of Biological Diversity (CBD) reveal that South Africa is amongst the countries that have invested the most in prevention policies, and, unlike the others, its expenditure is much lower as a percentage of GDP (Dalmazzone and Giaccaria, 2014).

According to van Wyk and van Wilgen (2002), South Africa has historically spent between R10 million and R15 million on clearing aquatic weeds for the period 1986 to 1999. More recently, Turpie (2004) found that the cost of controlling aquatic IAPs were an estimate of between R80 million and R200 million per catchment cleared; concluding that these costs were justifiable compared to the projected costs of IAPs. Van Wilgen *et al*. (1997) found that the costs of clearing IAPs in the Skuifraam catchment was R180 000 per annum for initial clearing and R25 000 pa for maintenance. Relative to alternatively building a dam for about R400 million and an additional operational cost of R2 million per annum, van Wilgen *et al*. (1997) inferred that clearing IAPs is a more cost-effective approach because it is also associated with a relatively low unit cost of water. Using two catchments (Krom and Kouga), McConnachie *et al*. (2012) found that the cost of clearing the two catchments from a condensed area decline of 2013 ha to 1055 ha between the period evaluation of the years 2002-2008; was about R20 133 per condensed hectare. To this, McConnachie *et al*. (2012) added that the WfW programme in South Africa spent about R19.27 million in total on the project during the period 2002-2008 evaluated in the study.

When doing economic analysis, economic tools used often depend on various factors such as the area of infestation, extent of invasion, risk of establishment, as well as the availability of resources (Pratt *et al*., 2017; McConnachie *et al*., 2012; Tamado and Milberg, 2000). The effort of such evaluation has grown over the years although has been subject to existing limitations such as lack of economic data available on the economic costs and benefits of IAPs, vagueness of data, poor sources of data, possibilities of double counting, statistical analytical issues in the estimation of past, present and future values, as well as the understatement of benefits and or overstatement of costs (Barbier *et al*., 1997; Born *et al*., 2005). There is however, an existing hypothesis in literature that the costs of IAPs exceed any perceived benefit; and that, similarly, the cost of clearing IAPs are most likely to be significantly lower compared to the benefit they produce (Mack *et al*., 2000).

For a programme like WfW in South Africa, Hosking and du Preez (2004) highlight the need to make a distinction between real costs and transfer costs. In most cases although subject to limitation, the WfW programme is more likely to have historical financial records of clearing costs than cost of impacts. Often, when measuring biological control management, costs that relate to exploration, quarantine research, establishment trials and post release monitoring to verifying establishment and efficiency are considered. While, for herbicides control management, initial clearing, follow-up costs overheads and other supporting equipment are included (see Table 2.1 below).

For example, with regards to wages and salaries, according to Hosking and du Preez (2004), due to the mandate of WfW, salaries and wages constitute a large part of the overall costs. However, due to the difficulty encountered when quantifying the cost of labour, the valuation of wages and salaries rest on three possible approaches, using the WfW wage rate, the unskilled normal market wage rate and the shadow price of labour.

Table 2.1: Cost of controlling IAPs commonly used in literature

Categories	**Detailed**	**References**
Research costs, exploration costs, quarantine costs, establishment costs, **post release monitoring and evaluation costs,** **overhead costs and operational costs**	Exploration, safety-screening and pre-release preliminaries, actual release and redistribution, monitoring and impacts evaluation costs of biological agents, other research costs not included under research on biological control, salaries, overheads costs, operational costs, infrastructure costs (capital), survey costs (travel and administration costs), transportation, vehicles, equipment, machinery, chemicals and training costs, the actual herbicides, diesel, dyes and wetters, filters and replacement parts, fuels and oils, stationery, printing and telephone expenses, protective clothes, industrial losses, health costs, other environmental costs, abatement costs.	Hosking and du Preez (2004), Fraser *et al*. (2016), van Wilgen *et al*. (2004), McConnachie *et al*. (2012), de Lange and van Wilgen (2010), McConnachie (2003), Doeleman (1989), Xu *et al*. (2006)

2.5 BENEFITS OF CLEARING INVASIVE ALIEN PLANTS

Various papers in literature have attempted to quantify different benefits in this study area. According to van Wilgen *et al*. (2004), about 70% of the benefits of clearing IAPs relate to water conservation. Although water related benefits are key, the measurement and valuation of such also prove to be a difficult task. Apart from the water yield saving benefit, clearing IAPs on water has other related benefits (see Table 2.2 below). In their study, McConnachie *et al*. (2003) makes broad assumptions taken from Wilgen *et al*. (2003); that future benefits of clearing IAPs are likely to increase by 3% per annum and that future costs of control per annum are likely to decrease by 20% per annum.

Table 2.2: Some of the benefits of controlling IAPs commonly used in literature

Benefits	**Reference**
increased water yield (quality and quantity), maintenance and conservation of biodiversity, improvement in the quality of water, secondary wood industry stimulation, poverty alleviation, floods and water damage reduction, improved tourism attraction, increased agricultural product yield, knowledge and training, increased value of land value, ecosystem services restoration, opportunity cost and avoided costs benefit (current and future ongoing costs).	Hosking and du Preez (2004), Fraser *et al*. (2016), van Wilgen *et al*. (2004), McConnachie *et al*. (2012), de Lange and van Wilgen (2010), McConnachie (2003), Doeleman (1989)

2.6 ECONOMIC EVALUATION

According to Carrasco *et al*. (2010), the government is faced with the allocation of limited financial resources to manage IAPs. They need access to quantitative economic models aimed at identifying the economically optimal control strategy, which combines the two disciplines of ecology and economics (Carrasco *et al*., 2010). This is especially the case as although there are sound ecological models and theories that focus on IAPs, many of them have not been modelled well with the integration of the economics of IAPs (Carrasco *et al*., 2010). Various models however have been used such as optimal control theory, stochastic dynamic programme application and genetic logarithms (Carrasco *et al*., 2010).

2.6.1 Guidance for economic evaluation

According to Born *et al*. (2005), the method applied in a study has severe implications on the reliability and usefulness of the findings in aiding a decision context. As a study that was primarily a review of 23 studies in literature, Born *et al.* (2005) reflected on these studies considering four key cornerstones that are deemed imperative as a guideline for economic analysis methodology towards aiding policy advice. Their paper advises that a study's method must be guided by an evaluation of the respective conservation strategy, the field of research application, the range of impacts to be considered as well as the type of data used. It seems that most studies evaluated by Born *et al*. (2005) were aimed at a decision aiding context and were applied ex-ante. Although this is the observed case, both Born *et al*. (2005) and Korsgaard and Schou (2010) argued that such studies should be done *ex-post*.

Although costly and time consuming, a good study should incorporate a complete analysis of all the total economic value categories, as well as the seven criteria suggested for analysing if a study/ method used is suitable for economic policy advice suggested (Born *et al*., 2005). The criteria are: geographic focus, economic sector, respective and evaluated conservation strategies, the level of assessment, methods applied, type of data used, total costs quantified and the consideration of uncertainty. For this reason, often mono-dimensional approaches may need to be neglected and a switch to multi-criteria decision aid might need to be adopted (Vincke, 1992; Bouyssou *et al*., 2000 and Rauschmayer, 2001).

2.6.2 Factors crucial to economic evaluation of biological invasions

In valuing benefits of ecosystem services within this kind of economic valuation, Korsgaard and Schou (2010) gave the assertion that benefits should be viewed in the context of scale. Proposing that there are three scales in which this should be approached, the spatial scale, socio-economic scale and temporal scale; to which factors such as time lag, discounting and uncertainty should be accounted for (Korsgaard and Schou, 2010). Usually, the type of study and valuation done informs the scale of focus. For example, Korsgaard and Schou (2010) emphasized that financial economic valuation differs from that of welfare economic analysis. Although Korsgaard and Schou (2010) looks at benefit-scales, the same context of scale can be applied to costs.

In addition to the context of scale, the issue of non-market goods and services or costs and benefits require attention. As it stands, the associated valuation of non-market goods and services is said to be a much broader and harder task for developing countries (Korsgaard and Schou, 2010). This is because, in developing countries, although subject to market distortion and limitations; economic evaluation usually practices the use of Market Price (MP) valuation method to value the market aspects of ecosystems (Korsgaard and Schou, 2010). Other methods available and often used to evaluate market values include, the effect-on-production method, factor income method as well as the dose-response method.

Within the market price-based method is the common use of the Shadow Price (SP) which includes the integration of, magnitude expenditure (ME), avoided costs (AC) and replacement costs (RC) (Korsgaard and Schou, 2010). According to Korsgaard and Schou (2010), it is common to use travel costs for valuing recreation values as well as contingent valuation and benefit transfer method to value stated preference. Although these methods are available, acknowledgement is given to the constraints, limitations, benefits, advantages and disadvantages of each of these methods despite their wide use. For example, reliance on the use of non-marginal changes is said to result in conceptual and practical problems, even though calculating marginal changes is difficult (Limburg *et al*., 2002; Korsgaard and Schou, 2010).

2.6.3 Limitations of economic evaluation

Economic evaluation of this nature is a subject associated with some weaknesses, the main being to give monetary units to IAPs, which is in itself a difficult task (Barbier, 1987; Born *et al*., 2005). According to Turpie (2004), economic evaluation of impacts needs better informed scientific research and modelling, resource evaluation studies as well as models equipped to measure changes in the quality and characteristics of environmental components. When facilitating economic evaluation there are prevailing uncertainties, lack of shadow pricing, existing market distortions such as price adjustments and subsidies as well as the need to incorporate socio-political dynamics (Turpie, 2004). An example of socio-political inclusion may be best understood through the incorporation of external costs, production costs, opportunity costs, non-values and subsidy distortions smart (Wit *et al*., 2001 and Born *et al*., 2005).

The lack of definitive synthesis, generalization, prediction and effective tools around IAPs economic evaluation also exist (Mack *et al*., 2000). For example, often most of the information available come from high income countries and there is little information from developing countries (Pratt *et al*., 2017); even though the latter is more susceptible to biological invasion as well as having detrimental impacts. All these limitations pose a big hindrance to successful economic evaluation.

2.7 INVASIVE ALIEN PLANTS IN SOUTH AFRICA

IAPs in South Africa were recognized as problematic over a century ago and they have now grown exponentially (SANBI National Status Report, 2017). According to van Wilgen *et al*. (2001), South Africa is counted amongst the most invaded countries in the world and has had more than 10 million hectares of its land invaded by over 180 IAPs. Initially, the first phase of the South African Invader Plant Atlas (SAPIA) (1994-1998) database recorded almost 60 000 locality records of 600 naturalized IAPs on 1 500 ¼ squares in South Africa, Swaziland and Lesotho (ARC, 2019). Following which, Henderson and Wilson (2017) recorded that as of May 2016, SAPIA had recorded about 773 alien plant taxa. To date, the National Environmental Managements: Biodiversity Act (NEMBA) and the Invasive Species Regulation (ISR) have recorded 775 species – most of which are terrestrial and freshwater plants (574 of the total number of species recorded) (SANBI National Status Report, 2017). The report reveals that currently, the estimated combined impacts of IAPs on surface water in South Africa is between 1 450 and 2 450 million m^3 water loss per year.

2.7.1 National status

The SANBI National Report Status (2017) has identified certain gaps around the issue of invasion and their management. For example, gaps in the area of invasion indicators – which means that most provinces need to develop a better account of their biological invasion to provide adequate data for national records. Another gap identified is that there is poor monitoring of the areas cleared, both at the national scale and for certain provinces. The figures below show a more detailed picture of the provincial stand of these IAPs across the country. Figure 2.1 is sourced from the SANBI National Report Status (2017), Figure 2.2 is sourced from Le Maitre *et al*. (2000) and Figure 2.3 is sourced from Gibson and Low (2003). For Figure 2.3 Gibson and Low (2003), acknowledged that at the time the study was done, the WfW programme had tended towards focusing on certain parts of different provinces more than on others. Hence, the existing disparity within these provinces as well as prevailing lack of data for other provinces.

Although the report indicates that KZN, EC and WC were the top three invaded provinces (Figure 2.1), Le Maitre *et al*. (2003) indicated that WC, NP (now called Limpopo) and MP had the top three largest hectares invaded while WC, NP and KZN had the largest hectare areas condensed/cleared (see Figure 2.2). The observations show that, when dealing with IAPs, three aspects need be considered: degree and type of invasiveness, cover and clearing efforts. While there is a considerable time lapse between the respective tables, they do give sound observations. The SANBI National Report Status (2017) recorded that, 80% of the recorded 379 terrestrial and freshwater plant taxa targeted for control is dominated by 8 species and that less than 1% of the total invaded area is subject to control/management. As such, while the report acknowledges that control measures have indeed shown to be more effective in some areas than others, it also reveals that they have, however, not been able to effectively reduce and or prevent ongoing spread in some areas nationwide. The later posing an important dilemma that will also be explored in this study.

Figure 2.1: Invasive species richness per province. These estimates are based on 538 species for which distribution data were available (out of 775 species regarded as invasive) (SANBI National Status Report 2017).

TAXON	PROVINCES								
	Eastern Cape	Free State	Gauteng	KwaZulu-Natal	Limpopo	Mpumalanga	North West	Northern Province	Western Cape
Terrestrial and freshwater plants	348	172	247	448	235	279	193	130	325
Total terrestrial and freshwater organisms	367	185	259	465	245	294	207	144	344

Figure 2.2: Areas invaded by alien plants in the different provinces both as hectares and as a percentage of the area of the provinces. The condensed area is the total area adjusted to bring the cover to the equivalent 100% (Le Maitre et al. 2000).

Province	Area (ha)	Total area invaded		Condensed invaded area	
		(ha)	%	(ha)	%
Eastern Cape	16 739 817	671 958	4.01	151 258	0.90
Free State	12 993 575	166 129	1.28	24 190	0.19
Gauteng	1 651 903	22 254	1.35	13 031	0.79
KwaZulu- Natal	9 459 590	922 012	9.75	250 862	2.65
Lesotho	3 056 978	2 4571	0.08	502	0.02
Mpumalanga	7 957 056	1 277 814	16.06	185 149	2.33
Northern Cape	36 198 060	1 178 373	3.26	166 097	0.46
Northern Province	12 214 307	1 702 816	13.94	263 017	2.15
North West	11 601 008	405 160	3.46	56 232	0.48
Western Cape	12 931 413	3 727 392	28.82	626 100	4.84

Figure 2.3: Estimates of the area covered by IAPs data per province (Gibson and Low, 2000)

Provinces	Estimated Area covered by identified/collected IAP data1 (km2)	Estimated area covered by WfW NBAL data2 (km2)	Percent coverage (%) by WfW NBAL data	Percent coverage (%) by WfW and collected IAP data
Eastern Cape	1081[3]	254	0.15	0.79
Free State		9	0.01	0.01
Gauteng	17 102	686	4.04	104.66
KwaZulu- Natal	3761	2426	2.62	6.67
Limpopo	129	402	0.33	0.43
Mpumalanga	1729	918	1.15	3.33
Northern Cape	85 181[4]	537	0.15	23.43
North West		441	0.38	0.38
Western Cape	7909	1145	0.88	6.93

1 This excludes the Working for Water and CSIR NBAL, and Southern African Plant Invaders Atlas (SAPIA) data sets. 2 Calculated from NBAL data received from WfW as at 21 December 2002. 3 Conservative estimates because certain data sets are unaccounted for.4 Consists of Prosopis mapping entirely.

2.7.2 IAPs legislation in South Africa

The national legislation around the management of IAPs has changed, grown and improved over the years. In the early stages, the Department of Forestry “Mountain Catchment Area Acts 63 of 1970” gained a lot of attention around the issue of IAPs on land. The purpose of this Act was mainly to “provide for the conservation, use, management and control of land situated in mountain catchment areas, and to provide for matters incidental thereto” (Government Gazette, 1970:2858). Since this act focused mostly on land invasion, the first policy to regulate the management of IAPs on both water resource and land was the Conservation of Agricultural Resource Act (CARA) no. 43 of 1982. The aim of this act, amongst others, was to prevent and combat the erosion, weakening and destruction of both water and land resources by combating IAPs in order to protect vegetation. The main issue, however, with this policy was that it focused on the control of agricultural weeds.

Since the passing of the new Constitution of the Republic of South Africa Act 108 of 1996 - the Bill of Rights granted provision for the need to protect and preserve the environment, conservation and biodiversity. Hence following this provision, improvements were made and a new act - the National Environmental Management Act (NEMA) no. 107 of 1998 - was passed. NEMA was passed with the aim to – amongst other things – establish principles and procedures that will help with IAPs management decision making as well as establish institutions that will facilitate the enforcement of those principles, procedures and decisions. From this NEMA framework, the National Environmental Management: Biological Act (NEMBA) no. 10 of 2004 – was introduced and established with the aim of providing IAPs framework, standards, norms, as well as sustainable and equitable benefit-sharing of biological resources in South Africa. The NEMBA also facilitates the inclusion of the National Botanical Institute into the South African National Biodiversity Institute (SANBI), as well as an Invasive Species Regulation, which publishes annual IAPs lists for South Africa since October 2014.

2.8 THE DEPARTMENT OF ENVIRONMENT, FORESTRY AND FISHERIES (DEFF) WORKING FOR WATER PROGRAMME

For South Africa, the issue of conservation grew largely around the time of the Cape Floristic Region dilemma in the 1970s (van Wilgen *et al*., 1997 and van Wilgen *et al*., 2016). Biological invasion spread and capacity grew exponentially, adding to the already existing dilemma. Historically, IAP management programmes around the 1940s were almost totally ineffective as conservation issues continued to prevail – especially in terms of growth rates (van Wilgen and Wannenburg, 2016). Some of the early control methods included manual removal, mechanical and chemical control, with little biological control. Although these control methods function differently from each other, they are all set on two main goals identified that a project can take; which is to either eradicate or manage and control IAPs. Of the two goals, Simberloff (2003:247) argued that "maintenance management is usually seen as the appropriate response-that is, controlling an invader at a density sufficiently low that we can tolerate it". Highlighting that maintenance management has an objective to reduce the density/spread/ population of an invader – not to completely eradicate it. Hence it is a preferred and feasible response to IAPs control. Alternative to this is the goal of eradication which is complete removal (Simberloff, 2009). Due to the complexity of IAPs, the goal of eradication may be unfeasible, unattractive and ineffective (Simberloff, 2003).

In the late 1980s, the responsibility of clearing IAPs was passed on to the provinces alongside a decline in funding towards IAPs control projects (van Wilgen *et al*., 1997) – this was a result of earlier ineffective control attempts (van Wilgen and Wannenburg, 2016). During the apartheid era (pre-1994); the management of IAPs was such that landowners were required by law to control their invaded area. This approach to control was said to have been continued until it was phased out by the new government in South Africa that came into power pushing for new funding models as well as overall development of poor and previously marginalized areas and its people. The political change that occurred in the country - around 1994 - propagated the call for political parties to take responsibility over the control, management and or eradication of IAPs (van Wilgen, 2012). This was following the realization that the apartheid era put more / additional pressure on South Africa's ecosystem causing further damage to it (Biodiversity and Conservation, 2002). This ecological damage translated to and included the aquatic ecosystem as loss in water yield continued alongside other conservation issues.

As such, studies have shown that IAPs need a feasible, effective, efficient and sustainable control method (van Wilgen *et al*., 2004). Which is why, to manage the ecosystem more sustainably and effectively, van Wilgen and Wannenburg (2016) suggested that ecologists need to develop better methods to prevent the degradation of the ecosystem while simultaneously deriving benefits from it. In their development and planning, these methods are also expected to develop strategies that will be consistent with relevant institutional values (Barbier, 1987). For example, the Global Sustainable Development Goals (SDGs) such as access to clean water and sanitation(Goal 6), climate action(Goal 13), life below water(Goal 14), as well as life on land (Goal 15) should be carefully considered and prioritized (United Nations, 2018:1).

These goals were recommended to be the driving force of policy recommendation and implementation as they capture the principle of universal sustainability. Imbedded in universal sustainability is environmental sustainability which helps in achieving real improvement in poor or developing countries, as well as socioeconomic sustainability which pays off economically through increased rates of return (Barbier, 1987). In addition to this, the Global Scientific and Policy Orientated Initiatives have provoked the inclusion of an economic perspective to inform decisions on policy planning, options and implementation in dealing with IAPs (Dalmazzone and Giaccaria, 2014). Highlighting the need for economic policy to consider environmental integration, as well as an interlaced need for ecological policy to consider economic reality. This is especially important because "the lack of economic valuation of the costs and benefits of IAPs control presents a significant barrier to the uptake of effective IAPs prevention and management in countries" (Pratt *et al*., 2017:39).

Around June 1995, a call for substantial effort in seeking and securing funding for a new IAP management strategy was launched; during the time of the Reconstruction Development Programme (RDP) and was facilitated by the then Minister of Water Affairs – Kadar Asmal. The strategy that emerged from those efforts was the Working for Water (WfW) strategic programme, the main prompting for which was to determine the true effects of IAPs on water resource regions (van Wilgen *et al*., 1997). This new WfW strategy was presented and deemed notable such that it was launched in November 1995. It was first administrated through the Department of Water Affairs and Forestry (DWAF); then became the Natural Resource Management Programme (NRMP) in the Department of Environmental Affairs (DEA) (Marais *et al*., 2004). The NRMP is currently hosted by the Department of Environment, Forestry and Fisheries (DEFF). This thesis will maintain the WfW programme name throughout.

2.8.1 Aims and objectives of Working for Water

The Working for Water (WfW) programme is a large, national-scale, government-sponsored alien invasive plant control initiative. It has now (in 2019) been operated for about twenty-four years and has become South Africa's longest serving conservation project (Hosking and du Preez, 2004). It is recognized both internationally and nationally as the lead IAPs management strategy (DEA WfW, 2018). Initially, the overall control strategies against IAPs were aimed at "reducing the risk of new introductions of invasive species, the control of existing invasions to mitigate impact, and the establishment of management and legislative capacity to guide implementation" (van Wilgen *et al*., 2012:1). In addition to this, the primary rational of the WfW programme is to improve the water yield catchment areas through the clearing of IAPs and to restore the low water-consuming indigenous vegetation (Hosking and du Preez, 2004). The programme's mandate is to identify areas of infestation, set objectives, and, initiate control through initial clearing and subsequent follow-up clearing actions consecutively.

The goals and objectives of the WfW programme include: to control IAPs, to protect the ecosystem services, improve water resource by preventing water loss and improving yield, protect biodiversity as well as create employment for the poor (Marais *et al*., 2004; van Wilgen *et al*., 2012 and van Wilgen and Wannenburgh, 2016). The above main objective, primary-rational, aims and goals were the reasons why the programme was passed at its proposal and inception stage (van Wilgen and Wannenburgh, 2016). Over the years, due to its successes and growth, the programme has secured continued support through its "ability to invest its allocated funds as well as create employment at a time when most government departments found this difficult due to lack of capacity” (van Wilgen *et al*. (2011) in van Wilgen, 2012:2).

2.8.2 Key control strategies by the Working for Water programme

On its website, the WfW programme’s stated main objective is to reduce the density of established terrestrial IAPs through mechanical and chemical control by 22% per annum. Although it mainly combines chemical and mechanical control of IAPs, it does use biological control as a supplement control method (Hosking and du Preez, 2004; van Wilgen *et al*., 2012). Hence, over the years, the WfW programme has relied heavily on mechanical and herbicide control to meet its mandate and achieved an adequate management of a few projects (van Wilgen *et al*., 2012). This reliance did, however, reveal issues of poor ecological understanding in their application, as well as lack of proper follow-up which led to some degree of wasted effort and money; prompting an emergent reliance on biological control (Wilgen *et al*., 1997). Although a supplement control method for WfW South Africa and has a small component in terms of budget allocation; biological control has played a significant role in the reduction of IAPs populations and spread (Stiers *et al*., 2011; van Wilgen, 2012). Hence, biological control has gained momentum as a sustainable and relatively less ecologically harmful method in South Africa (van Wilgen and van Wyk, 2002; McConnachie *et al*., 2003; Hill and Coetzee, 2017).

2.8.2.1 Chemical control

Chemical control is the use of registered environmentally safe aquatic herbicides and algicides (Gettys *et al*., 2014). An herbicide is a chemical substance that is used to kill unwanted plants; it is the most dominant and commonly used type of pesticide in aquatic weed chemical control management projects. According to Getsinger *et al*. (2007), the application of herbicides is a straightforward and easy to use control process. Its use, however, depends on several factors such as the application rate, growth rate of the weed and conditions that will not facilitate easy wash offs as herbicides wash away quickly under conditions such as heavy rainfall. Since the start of herbicide use, its applicability and processes of use have evolved over time. More recently, Kraehmer *et al*. (2014) highlighted the concept of modern herbicide use which is driven by an understanding and analysis of the related definitions, goals and objectives of a project, as well as an adequate use thereof. This is important because, ideally, a good management project objective is one that has both ecological and economic goals.

2.8.2.2 Biological control

The biological control method is a green alternative control initiative to reduce the distribution and abundance of IAPs where the mechanical and chemical control methods failed to do so effectively (Simberloff and Stiling, 1996). The original definition of biological control was by Smith (1919) which stated that it is the use of natural enemies, being 'those that exist in nature'. Harris (1991) argued that a better definition of biological control is that it is "the study and utilization of parasites, predators and pathogens to regulate populations of pests" as defined by Harley in 1985. McFadyen (1997) added that there were three techniques of biological control, namely, conservation, augmentation and classical biocontrol which is "the importation and release of exotic biocontrol agents, with the expectation that the agents will become established and further release will not be necessary" (McFadyen, 1997:2). To this, Zachariades (2017:11) defines biological control as "the use of introduced, highly selected natural enemies to control plants".

2.8.3 Financial summary of the WfW programme between 1995 and 2017

The WfW programme incurs costs and benefits that accrue from the process of control projects initiatives. For example, in its first six months of operation, the WfW programme had employed over 6 000 people, cleared about 33 229 hectares and had 10 projects, with the initial budget of R25 million (van Wilgen *et al*., 1997 and Marais *et al.,* 2004). By 1998, about 260 000 people were employed by the programme (Hosking and du Preez, 2004). According to Marais *et al*. (2004) within the next few years, the success of the programme had compelled an increased investment of over R400 million per annum by 2003/2004, supporting over 300 projects in that financial year. Around 2003/2004, the programme had used up about R1.95 billion for the total period of 1995 – 2004 (Marais, 2004). The SANBI National Status Report (2017:136) highlighted that the programme "has spent R12 billion (unadjusted for inflation) on invasive plant control projects between the period 1995 and 2012".

In its early stages, the programme initially had several disorganization problems and incompetence's (van Wilgen and Wannennburg, 2016). It had concerns about the employment of unskilled workers, poor protocols put in place, as well as the use of misleading financial estimates due to poor documentation and data collection – especially before the GIS system was adopted (SANBI National Status Report, 2017). However, it is impressive that it has – since 2012 - kept records of expenditure per species and geographic area (van Wilgen *et al*., 2012). Apart from these challenges, threats and limitations, the WfW programme went from working on 10 projects in 1995 at a cost of R25 million to over 300 projects by 2016 supported by an annual budget of about R1.5 billion (van Wilgen and Wannenburgh, 2016). This R 1.5 billion per annum, however, includes only money spent on the control of terrestrial and freshwater plants by the DEFF (SANBI National Status Report, 2017).

The SANBI National Status Report (2017) does acknowledge the gap in financial reporting and suggests the need to account for money received from other sources of funding; such as from all state departments at all levels as well as from the private sectors (if any) - instead of just from the DEFF. In accounting for the WfW financial literature review, some of the figures are either a total budget, total investment or actual costs. According to Marais *et al*. (2004), in most cases, costs of clearing generally increases with density and follow-up costs exceed the initial clearing costs, because usually, more than one follow-up is required. The table below summarizes the overall, historical financial literature by the WfW programme since its inception until the financial year 2016/17. Figures 2.4 below shows the growth trends of costs incurred and recorded by the WfW programme. It is observable that the programme would usually under or over spend relative to the allocated budget and has in the more recent years tended towards under spending the budget. Although the recent cost expenditure of the WfW programme has been under budget since the financial year 2009/10, this observation on its own is not enough to warrant cost effectiveness. Thus, apart from actual costs and cost-trends, the issue of cost-efficiency and cost-effectiveness is imperative and requires careful evaluation (SANBI National Status Report, 2017). It is important, however, to assess the growth, effect, productivity and success of the financial investment that has gone into the control and therefore clearing of IAPs relatively.

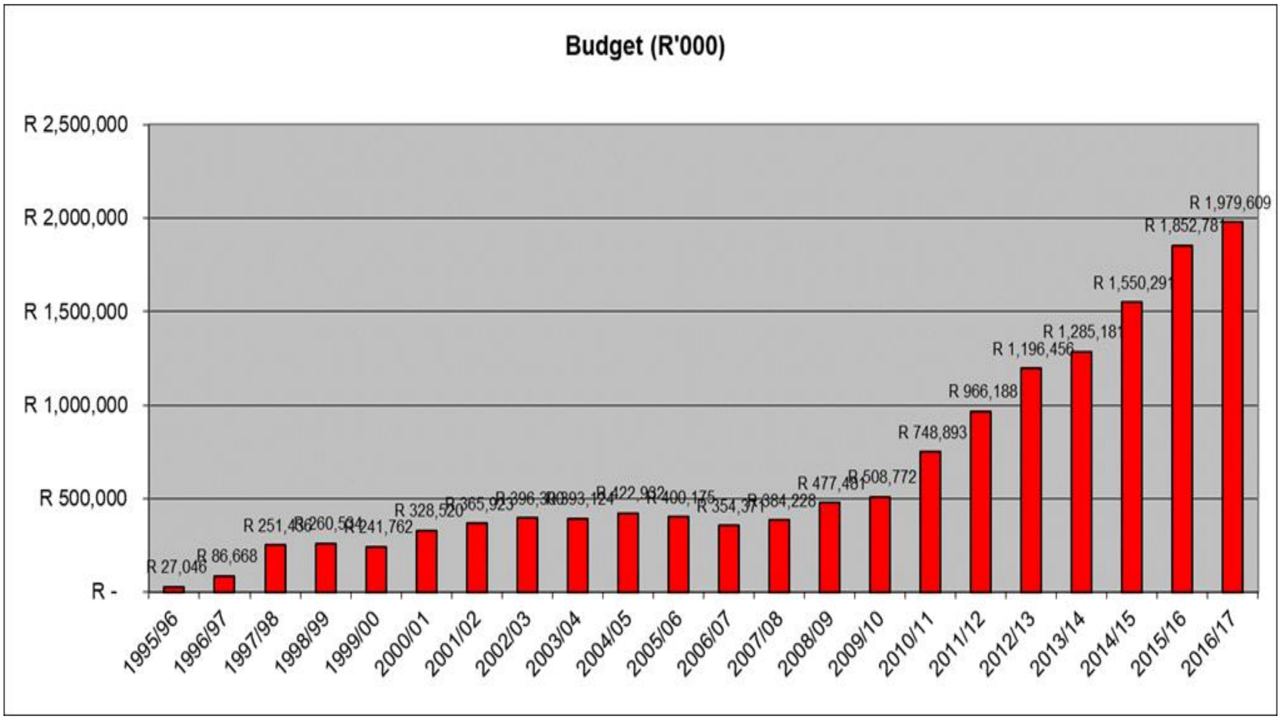

Figure 2.4 Growth trends of costs incurred and recorded by the WfW programme

2.9 SYSTEMATIC REVIEW

The discipline of economics has historically been used to address different environmental problems or projects. For example, papers such as Diakoulaki and Karangelis (2007) evaluated the expansion of the electricity system in Greece using both the multicriteria decision analysis and the cost benefit analysis as evaluation decision tools. Gine´s de Rus and Vicente Inglada (1997) did an economic evaluation of the high-speed train in Spain using the CBA framework while Litman (2009) did a transport CBA looking at alternative techniques, estimates and implications. Other examples include Haruvy (1997) - a cost benefit analysis study on the agricultural reuse of treated effluent. As well as a study by Huttin *et al*. (2002) who investigated the costs and benefits of interventions to reduce air pollution by halving the global population currently lacking access to cleaner fuels as well as to cleaner-burning and more efficient stoves. Similar, studies include those done by Malla *et al*. (2011) on indoor air pollution mitigation incentives in Nepal, Kenya and Sudan. All these studies and more, prove the usefulness of the economic discipline and frameworks towards addressing environmental issues.

With regards to the usefulness of economics in addressing and understanding biological invasions, the discipline is used to evaluate the impact and benefits of IAPs, as well as the cost and benefits of clearing IAPs. In addition to this, economics is useful in addressing the cost-effectiveness, efficiency and economic feasibility of IAP clearing efforts. For example, in the study by van Wilgen *et al*. (2016), the weeds under review were said to have covered about 60% plus of the 750 000 hectares in 2014. They included trees and shrubs in the *Pinus, Acacia, Eucalyptus, Hakea, Leptospermum* and *Populus* genera in 25 protected areas of the Cape Florist region in South Africa. They were excessive water users and thus have a large significant impact on water. Van Wilgen *et al*. (2016) sought to evaluate the historical costs and extent of management efforts as well as estimate the resources needed to bring the existing problems under control. To do this the paper made reference to the management efforts from as early as 1970s (Fenn 1980 in van Wilgen *et al*., 2016) up to when the WfW programme took over and extended the management efforts. Using historical cost data obtained from Cape Nature and SANParks – adjusted for inflation using 2015 prices per CPI.

Where data gaps were persistent, cost estimates were made based on the total national expenditure by the WfW since 1995. Certain assumptions needed to be made, however, such as the assumptions that funds were allocated with equal proportions between the individual protected areas for cost estimates before the records as well as after for individual genera. The costs used in the study included contractual amounts on different projects – which included direct costs paid out to labour and herbicide costs. Although overhead costs were not included (equipment, transport, supervision and administration), a levy mean of 32.5% on direct costs was used to capture the overhead clearing cost estimate. The resulting estimated historical costs were calculated to be R564 million spent over the past 20-year period.

For future estimated costs of management, van Wilgen *et al*. (2016) used different scenarios to account for estimation such as different levels of annual funding, rate of spread, number of follow-up treatments and mix of species to be controlled. The main assumption for this was that, to achieve the acceptable maintenance level, one initial clearing would be required followed by three follow-up clearings; the 32.5% overhead cost inclusion rate was maintained. The paper outlines a more detailed methodology, however, important to note is that an estimated future spread range of 4-8% per annum was used. To which, the estimated future costs to bring the remaining invasion under complete control was a cost of between R170 – R2 608 million depending on the above scenario applied (also in 2015 prices); which is expected to be 4.6 times more than the past 20-years estimate.

Le Maitre *et al*. (2002) evaluated the costs and benefits of management of IAPs (trees) in South Africa - with a subsidiary focus on the water resource. The study observed four catchments (Sonderend, Keurbooms, Upper Wilge and Sabie Sand) and estimated the initial plant cover, future projected plant cover, current and future river flow reduction, as well as the current and future costs of control. Initially, the observed plant cover was of 44%, 54%, 2% and 23% with corresponding river flow reductions of 7.2%, 22.1%, 6.0% and 9.4% respectively. According to Le Maitre *et al*. (2002), the potential spread if the catchments were not controlled could reach up to an estimated 51%, 77% and 70% for the first three catchments with projected river flow reductions increasing to 41.5%, 95.5%, 25.1% and 22.3%. Le Maitre *et al*. (2002), further proposed that it would take about 13, 26, and 63 years respectively to clear these – provided an annual expansion rate of 10% -15%. Different methods were applied for different catchments especially as it relates to rainfall, surface runoff and water-use.

Another essential objective of the study was to quantify the costs and benefits of the management programme on these catchments. To achieve this, Le Maitre *et al*. (2002) obtained cost data from project managers for the different catchments which included costs such as clearing costs, follow-up costs, overhead costs (transport and administration). Each catchment was divided into three densities and using species specific data, costs were expressed as total cost of mean percentage cover for each density class – using both linear and non-linear regressions where applicable. The cost of control was calculated as a product of size of area or site multiplied by cost per ha. Taking into account the issue of possible double counting, Le Maitre *et al*. (2002) applied the principle of distributional weighting to which the total cost was a product of the weighted mean cost per ha multiplied by the total equivalent dense area. The results presented were of an initial control cost estimates of US $13.2, 9.9, 4.1 and 6.6 million accordingly. Future costs were estimated to could increase to US $86.5, 20.5, 278.0, and 11.1 million respectively should the catchments be fully invaded or for future invasion in this context. Similar to the results found by van Wilgen *et al*. (2016), current or historical costs were relatively less than future costs.

However, like other studies in literature, Le Maitre *et al*. (2002) disclosed issues that may affect the reliability of the result of this study. For example, these issues included the fact that the study itself was subject to various sources of uncertainty, expert opinion was consulted in the absence of relevant data, the regression confidence interval limits of biomass and river flow reduction estimates were +- 20-30%, and, there could be possible over and underestimation in some instances.

Hosking and du Preez (2004) did a cost-benefit analysis study on the WfW programme using a case study of six sites (Tsitsikamma, Kouga, Port Elizabeth Driftsands, Albany, Kat River and Pott River) in the Eastern Cape Province in South Africa for the period 1996-2000. The aim of the study was to evaluate the efficiency of the working for water programme based on an analysis of the selected sites with dominant invasive species such as *Acacia* spp*, Pinus* spp*, Hakea* spp and *Populus* spp. With the WfW using the chemical control approach on these sites, the paper evaluated initial, follow-up and maintenance costs. These costs were made up of costs such as capital equipment, herbicide cost, protective clothing, wages and salaries, transport, clearing work contracted out to private institutions, running expenses, fuels and oils, stationary, printing and telephone expenses. All these costs were obtained from respective WfW project managers in the Eastern Cape Province. In addition to these costs, the cost of reduction in available trees for firewood use was also included. For the benefits component, benefits such as the maintenance and conservation of biodiversity, improved quality of water, wood industry stimulation, increased agricultural product yield, reduced flooding and fire damage, training and poverty alleviation and improved tourism attraction were highlighted but could not be granted a monetary value. Hence the main benefit of the study was increased water yield and increased yield of agricultural products.

In terms of the method employed to estimate the increased water yield benefit, the paper used the Versveld *et al*. (1998) stream flow reduction model as well as the rate of spread model applied by Le Maitre *et al*. (1996). To these methods, Hosking and Du Preez (2004) varied the value of water according to the use of water in the cleared water bodies. These included valuation by willingness to pay (used for agricultural purposes), marginal cost (used as the main water supply source), potential user response (if it is sustainable groundwater but not potential source of municipal water supply), environmental opportunity cost (if used for agricultural purposes and fresh water flow supply but without suitable water rights market and irrigation prices) and non-scarce resource value (if used solely for fresh water flow supply into another catchment). Using a 10% social discount rate.

Also looking at a similar site to Hosking and du Preez (Kouga), McConnachie *et al*. (2012) evaluated how effective the WfW efforts were in reducing IAP cover in Krom and Kouga catchments over a 7-year period (2002-2008). Using 740 sites observations, the study further investigated the cost-effectiveness of reducing plant cover in these catchments that were the WfW's oldest projects with the largest number of hectares cleared by the programme. These sites were particularly important because, they support fynbos vegetation and supply 80% of Port Elizabeth with water. The change in IAP cover was calculated by a subtraction of post-treatment cover from pre-treatment cover and plain cover estimates were converted to 100% equivalent cover (henceforth called condensed ha). With the period data obtained from the WfW spatiality-explicit database (WIMS), costs, included operational costs and overhead costs which made up an inclusion of management and implementing agent fees. McConnachie *et al*. (2012) used 2010 values adjusted for CPI. However, the WfW management cost data was excluded due to unavailability of reliable data estimates. Other exclusions done in the study were exclusions of some sites treated since before 2002 due to poor documentation as well as those falsely recorded as treated. Post these exclusions, the total area treated in the 740 sites was thus set at 11 202 ha with an average area of 15.2 ha and a site area range of between 0.03 and 227.6 ha. The total of treatments recorded were 2 213 and treated area was defined as one that had received at least one treatment; 987 at Kouga and 1 226 at Krom. This was after removing sites that were falsely recorded as treated when in fact no treatment was done. These sites had a treatment range of between 1 - 9 with an average of about 3 treatments per site.

The difference between Hosking and Du Preez (2004) and McConnachie *et al*. (2012) is that one measured efficiency while the other measured effectiveness. Although the two concepts are different, they are often interdependent. For example, Mbuvi *et al*. (2012) explained that productivity analysis depends on an understanding of effectiveness and efficiency – particularly technical efficiency. Mbuvi *et al.* (2012) further explained that while efficiency is obtaining or expanding output with the given input resources, effectiveness is the extent to which the necessary objectives are met to reach the set target. Broadly, efficiency is known as 'doing things right' while effectiveness is known as 'doing the right things'.

On the issues of valuation in the context of plant cover, Kraaij *et al*. (2017), concerned with the IAPs management reporting by the WfW, evaluated the effectiveness of IAPs management in a large fynbos protected area. The study had three objectives: alignment, effectiveness and the relationship between IAP species, age classes, cover and treatment efforts. Throughout the study, cover referred to percentage projected canopy cover of IAPs recorded as density that was determined from actual stem counts. Management units in a large fynbos protected area at the Garden Route National Park of South Africa were the main units of assessment. Pre-clearing field surveys were conducted and the WfW data was reviewed to observe changes in IAPs cover post successful treatments. The study looked at work carried out by the WfW between 2004 and 2015 for only areas covered with fynbos vegetation; emphasizing on the 2014/2015 financial year. Management units were the main units of assessment.

To evaluate effectiveness, Kraaij *et al*. (2017) estimated the pre-treatment cover and size classes of IAPs through a six months field survey after the management unit was treated. These pre-treatment field assessments were then compared with those recorded by the WfW prior to the awarding or allocation of management units to contractors for verification using the Wilcoxon matched pairs test. The 103 management units covering 4 280 hectares were evaluated for the 2012-2015 period. For efficiency however, the IAPs cover recorded in WIMS was assessed to see if it decreases with successive follow-up treatments for the entire treatment period of 2004-2015. The maximum follow-up treatments included were up to 7 treatments, with exclusion of those that needed more than 7 treatments; leading to an observation of 2 738 treatments and 764 management units for efficiency. Following which a comparison of the change in cover between successive treatments were done to observe the treatment effect. This treatment effect was then expressed as ratio of cover before treatment to indicate the proportional change and the difference between treatment before a specific treatment and the treatment before the prior treatment was calculated to get the absolute change.

The results revealed a widespread ineffective treatment in the field as well as that about 85% of the evaluated units' treatment were not done up to standard. Hosking and du Preez (2004) found that all sites where inefficient; together producing an NPV of R-97 996 826 and a BCR of 0.59:1, as well as an IRR of less than 10% (the applied discount rate). The main conclusion of Hosking and du Preez (2004) was that the WfW programme was overall inefficient although some of the individual sites were considered efficient. A sensitivity test was done which included varying the social discount rate to 8.1% and 5.1%, as well as varying the estimated productivity of clearing teams and management efficiency. The results are explored in the next sensitivity test section. However, Hosking and du Preez (2004) proposed that if a lower discount rate of 5% was employed, Kouga would prove efficient and assuming a possible achievable cost saving of 30%, the catchment would be efficient.

For Mc Connachie *et al*. (2012) the average money spent on each site was estimated to be R2634 per ha while the overall cost per ha for both projects was R20 113 per condensed area cleared. For the full period (2002-2008) the WfW spent a total clearing cost of about R19.27 million. Thus, to achieve the primary objectives, McConnachie *et al*. (2012) sought to observe the change in plant cover by a comparison of pre and post treatment IAP cover in the selected sites to evaluate the effectiveness of clearing effort. In addition to this, McConnachie *et al*. (2012) calculated the cost-effectiveness as a division of the total cost of clearing by the change in IAP cover. In terms of the effectiveness of efforts, the result found by McConnachie *et al*. (2012) were that the total condensed ha of the reduced IAP cover between 2002 and 2008 was between 2 013 – 1 055 ha, to which 86% of the reduction was experienced by Krom. Kouga had a relatively low IAPs cover reduction and in some cases experienced an actual increase in cover. With this, the cost-effectiveness results reveal the same patter; Krom was more cost-effective than Kouga (R11 987 per ha and R70 517 per ha respectively).

McConnachie *et al*. (2012) does recognize that the overall cost-effectiveness measurements were relatively lower than most studies because even with the necessary exclusions made, the cost estimates were relatively the highest yet made. Lastly, McConnachie *et al*. (2012) used both linear and multilinear regression models to evaluate predator variable on cost-effectiveness with cost per condensed ha as the response variable. The later was used to show the combined effect of predator variable and the former was log transformed and used to show the individual effect of each. The single predator variables showed low variability in cost per condenses ha and a strongly significant influence of money spent per ha, number of treatments, pre-treatment IAP cover on cost effectiveness; while the multiple predator regression showed a high variation and that the above variables including average altitude of site had a large impact on cost-effectiveness.

Under the study by Kraaij *et al*. (2017), the issue of standard was evaluated through an assessment of IAPs management quality by an observation of the degree to which satisfactory treatment standards were met as well as evaluating the extent of deviation from acceptable standards (calculated as rate of incidence). These results were believed to be caused by factors such as partial or no work done on some units even following payment to contractors to do the work, wrong treatment methods and or below standard applications, as well as regularly overestimated cover prior to contract allocation. In addition to these, implementation and coordination problems were observed and relatively few projects met their annual area targets. This revealing issues of underachievement and poor quality. To this, it has also been proven that frequent repeated treatment often increases cover rather than reduce it.

South African, through the DEA: NRM programme, practices the ‘hollow state’ principle of outsourcing the delivery of social goods and services funded by tax-payers from either profit oriented or non-profit oriented third parties or contractors (Guttman, 2003). Morokong *et al*. (2017) sought to investigate the efficiency of contractors employed by the NRM to clear IAPs in South Africa. This investigation evaluated if the State awards IAPs clearing contracts efficiently as well as explored possible reasons behind the (in)efficiency, if any. Looking into 49 contractors working on two catchments (Tzaneen and Lebata both in the Mopani District in Limpopo) with about 675 hectares dominated by species such as *Chromolaena odorata* and *Lantana camara*. Although the study investigated a 12-year period from 2003–2014, this period was split into three time periods, 2003-2006, 2007-2010, 2011-2014. The contract data observed for the purposes of this study included: rand per ha, person day per ha, rand per person day per ha, actual expenditure per contract, size of clearing per contract and total hectarage cleared per contract. These were recorded as either initial clearing costs or follow up clearing costs due to WIMS data capture format, which was the main source of data.

When analysing the data, Morokong *et al*. (2017) found that these contracts had large budgets and smaller clearing targets but required more labour to complete the assigned work. These findings were alarming since Morokong *et al*. (2017) projected that, one would expect the smaller clearing targets to require less labour. The positive correlation of 0.869 between the average labour productivity and average unit cost per contract should be associated with a much smaller project expenditure; which was not the case for the observed contracts. Indicating the existence of inefficiencies, Morokong *et al*. (2017) further explored the possibility of these perceived changes in labour productivity as one of the main sources of these inefficiencies. Just as Hosking and du Preez (2004) found.

Besides the main limitation of the study which - that it did not evaluate the environmental improvements associated with these contractors' clearing efforts – when presented with time plots, the data showed that only a few contracts were observed in the second half of the period covered by the study. Morokong *et al*. (2017) also observed that most of the efficient contractors' data was captured for the first few years, that labour productivity was lower in the subsequent years as well as that the variance of labour productivity increased overtime. These observations are said to explain the prevalent diseconomies of scale. In addition to these, other contributing factors to inefficiency included: the effects of changes in the biophysical characteristics of sites, relatively less competent contractors, state allocation of smaller plots to contracts and the operation protocol of the NRM to clear site with lower densities first then those with higher last. According to Morokong *et al*. (2017), this protocol and higher densities may be the main explanation for the subsequently lower labour productivity, diseconomies of scale thus inefficiency. With respect of the density impact evaluation, Morokong *et al*. (2017) found a positive correlation between the rand per ha cleared and density (with the exception of a scenario where the rand per ha cleared remained constant while density decreased). Thus, Morokong *et al*. (2017) did not infer that the contactors were inefficient but rather inferred that it is more expensive to clear higher densities than lower densities.

While the above studies focused on chemical control, de Lange and van Wilgen (2010) did an economic evaluation which assessed the contribution of biocontrol with respect to the protection of ecosystem services in South Africa. Five terrestrial biomes in South Africa were evaluated and 11 IAPs were grouped into four categories. Looking at both a historic review and a future estimated projection of prevailing costs and benefits. The impact and control costs of the respective IAPs were evaluated in comparison to the benefit of protected ecosystem services that flow from the clearance of those IAPs. To do this, researchers in the field of biological control were interviewed to source out data on annual costs of research (exploration, safety and screening, pre-release preliminaries in the laboratory), actual release costs, as well as redistribution, monitoring and impact-evaluation costs. In addition to these, de Lange and Van Wilgen (2010) looked at the total area historically subjected to all clearing efforts (that is, using all the available control methods) as well as the proportion that only used biological control to account for data on areas cleared.

Van Wilgen *et al*. (2004) sought to evaluate the costs and benefits of biological control as a management tool for using South Africa as a case study. The study looked at 6 species (jointed cactus, red sesbania, lantana, long-leaved wattle, golden wattle and silky hakea). To achieve the objectives of the study, van Wilgen *et al*. (2004) estimated the cost of biological control (research), the rate of spread of each IAP, the degree of control achievable of each, the likely levels of uncontrolled spread, as well as, the consequences (effect) of uncontrolled spread. The benefits covered in this study were categorized into three groups of benefits that flow from invasion prevention; water resource, grazing and biodiversity benefits.

Both de Lange and van Wilgen (2010) and van Wilgen *et al.* (2004) applied an 8% discount rate when conducting their CBA. De Lange and van Wilgen (2010) covered a period of over 140 years while van Wilgen *et al*. (2004) covered the period of the start of the biological research (year) until the year 2000. For van Wilgen *et al.* (2004), BCRs were then calculated from two perspectives, historical (retrospective) and future projections. For the historical or retrospective analysis, the BCR range was 8:1 for lantana and 709:1 for joined cactus; while for the future analysis the range increased to 34:1 for lantana and 4 333:1 for golden wattle (this is considering future benefits of prevention). Costs were then converted to 2000 prices using the annual PPI and future costs were estimated with the assumption that they would only be maintenance costs and will possibly be about 20% of the mean annual historical costs of research.

De Lange and van Wilgen (2010) found that the NPV for estimate of future annual flows; the total cost of impacts amounted to about R6.5 billion pa with all control efforts and R41.7 billion pa without control. It was said that about 5%-75% of this protection was a result of biological control evidenced by the cost-saving from each group of IAPs. The actual cost of biological control on these weeds was about R102 million with individual groups ranging from between 10 million for fire-adapted trees and 50 million for sub-topical shrubs each. The main benefits that the study was categorized were the water resource, grazing and biodiversity benefits. Looking at the magnitude of these ecosystem services and estimated reductions at the time to indicate the value of the ecosystem. The potential ecosystem services were found to have the value of about R152 billion per annum. As such, when comparing the cost of weed biological control to that of the estimated value of the ecosystem services protected by biological control, de Lange and van Wilgen (2010) found a prevailing BCR range of between 50:1 for subtropical shrubs and 3726:1 for Australian trees. This is with the estimated NPV of benefits ranging between R 840 million for fire-adapted trees and R 104 billion for Australian trees. These ratios remained positive even when certain variables and estimated were varied. Where necessary (due to lack of data), expert opinion was sought and applied in the methods of the study.

Although the results by van Wilgen *et al*. (2004) were achievable, the study was subject to lack of adequate data on the invasion extent, population effects of biological control and associated economic consequences; to which certain assumptions were made. Similarly, although historical data on human resource, overheads and running costs were obtained, the study was still subject to incomplete data to which estimates had to be made (based on averages). For impact which were also translated into benefits, expert opinion was consulted through interviews due to lack of data – as well as literature and unpublished reports.

Many studies have investigated the issue of effectiveness in one of two ways, either the effectiveness of clearing efforts in terms of efficiency or reduced plant cover as well as the cost-effectiveness of clearing projects. A study looking at, and distinguishing, both is McConnachie *et al*. (2016) which used counterfactual analysis to evaluate the cost-effectiveness of controlling biological invasion. The study area of interest was the untransformed mountain land of the Hawequas Mountain Fynbos Complex in the Western Cape in South Africa; mostly invaded by *Pinus pinaster, P.radiata,* Australian *Acacia* spp. and *Eucalyptus* species. A counterfactual study is one that "compares what actually happened and what would have happened in the absence of an intervention" (McConnachie *et al*., 2016:476) – especially with regards to outcomes that are observable and unobservable. The study explained two options with which they could account for counterfactuals but went with the option to measure the cost effectiveness of nonexperimental landscapes-scale operations. This was done with some adjustment to cater for the absence of experimental manipulations, as it was not feasible to compare treated and untreated units simply due to possible bias results.

For example, Mc Connachie *et al*. (2016) used the statistical matching technique to measure the cost-effectiveness of the WfW programme in the selected areas, to avoid treatment selection bias that could lead to naïve comparisons. McConnachie *et al*. (2016) also highlighted that unbiased comparison depend on retrospective identification and adjustment of confounding factors that may have significant impact on estimates as well as that may be closely related to programme implementation reasons or objectives. Hence the paper accounted for robustness in terms of possible spill overs and unobserved confounding factors. Data on clearing costs and other needed variable data was obtained from sources such as WfW spatial records (1996-2000), Department of Forestry (1987-1990) and Cape Nature (1990-1995). These costs included the cost of clearing trees, excluding overhead costs such as management and implementing agent fees, future invasion or follow-up costs as well as costs related to clearing of invasive shrubs.

The cost-effectiveness estimate was derived from dividing total treatment costs with the area previously invaded that had been cleared in the year 2010. The study found that the cost of clearing to date was significantly lower than the earlier projected clearing cost estimate. For example, the costs at the time of the study were about 84% of the projected amount. The clearing of tree invasion on untransformed land had relatively lower treatment effect than that of densely occupied transformed land; inferring that clearing the latter has proved more cost-effective over the period covered in the study. To achieve these findings McConnachie *et al*. (2016) recognized that the respective cost estimates were in fact 2.7 times and 4.9 times higher than elsewhere or in previous studies in literature. The exact cost estimates used in this study was R35 million for the 2.8% reduction in tree invasion. Although McConnachie *et al*. (2016) clarified that these results indicated that clearing efforts of reducing the IAP occupancy in this study were among the most effective projects in that region; these results may be different when assessed by the overall CFR scale. Moreover, McConnachie *et al*. (2016) further acknowledged the possibility of likely underestimation of costs as they excluded overhead costs and cost of clearing future invasion (follow up costs). With respect to the high cost-effectiveness results found in the study, McConnachie *et al*. (2016) maintains the suggestion that the significantly high cost estimates and thus relatively high cost-effectiveness results found in this study can be a result of some of the assumptions made in previous studies such as that of no reestablishment and two follow-up treatments only.

Dahlsten *et al*. (1998) evaluated whether the use of biological control of the insect pest, the blue gum psyllid is economically beneficial. Using CBA as the main framework of analysis (with an 8% discount rate). Dahlsten *et al*. (1998) found that biological control produced a relative BCR range of 9:1 and 24:1. To which a detailed analysis of results revealed a BCR of 9:1 for a 5-year period and 20:1 for a 15-year period for the hot scenario and 11:1 for a 5-year period and 14:1 for a 15-year period for the cold scenario. In computing the actual insecticide costs, the paper included the cost of labour, the cost of chemicals and the cost of any additional equipment bought specifically for the treatment process. These actual insecticide costs were then used as the prevailing benefit of successful biocontrol – an 'avoided cost' benefit. For the cost component of the BCR, costs associated with the biological control approach were used and they included "project organization, foreign exploration, parasitoid shipment, quarantine, rearing, releasing, monitoring and evaluation" (Dahlsten *et al*., 1998).

Like most studies, this study was not short of methodological pitfalls. There were four methodological challenges encountered. The first one was unavailability of data to which they incorporated only data from the growers interviewed, the second is shifts in prices and acreage overtime which were expected to have an influence on the psyllid damage. Thirdly, because the biocontrol agent established soon after the release and detected the weed quickly – it resulted in a short window of time for observation making it hard to track changes. The last challenge was that it was difficult to evaluate and give monetary value to other social and environmental benefits that accrued; hence avoided cost was used as the main benefit of study. Apart from challenges, the key assumptions of the study included the assumptions that benefits were understated due to the inclusion of only those accrued to the 13 interviewees. In addition to this, another key assumption is that future insecticides will be lower than they were at the time of the study and that benefits do not include avoided rip-out and replacement costs.

2.9.1 Discount rate

An important part of conducting a CBA study is the process of discounting involved as well as the choice of a discount rate. The choice of discount rate hold substantial power of influence over the respective decision-making criteria and the results of a project under review. Although influential, the discounting phase has been considered the weakest element of the framework; hence it has continually been subject to change and to major debate (Kousmanen *et al*., 2009). For example, different discount rates have been used across global and national literature. Ranging from those considered to be acceptable, common, high and or low.

In South Africa, projects under the WFW programme have been administrated using a rate of 8%, which is a rate that brings to present value any costs and benefits of between 25 and 30 years – of which the duration of the programme falls within (Turpie, 2004). The 8% discount rate is considered a better rate to use because, at a 3% discount rate, many control projects would be deemed cost effective or rather be considered justifiable primarily due to the use of a low rate (Turpie, 2004). Van Wilgen *et al*. (1997) and van Wilgen *et al*. (2004) used an 8% discount rate to produce a net present value of the cost of water. At the time of van Wilgen *et al*. (1997), the main argument towards the use of an 8% discount rate was fostered by the fact that the Department of Water Affairs and Forestry used the same rate in comparing water supply schemes. Other studies such as McConnachie *et al.* (2003) and de Lange and van Wilgen (2010) also applied a discount rate of 8%.

Although the use of an 8% discount rate is common in most WfW programme projects, other studies have applied other discount rates they consider more suitable such as a 10% discount rate application by Hosking and du Preez (2004). Hoskings and du Preez (2004) first provides a formula used to determine this discount rate which took into account various sources of funding. However, this 10% discount rate was considered too higher; leading to the additional use of lower discount rates of 8.1% and 5.1%. The common use of these discount rates in some agricultural projects in South Africa was the reason for their use in this study (Hosking and du Preez, 2004).

Another use of a 10% and 5% discount rate is seen in Fraser *et al*. (2016) with the application of two discount rates – a 10% and 5% - in the main results of their study. Although Fraser et al. (2016) did not give reason to their choice of rates, it was perhaps to cater for the ambiguity around the possible use of a discount rate that is either too low and too high rate. Other scholars such as Doeleman (1989) also used a 10% and 5% discount rate, as well as an additional 15% discount rate to cover the low, medium and high categories of discount rates. Often, most studies choose a main discount rate and then vary it in the sensitivity test to see if the results change under different discount rates. Usually the variation between a somewhat lower and higher discount rate to the main discount rate used.

2.9.2 Sensitivity test

The main purpose of this test is to show the robust nature of the results should some of the core assumptions used in the study change such as the discount rate, associated estimated costs and benefits and other pivotal variables (van Wilgen and de Lange, 2011). The sensitivity test is often done alongside the main results to check if they are in any way dissimilar. For example, the sensitivity test done by Hosking and du Preez (2004) was based on varying the social discount rate (from 10% to 8.1 % and 5.1%) as well as varying the costs estimates. For Hosking and du Preez (2004), the sensitivity tests revealed the same results of inefficiency of sites except for one site (Kouga) that proved efficient under those variations (with a positive NPV and greater than one BCR under the 5.1% discount rate but however held on to inefficient results under the 8.1% rate).

That said, the sensitivity test is crucial and its related variations in literature include for example, changes in clearing costs, improvements in management efficiency, changes in the rate of spread, changes in the effect of invasion, changes in the estimated proportion of benefits that had been attributed to control methods and many others (Hosking and du Preez, 2004; van Wilgen *et al*., 2004; de Lange and van Wilgen, 2010). Interestingly, according to Marias *et al*. (2004), a 20% decrease in the costs of clearing overtime is possible – as well as a 40% reduction which can also lead to a doubling of the NPV. This makes it crucial for marginal changes to be observed throughout the analysis. The results in the sensitivity test could either change or maintain robustness with the main study results.

2.10 CONCEPTUAL FRAMEWORK

According to Barbier (1987: 107), "the growing recognition that environmental consideration must be incorporated into development strategies is having some influence on policy making and planning". Using this to argue that economics is the best discipline to have felt such significant influence, Barbier (1987) further highlights that the economics discipline is best able to analyse trade-offs among environmental costs and benefits associated with IAPs.

Typically, the environmentally and socially inclusive frameworks are different from the traditional approach in that, the latter included merely looking at direct costs and benefits associated with a project. They disregarded the social responsibility and impact of most investments, even those led by the government with the more inclusive frameworks. Hence, the extended economic approach leaned towards the costs and benefits that relate to not only economic or financial inputs but also environmental and external impacts, related externalities as it relates to both external and environmental control initiatives. For the purpose of this study, the chosen method will be on the extended and or inclusive rates. This is because in addition to the above expressed factors, Turpie (2004) argue that the WfW programme is not as costly as it appears to be especially when taking into account the social costs and benefits of the programme. As with the above systematic review of frameworks applicable in this area of study, CBA is the most used framework on analysis and is briefly explored below.

2.10.1 Cost benefit analysis framework

For such proposed economic evaluation of IAPs, various scholars encourage the use of Cost benefit analysis (CBA) (McConnachie *et al*., 2003; Turpie, 2004 and Born *et al*., 2005). The framework can compare different costs, benefits and economic data to reveal which control option has the highest benefit-cost ratio. In most studies in literature, CBA has been used to deduce on cost-effectiveness, efficiency, economic feasibility, return on investment and other crucial decision-making concepts (Born *et al*., 2005).

Being our main tool/framework of interest, CBA is an economic framework that values all the outcomes of alternative actions in monetary terms; it values the benefits of an outcome per currency unit spent towards that outcome (Drummond et al., 1997). According to Born *et al*. (2005), the highly recommended framework is the classical cost benefit analysis, due to its ability to accurately and effectively indicate the economic costs of IAPs control. CBA has been considered the best procedure to evaluating the biological invasions since as early as the 1930s (Munda, 1996; Hoagland and Jin, 2006). It can play a huge role in reconciling the private and social costs and benefits, as well as use the sensitivity analysis with an employment of different discount rates to account for uncertainty and vary variables that can have a significant impact on results (Tisdell, 1990; Pimentel *et al*., 2001 and Cuyno *et al*., 2001). Although CBA and its related sensitivity analysis are useful, both are however not fully equipped to capture all uncertainty (Munda, 1996; O'Connor, 2002).

The CBA framework has three decision criteria and four basic elements. The three decision criteria: the net present value (NPV), the internal rate of return (IRR) and the benefit-cost ratio (BCR) while the four basic elements are costs, benefits, discount rate and time consideration (Hosking and du Preez, 2004). Typically, a good investment is one that has a positive NPV, an IRR that is greater than the employed discount rate and a BCR that is greater than one. Careful attention should however be given to the use of significant benefits, which are those that carry a meaningful impact. As a monitoring and evaluation (M&E) tool, CBA is often used to assess if the costs of the project under evaluation are justified by the impact or benefit, they have or produce by measuring the project inputs (costs) with the project output (benefits).

On a basic level, the CBA method includes an establishment of a framework to outline the parameters of the analysis, the identification and measurement of environmental effects, followed by the translation of those into monetary values, and an identification of non-monetary and intangible effects, a determination of an effective discount rate towards an optimal environmental analysis, a comparison of costs and benefit, then calculation of the estimated cost benefit ratio and an analysis of results (Barbier, 1987). For example, in cases of running a cost benefit analysis on the use of the chemical control methods on IAPs in South Africa, one will need to first identify and quantify the effects of chemical control as it related to its costs and benefits over a desired period of evaluation with the aim of reflecting that period feasibility of the project (De Groot et al., 2003). These costs and benefits vary from initial research costs, technical costs and operation costs as well as invasion prevention benefits, increased water yield or biological control cost saving if any, and others detailed under the cost section. Once the quantification stage is done, using a suitable discount rate, the cost benefit ratio may be calculated which is really a comparison of the present value of costs and benefits (Hosking and du Preez, 2004; van Wilgen *et al*., 2004; McConnachie *et al*., 2003; McConnachie *et al*., 2012; and Fraser *et al*., 2016).

CHAPTER THREE: STUDY SYSTEM

This chapter seeks to bridge the gap between the first two chapters and the last three chapter of this study. First, the chapter gives a brief historical background of the big bad five aquatic weeds in South Africa. This is followed by a detailed overview of the four selected aquatic weeds that looks at the nature of each aquatic weed and their respective biological control agents. The chapter then includes an impact-analysis of the degree of weed invasiveness of the big bad five weeds in South Africa as well as a brief report on their current national status. It ends off with a brief systematic literature review that is specific to the four selected aquatic weeds with a table that summarizes key finding in this chapter. All this information is pivotal to the methods chapter, results chapter as well as the discussion and conclusion chapter. The inclusion of the fifth weed *Eichhornia crassipes* (water hyacinth) in some cases is due to the use of the weed as a surrogate weed in the methods chapter; affecting also the results and discussion and conclusion chapter.

3.1 INTRODUCTION: THE BIG BAD FIVE AQUATIC WEEDS IN SOUTH AFRICA

The global increase in the distribution of aquatic weeds over the last 30 years has become a growing problem that continues to threaten numerous lakes and river systems of Africa since the late 1800s (Hill and Coetzee, 2017). It was the Lake Victoria crisis in East Africa in the mid-1990s that heightened the world’s attention to the extent of socio-economic impacts the weed can cause. Hence, Cilliers *et al*. (2003) argued that the introduction of aquatic weeds into African lakes and river systems is the greatest threat to African socio-economic development.

In South Africa, aquatic weeds were first recorded in the late 1800s (Hill and Coetzee, 2017). Since then, the country has been invaded by various aquatic weeds; including the five key aquatic weeds that have gained global awareness due to their invasiveness. They are *Pistia stratiotes* (water lettuce), *Salvinia molesta* (salvinia), *Azolla filiculoides* (red water fern), *Myriophyllum aquaticum* (parrot’s feather) and *Eichhornia crassipes* (water hyacinth); all free-floating except for the rooted *M. aquaticum*. They originate from South America (Hill, 2003; Cilliers *et al*., 2003), and are commonly known as South Africa’s Big Bad Five Aquatic Weeds (Henderson and Cilliers, 2002). Their mode of introduction is unknown for some of the weeds while known for others.

However, they have been commonly transported for medical reasons, as ornamentals, for horticultural and aquarium trade, as well as for use as fodder for animals (Harley, 1990; Martin and Coetzee, 2011). Although these weeds spread mostly to warmer parts of the world (Coetzee *et al*., 2011); Hill and Coetzee (2017) highlighted that, in South Africa, these weeds are found in various regions of different conditions throughout the country such as winter rainfall western areas, subtropical eastern areas, as well as in cool temperate areas (Hill and Coetzee, 2017). As much as these aquatic weeds are back-seat drivers, requiring disturbance such as eutrophication, their problematic invasive nature in South Africa is also due to the lack of natural enemies, (McFadyen, 1998; Cilliers *et al*., 2003; Hill, 2003; Coetzee *et al*., 2011 and Coetzee and Hill, 2012).

Biological control has been implemented on all five of the aquatic weeds, with great success (complete control status) being achieved on *P. stratiotes, S. molesta*, *A. filiculoides*, *M. aquaticum*. While the control of *E. crassipes* has been successful, it still relies on an integrated approach (Coetzee *et al*., 2011; Hill and Coetzee, 2017). Complete control is “the level of control achieved through the actions of biological agents alone, requiring no other management interventions” (Hoffmann 1995 in Coetzee *et al*., 2011:451). This means that the impact of the weed under complete control has been significantly reduced to an acceptable level using only biological control agents, such that the weed no longer holds a threat in South Africa (McConnachie *et al*., 2003; McConnachie *et al*., 2004 and Hill and McConnachie, 2009). On a practical level, complete biological control status is obtained due to the biological control success on weeds “as measured by an increase in the number of sites under biological control, coupled with a significant reduction in the percentage plan cover of these weeds and a recovery of ecosystem services” (Hill and Coetzee, 2017).

3.2 BACKGROUND OF THE FOUR WEEDS IN SOUTH AFRICA

3.2.1 *Pistia stratiotes* (Water Lettuce)

Pistia stratiotes (shown in figure 3.1 below) is a widespread aquatic weed in most tropical regions of Africa (Julien and Griffiths, 1998), it was first reported in South Africa in the KwaZulu-Natal Province in 1865 (Hill, 2003). It is a free-floating aquatic weed with leaves, roots and heads (see Figure 3.1 below); it flows freely mostly in still and or slow-moving water systems (Cilliers *et al*., 2003; Hill, 2003). It reproduces vegetatively in that, it creates stolons and daughter plants (Hill, 2003), but also releases seeds into water bodies that can survive dry mud seasons (Cilliers *et al*., 2003) germinating during the following wet season (Coetzee *et al*., 2011). Although present throughout the year, water lettuce is more problematic in mid-summer (Cilliers *et al*., 2003). It invades both sub-tropical and colder regions of the country (Henderson and Cilliers, 1991; Diop and Hill, 2009); although it has over time become a problem in various regions of South Africa (Hill, 2003).

The water lettuce weevil (*Neohydronomus affinis)* (shown in Figure 3.1 below); was first released in South Africa in 1985; established quickly and spread rapidly around the country (Cilliers *et al*., 2003; Hill 2003). *N. affinis* takes between eleven and fourteen days to cause detrimental damage to the weed (Moore and Hill, 2012). Its success is subject to possible resurgence of the weed from seeds of isolated plants (Diop and Hill, 2009). Although the weed is more effective during warm seasons due to rapid weevil increase during warm seasons or in tropical regions (Diop and Hill, 2009); in some parts of the country, the weevil can have a slow rate of control; this is due to factors such as low temperature effect on the spread and breeding ability of the weevil especially in winter (Diop and Hill, 2009 and Diop *et al*., 2010). The size of population of *N. affinis* released is also detrimental to success as the larger the size of the release, the better the establishment and quicker the control (Diop *et al*., 2010). Hence, as with Center and Pratt‘s (2004) critic of the concept of ‘release and pray’, the effort put prior to and during the process of release affects the success and effectiveness of biological control agents. As such, a degree of knowledge (about the agent, weed and environment) is required before the agent is released (Diop *et al*., 2010). For example, the sites’ nutrient-enrichment can enhance quick plant growth as well as hinder effective weevil damage on the plant (Diop and Hill, 2009); and because the rapid increase of the weed despite active impact of the weevil is in most cases due to high nutrient levels in water, it prohibits successful weevil impact on the weed (Cilliers, 1991).

Figure 3.1 The aquatic weed *Pistia stratiotes* and *Neohydronomus affinis* its biological control agent.

The 500 *N. affinis* initial release in South Africa (in December 1985) in the Nhlangaluwe Pan situated in the Kruger National Park, achieved complete clearance of the weed within ten months (Cilliers, 1991). The second release of the weevil was on the Dakamila Pan in June 1986, which also caused the weed to rot and sink within eleven months (Cilliers, 1991). In September of 1987, *N. affinis* was released in the Sabie River – a fast flowing river also situated in the Kruger National Park; causing slow damage overtime proving the point raised by Hill (2003) and Cilliers (1991) that the weevil can be slow and less effective in fast flowing and free flowing rivers. Hence at the time, the Sabie river was to be under successful biological control with chemical control augmentation where necessary (Cilliers *et al*., 1996). *N. affinis* was also released onto *P. stratiotes*, in a 1.5 ha pond at the Cape Recife Nature Reserve in Port Elizabeth in the Eastern Cape Province, in 2002, resulting in complete control within a year (Moore and Hill, 2012). Comparing the performance of *N. affinis* in South Africa to its performance internationally, it seems that the weevil is doing equally well. For example, Diop and Hill (2009) found that the weevil managed to reduce the percentage cover of the weed at Keur Momar Sarr on Lake Guiers by an average of 25% every two months; achieving complete clearing within 12 months (September 1994 – August 1995). At

Djoudj National Park, the weevil took about 18 months to clear. These clearing period averages are similar to clearing period averages in South Africa.

Although there is theoretical or qualitative proof that biological control is more cost-effective on this *P. stratiotes*; no Cost Benefit Analysis has been done on either chemical or biological control of the weed in South Africa. However, there is a standing hypothesis that the control incentives of the weed are likely to produce a positive benefit-cost ratio; although there is no quantitative evidence on this regard yet.

3.2.2 Salvinia molesta (Salvinia)

Salvinia molesta (shown in Figure 3.2 below) is a weed of South American origin and was first reported in South Africa in the early 1900s (Martin *et al*., 2018). It is a free-floating sterile weed that reproduces vegetatively (Forno and Julien, 2000 and Diop and Hill, 2009). It is usually present during all seasons but is dominant in sub-tropical areas, inlands, coastal regions, still and slow flowing water (Cilliers *et al.,* 2003; Hill and Julien, 2003 and Diop and Hill, 2009). It has the potential to double its rate of infestation within two days under certain conditions (Doeleman, 1986); hence it was initially considered a major weed in South Africa (Coetzee *et al*., 2011; Martin *et al*., 2018). *S. molesta* has historically infested areas such as the Southern and Southwestern-Cape Province of the country as well as Limpopo, Mpumalanga, Kwazulu-Natal and Eastern Cape provinces (Hill, 2003; Coetzee *et al*., 2011). Often, *S. molesta* forms dense mats that result in ecological and economic harm (Diop and Hill, 2009).

Figure 3.2 The weed *Salvinia molesta* and the biological control agent *Cyrtopbagous salvinae*

The *Salvinia Molesta* weevil, *Cyrtopbagous salvinae* (Figure 3.2 above) has proven to be very successful in in controlling *S. molesta* in Africa (Cilliers *et al*, 2003); and has shown to be an effective control agent in South Africa. The adult eats the growth tips of the weed to prevent the weed from growing, while the larvae eats the roots and buds to cause the weed to rot and sink (Julien *et al*., 1987 in Hill and Julien, 2003). The weevil was released in South Africa in 1985 (Cilliers *et al*., 2003; Hill and Coetzee, 2017), on three impoundments. Of the three dams, the smallest one was effectively cleared within 13 months and the largest dam took about 14 months to clear while the other took about 9 months to clear (Cilliers, 1991). According to Diop and Hill (2009), *C. salvinae* usually takes between 3 months to 12 months and at most 3 years to clear depending on the region (Diop and Hill, 2009). However, in cooler and temperate regions of South-Eastern Cape Province, the effectiveness of *C. salvinae* has been slow, producing weed control period that can take up to four years (Cilliers, 1991). This is due to the likelihood of weevil death in winter and cold temperatures (Cilliers, 1991).

According to Coetzee *et al*. (2011), appropriate implementation is imperative because it is subject to factors such as temperature and eutrophication which can affect the time required to reach control (Cilliers, 1991). In addition to this, Martin *et al*. (2018) also highlighted that biological control is more successful and thus effective in small sites than it is in larger and shaded sites; as well as that complete and substantial control is most likely achievable in the north parts of the country. In some instances, the success of biological control on salvinia depends on the number of weevils released and can also require a few sequences of release although not always (Diop and Hill, 2009).

In 2008, a post-release evaluation was done on *S. molesta* and revealed that biological control programme has reduced the weed cover in South Africa from 51-100% cover to about 0-5% cover in 2017 (Martin *et al*., 2018). As such the *C. salvinae* has brought salvinia under biological control to a low level that no longer requires manual and or chemical control (Cilliers, 1991). Agreeing with Coetzee *et al*. (2011) that augmented release will be required in some cases as with the 80ha farm in Greytown KZN invaded with *S. molesta* in 2009. Although the weed can be controlled using herbicide, it is for environmental and sustainability implications that biological control was pursued and is favourable (Hill and Julien, 2003).

Comparing national performance to international, the clearing period averages seem relatively similar. For example, in 1999, *S. molesta* was found in the Senegal River and *C. salvinae* was released against it in April 2001 (Pieterse *et al*., 2003; Diop and Hill 2009). According to Pieterse *et al*. (2003), the weevil showed significant damage on the weed (in Senegal River) by October 2001, soon after which it was declared to hold the status of 'no longer a threat'. This was because the weevil was declared highly successful on this river as it took about six months to cause significant damage and about a year to clear the *S. molesta* (Diop and Hill, 2009). In 1980, the Australian Centre for International Agricultural Research (ACIAR) funded the application of the biological control programme against *S. molesta* in Sri Lanka. In 1986, the weevil was released to approximately 25% of 50 000 reservoirs infested with between 5 and 25 ha size of infestation (Doeleman, 1989). The programme produced a full recovery of costs within a year as well as a decline in ongoing costs and as such a build-up of high and increased rates of return (Doeleman, 1989). These results are not dissimilar to those found in South Africa (with 13-19 months clearance range) with the exception of possible maximum time period of 4 years (Cilliers, 1991).

3.2.3 *Myriophyllum aquaticum* (Parrot’s feather)

Myriophyllum aquaticum is a rooted aquatic weed from South America – see Figure 3.3 below. It was first reported in South Africa in 1918 in the Berg River in the Western Cape Province (Jacot-Guillarmod 1979 in Oberholzer *et al*., 2007) and is present throughout the year mostly in tropical and subtropical areas but is often found in other areas during the spring season (Hill, 2003; Hill and Julien, 2003). *M. aquaticum* can grow up to 1.5 cm deep with emergent shoots that can come up to between 200 and 500 mm above the water level (Hill and Julien, 2003). It dies out in winter due to frost, however, the dead parts of the weed usually shelter new shoots that persist in spring and cause re-infestation (Cilliers, 1999); making it prone to regrowth (Hill and Julien, 2003). It produces vegetatively because there are only female plants in South Africa (Henderson, 2001; Cilliers *et al*., 2003). However, *M. aquaticum* has a regrowth potential of less than three weeks and can grow fully within six weeks due to the ability of the weed to sprout 1-4 new shoots for each damaged weed (Cilliers, 1999). In South Africa, *M. aquaticum* has been dominant in provinces such as the Eastern Cape, Western Cape, North West, Mpumalanga, KwaZulu-Natal, Limpopo and small rivers in Gauteng Province (Cilliers, 1999; Hill, 2003 and Oberholzer *et al*., 2007).

Figure 3.3 The weed *Myriophyllum aquaticum* and the biological control agent *Lysathia* sp

Biological control on M. *aquaticum* was first initiated in South Africa in the 1991 (Hill and Julien, 2003). The biological control agent – figure 3.3 above - *Lysathia* sp (Coleoptera: Chrysomelidae) was released in 1994 at five sites in South Africa (Cilliers, 1999; Coetzee *et al*., 2011; Hill and Coetzee, 2017). This beetle established quickly and dispersed well (Cilliers *et al*., 2003; Coetzee *et al*., 2011) with a life cycle of about 24 to 26 days to fully develop into an adult weevil (Cilliers, 1999). Although the weevil struggles in winter (but can survive it), it is generally stronger and has more build-up in summer (Cilliers *et al*, 2003).

In South Africa, the biological control programme on *M. aquaticum* has been highly successful, so much so it is now considered to be under complete control in South Africa (Hill and Coetzee 2017). According to Coetzee *et al*. (2011), the weevil is sometimes abundant such that not a single healthy (green) leaf would be found on the weed. However, Coetzee *et al*., (2011) also acknowledged that, despite the weevil population build up in summer, augmented releases are advised to be done early in the season. Although there are two herbicides are available for control of *S. molesta*, there is still no registered herbicide against this weed in South Africa (Hill, 2003; Cilliers *et al*., 2003; Oberholzer *et al*., 2007). This may be due to their environmental impacts associated with the herbicide application and the failure to translocate well down the shoots of the plant (Cilliers *et al*., 2003; Hill and Julien, 2003; Oberholzer *et al*., 2007). Mechanical control is discouraged due to its impractical nature relative to the growth and regrowth rate of the weed (Hill, 2003). Since 1999 until around 2008, Coetzee *et al*. (2011) highlighted that not much research and monitoring and evaluation was done on the biological control method on *M. aquaticum* compared to that on *P. stratiotes* and *S. molesta*.

3.2.4 *Azolla filiculoides* (Red water fern)

Azolla filiculoides is a weed of South American origin that has invaded South Africa since its first discovery in the year 1948 (Oosthuizen and Walters, 1961). *A. filiculoides* is mostly present in winter and through drought conditions; it excels in nitrogen deficient water, small dams, small streams and in slow moving rivers (Cilliers *et al*., 2003; Hill, 2003). The weed reproduces through rapid vegetative reproduction and sexual reproduction of spores (Cilliers *et al*., 2003; Hill, 2003). It has a 15% daily growth rate as well as a doubling reproduction rate between 5 to 7 days (Lumpkin and Plucknett, 1982; Hill and Julien, 2003). *A. filiculoides* creates a dense mat which causes a reduction in the quality of water, in the availability of water for transport, irrigation and recreation, increases in the siltation of dams, threatens livestock and causes in water related diseases, as well as a reduction in the overall biodiversity; and can get up to 5-30cm thick – see Figure 3.4 below (Cilliers *et al*., 2003; Hill and Julien, 2003). By 1990, the weed had done a lot of damage throughout the country and had resulted in large infestations (Hill *et al*., 2008). *A. filiculoides* infested most provinces in South Africa such as the Eastern Cape, Western Cape, Northern Cape, Mpumalanga, Gauteng, Limpopo, North West and especially Free State Province.

Figure 3.4 The weed *Azolla filiculoides* and the biological control agent *Stenopeimus rufinasus*

The *Azolla filiculoides* weevil *Stenopelmus rufinasus* – see Figure 3.4 above was released in 1997 (Coetzee *et al*., 2011; Hill and Coetzee, 2017). It originates from Florida in the USA (Hill, 2003) andt is said to establish quickly with an average clearance period of between 2 months and a year (McConnachie *et al*., 2004; Hill *et al*., 2008). *Stenopelmus rufinasus* has a dispersal ability of between 300 and 350 kms and is able to locate the weed should it return (McConnachie, unpublished data; Cilliers *et al*., 2003; Hill *et al*., 2008; Coetzee *et al*., 2011). Within a space of five years of the release of the weevil, the weed was considered to no longer hold a threat in South Africa as it had successfully controlled all the sites it had been released into resulting in local extinctions of the weed (Hill and Julien, 2003; Cilliers *et al*., 2003 and Coetzee *et al*., 2011). The biological control programme of *A. filiculoides* in southern Africa has been ranked amongst the most successful biological control cases in the world (McConnachie *et al*., 2004; Coetzee *et al*., 2011). So much so, Zachariades *et al*. (2017) suggested that the success of biological control ofthis weed should warrant its removal from the 2004 National Environmental Management: Biodiversity Act (NEMBA) list of invasive species in South Africa.

Although mechanical and chemical control are available, the former is discouraged because it is considered impractical and labour intensive; while the later – although has three herbicides available for *A. filiculoides*: glyphosate, paraquat and diquant - none of them are registered for use in South Africa (Cilliers *et al*., 2003; Hill and Julien, 2003).

3.3 RELATIVE IMPACT ANALYSIS AND CURRENT STATUS OF THE BIG BAD FIVE

With the existing argument that much less attention has been given to the study of impacts of invasive species that affect aquatic ecosystems relative to the devotion towards terrestrial ecosystem (Stiers *et al*., 2011); there is a gap in studies that compare the relative impact caused by the four selected weeds. Hill and Coetzee (2017) presented a comparison and ranking of the impact of aquatic weeds in South Africa in the context of both environmental and socio-economic impact – 12 impact categories. The paper looked at this degree of impact before and after biological control using the Genetic Impact Scoring System (GISS) by Nentwig *et al*. (2016). Figure 3.5 below shows a table from Hill and Coetzee (2017) that presented the respective impact scores.

This type of impact assessment is important as Hoffman *et al*. (2019) argued that to classify weed biological control as successful, the combined effect of the biological control agent on the degree and extent to which the agent has managed to supress the weed and reduced impacts should be measured. According to Hill and Coetzee (2017), the results of the initial degree of weed impact show a rank order of the highest impact associated with *E. crassipes, A. filiculoides, P. stratiotes, S. molesta* and *M. aquaticum.* Following biological control clearing incentives, Hill and Coetzee (2017) further found that the degree of impact was reduced more for *A. filiculoides* followed by *S. molesta, P. stratiotes, M. aquaticum* and the least for *E. crassipes*. This suggesting that the impact rank of the weeds post biological control efforts were high for *E. crassipes, M. aquaticum,* *P. stratiotes, S. molesta* and *A. filiculoides* taking up the least impact score. Historically, *E. crassipes* has indeed proven more difficult to control using biological control than the four selected weeds (Hill and Cilliers, 1999; Coetzee *et al*., 2014; Martin and Hill, 2016; Hill and Coetzee, 2017).

Figure 3.5: The impact scores with level of confidence per impact categories of the GISS (Nentwig et al. 2016) for five water weeds in South Africa, presenting the worst-case scenario in the absence of any biological control, and the current situation in South Africa, post biological control, where applicable (Hill and Coetzee,2017)

Weed	**Prior to biological control**			**Post biological control**		
	Environmental impact (level of confidence)	**Socio-economic impact (level of confidence)**	**Total**	**Environmental impact (level of confidence)**	**Socio-economic impact (level of confidence)**	**Total**
Eichhornia crassipes	22 (2.67)	21 (3.00)	43 (2.83)	12 (2.50)	11 (2.67)	23 (2.58)
Pistia stratiotes	22 (2.67)	16 (2.83)	38 (2.75)	2 (3.00)	4 (2.83)	6 (2.92)
Salvinia molesta	22 (2.67)	16 (2.83)	38 (2.75)	2 (3.00)	4 (2.83)	6 (2.92)
Azolla filiculoides	20 (2.83)	20 (2.83)	40 (2.83)	0 (3.00)	0 (3.00)	0 (3.00)
Myriophyllum aquaticum	18 (2.83)	20 (2.83)	38 (2.83)	8 (2.83)	7 (2.83)	15 (2.83)

With regard to the control of the bid bad five weeds in South Africa, Hill and Julien (2003) proposed various factors that aid the high success rate of the control on the weeds in Africa. They (Hill and Julien, 2003) suggest that factors such as the reliance on fundamental research already done by developed countries, the development of effective mass-rearing techniques to ensure release of healthy agents, sound post-release monitoring techniques, as well as committed individuals on project and community involvement; actually enhance success of control in developing countries of Africa (Hill and Julien, 2003). Alongside this, Hill and Coetzee (2017) further eluded that the coordinated effort of various stakeholder – such as the biological control programme on water weeds is coordinated by Rhodes University Centre of Biological Control (CBC) together with

University of the Witwatersrand and the Plant Protection Research Institute of the Agricultural Research Council (PPRI-ARC) and many others - aid successful biological control in South Africa.

3.4 SYSTEMATIC REVIEW OF THE BIG BAD FIVE AQUATIC WEEDS

3.4.1 *Eichhornia crassipes* (Water hyacinth)

Out of the big bad five aquatic weeds in South Africa, *Eichhornia crassipes* seems to have drawn the attention of most economists. Studies such as van Wyk and van Wilgen (2002) and Fraser *et al*. (2016) – amongst others – have done an economic review of *E. crassipes*. van Wyk and van Wilgen (2002) evaluated the cost of *E. crassipes* in South Africa, on four different sites (Hartbeespoort Dam, New Year's Dam and Nseleni River and Lake Nsezi) focusing on three different control strategies (chemical, biological and integrated control methods) respectively. The main goals of the study were to investigate the cost effectiveness of each control method to bring out important lessons for the management of *E. crassipes* nationally. Fraser *et al*. (2016) investigated the prevailing water loss saving from the use of biological control on New Year's Dam.

With respect to methods and material, the main data source for van Wyk and van Wilgen (2002) was the Department of Water Affairs and Forestry (DWAF) water weeds office. Hartbeespoort (HBP) Dam was evaluated for a 24-year period for the use of herbicide. Although only data on the years 1977/78 and period 1991-2001 was available, data for the interim 12-year period was not recorded. This compelled the use of conservative estimation for the cost of control; achieved by using an estimate of the number of hectares cleared. For this, assumptions on the gradual reduction rate, maintenance levels and budget spending on the dam were made and market prices were used to account for the herbicide control cost estimates. This herbicide control cost estimate were affected by the variation between the spray approach used (boat and aerial) for clearing (Van Wyk and van Wilgen, 2002).

For the biological control management programme approach, the costs covered by van Wyk and van Wilgen (2002) were research and development costs since the start of the New Year's Dam project. With data obtained from the Plant Protection Research Institute (PPRI), the estimated biological control cost per hectare used in the study was about R309 while the initial clearing cost was about R10 089.45 in 1991. On the same site, Fraser *et al*. (2016) investigated the degree of water loss saving caused by successful biological control effort; looking at the period 2002-2012

– the continuing period from the once covered by van Wyk and van Wilgen (2002). Fraser *et al*. (2016) used a 1990 start-up cost of R48 088 and a full 23-year period total estimated cost of R402 358. Fraser *et al*., (2016) also used the 1991-2000 costs expressed in van Wyk and van Wilgen (2002) study as well as monitoring and evaluation data for the period 2002 and 2012 obtained from the Rhodes University Department of Zoology and Entomology – Centre of Biological Control (CBC) - adjusted for inflation using the 2012 PPI time series.

Although the time periods of evaluation differed from one control method to another due to the availability of data, the results found by van Wyk and Wilgen (2002) were that herbicide control management programme is a cost-effective short-term solution while biological control management is a cheaper, less resource intensive long-term cost-effective solution and the integrated control management programme is the most cost-effective control method on average. Van Wyk and van Wilgen (2002) also inferred that herbicide control is relatively five times less effective than biological control, while recognizing that herbicides do in some cases perpetrate the long-term solution to the control of IAPs. The detailed results found by van Wyk and van Wilgen (2002) were an estimated cost per ha of about R1 487 for the herbicide control programme on Hartbeespoort Dam. With these, van Wyk and van Wilgen (2002) confirmed that, for the biological control programme, the initial cost was relatively higher than that of subsequent years – as costs decrease with time. However, van Wyk and van Wilgen (2002) recommended that the future use of a CBA framework would be the most ideal evaluation process.

On the issue of a CBA, Fraser *et al*. (2016) found that the estimated total net benefit was between R282 458 and R3 671 954 using the raw agricultural value of R0.26 per m^3 to value water. Using a 10% and 5% discount rate, Fraser *et al*. (2016) found a BCR range of between 0.52:1 to 7.58:1 (between the two rates). To get the total net benefit, Fraser *et al*. (2016) multiplied the net benefit (water saving) by the price per m^3 of water for irrigation converted to 2012 prices. The prevailing water saving was estimated by use of a range of evapotranspiration rates found in literature to determine the degree of water loss by transpiration cause by *E. crassipes*; then translated them into a water saving benefit that result from perceived transpiration reduction caused by the use of biocontrol. The initial plant cover found by Fraser *et al*. (2016) of about 80% of the dam was reduced to a cover of about 5% over the period 2002 and 2012 – obtained from the Water Research Commission Report (Midgley *et al*., 1994).

3.4.2 *Azolla filiculoides* (Red water fern)

McConnachie *et al*. (2003) evaluated the successfulness of biological control on the weed *Azolla filiculoides* in South Africa for the period 1995 – 2000; with the aim to assess how economically viable the biological agent was in controlling the *A. filiculoides*. The biological control costs included in the study were: development costs, salaries, operational and overhead costs obtained from the Plant Protection Research Institute in Pretoria. These costs were adjusted for inflation using the producer price index (PPI) at 2000 ZAR constant prices. For benefits, a questionnaire was set out to about 30 individuals with the objective to source out costs associated with the presence of *A. filiculoides*. These costs were then considered to reflect the avoided cost of clearing *A. filiculoides* using biological control. From the 30 individuals interviewed, the direct cost of *A. filiculoides* disclosed were stock losses, water pumps replacement costs, alternative water supply set up costs as well as recreational activities loss related costs. These direct costs - when avoided – made up the estimated benefit value and were assumed to be constant; a 2000 ZAR PPI adjustment was employed.

Although the fundamental (initial) estimates of the study were an average water cover estimate of about 2.17 hectares; an expected annual weed expansion rate of 1.33% was assumed; McConnachie *et al*. (2003) used the historical data to estimate this future rate of spread and maximum possible invasion using the South African Water Social Accounting Matrix. McConnachie *et al*. (2003) further assumed that the economic value of associated benefits will increase by 3% pa while costs will be about 20% of the average costs incurred during the period 1995-2000 was incorporated (assumed to decrease).

McConnachie *et al*. (2003) found that the total costs of developing the biological control program was US $ 46 962, and the total number of hectares cleared with that were about 170 ha – making the cost per ha US $276. Since the US $46 962 excluded investment costs, the cost per ha increased to US $1 511 when the initial investment costs incurred in 1995 were included. The average benefits – from the surveyed 30 interviewees – were about US $450 per ha based mostly on replacement costs. Using the investment inclusive amount, overall results of the CBA showed a BCR of 2.5:1 for the year 2000, of 13:1 for 2005 and a further estimated increase to about 15:1 in 2010 – discounted at 8%. This providing the concluding remarks that the benefits to costs of clearing *A. filiculoides* using biological control agents is positively related to time as they increases with time. The NPV from the year 1995-2000 was about US $206 million, a positive NPV; rising up to about US $2.9 billion after taking into account the sensitivity test. The estimated cost-saving for the year 2000 was a decrease in the value of associated damages by US $589 per annum. These results led to a conclusion that biological control programme on *A. filiculoides* has an overall economic viability and that the on-site benefits of the programme are self-justifying; while costs are negatively related to time (they decrease with time).

3.4.3 *Salvinia molesta* (Salvinia)

Although there is no CBA study done on salvinia in South Africa, Doeleman (1989) did a study that aimed at estimating the economic benefit of biological control on Salvinia in Sri Lanka for the lifetime of the project period of 25 years. The results of the study were considered to be provisional results because the study was undertaken before the biocontrol programme on salvinia was finished. With respect to the method applied, the benefits captured by Doeleman (1989) were based on a category of costs associated with the impact of the presence of *S. molesta* without biological control. The prevailing reduction in these costs was considered the main benefits of having a successful biological control programme on the weed (as assumed by Mc Connachie *et al*., 2003). The following impact costs were considered as the prevailing avoided-cost benefits: “losses in rice production, fishing losses, other commercial losses, human health costs, environmental costs and abatement expenditure” (Doeleman 1989:7). Before the monetary value of these avoided costs could be used to present the prevailing benefit value, the value of commercial benefits associated with *S. molesta* were subtracted to derive a net (impact) benefit cost for the study. These were calculated per 1987 benefits to which the assumption that benefits are expected to have a 3% annual growth rate was applied. For costs, Doeleman (1989:7) assumed that a “full recovery of the control programme costs is expected to take less than 1-year and ongoing costs are expected to be negligible”.

Similar to this study, Chikwenhere and Keswani (1997) did an economic evaluation of the *S. molesta* in two water bodies with a total of 16 ha at Tengwe Tobacco Commercial Farming north-western Zimbabwe. The focus of the paper was to assess the feasibility, practicality and economics of biological control on the weed for a four-year period 1992-1995. During this period, the biological control agent was able to control 99% of the covered hectares within two years. The water infested at the Tengwe Tobacco Commercial Farming had economic value in terms of irrigation purposes, domestic livestock water supply, fisheries and overall environmental significance. Hence, identified benefits related to restored clean water, improved aesthetic value and cessation of herbicide use. These benefits however could not be given monetary value due to a poor database and lack of adequate methodology available. Thus, to conduct the CBA, Chikwenhere and Keswani (1997) used the relative chemical control clearing cost or prevailing benefit value.

The costs captured by Chikwenhere and Keswani (1997) included costs based on the biological control activities costs such as the cost of insect rearing, insect releasing (including salaries, travel and subsistence) as well as monitoring costs (which also included salaries, travel and subsistence). These costs presented a total biological control cost of Z$6 385 (Zimbabwean Dollar) for the four-year. Doeleman (1989) only included the value of the Australian investment made towards the control of *S. molesta* which was about US$298 179, as well as the cost of Sri Lanka number hours budgeted toward the programme (4 127 hours which amounted to about US $3 281). The total cost of control was a sum of the two cost components US$302 001. Although these estimates were achievable, the study did experience some difficulty converting the currency values of the two countries.

With respect to conducting the CBA, Doeleman (1989) applied a 5%, 10% and 15% discount rate. For both studies, the biological control projects on *S. molesta* indicated positive returns. Doeleman (1989) found a BCR range of 53:1 to as high as 1673:1 (when including the cost of Sri Lanka labour); to which, when taking into account the time return ratio of the project, the results were a BCR range of between 1133:1 and 2771:1. These results and BCRs are not per annum ratios but cover the full period of 25 years and have led to the conclusion that the biological control method on *S. molesta* is favourable and is associated with significant economic returns. Chikwenhere and

Keswani (1997) found a BCR of 10.6:1; interpreted as Zimbabwean dollar saved compared to chemical control which had a BCR or 1:10.6 presenting a relative BCR. Chikwenhere and Keswani (1997) concluded that biocontrol has a positive return on *S. molesta* and further suggested that biological control on floating aquatic weeds is relatively slower approach but is also the best long-term solution.

Table 3.1 shows a summary of this chapter. It highlights key information on the selected aquatic weed under study such as the scientific and English name of each weed, the Conservation of Agricultural Resources Act 2002 (CARA) National Environmental Biodiversity: Management Act (NEMBA) category of the weeds, as well as regions that the weeds have historical invaded in South Africa. The summary also shows the control method used in South Africa and the biological control agent released for control of each weed as well as the type of supplementary or alternative method that could have been used had the weeds not been under complete biological control management. The table further highlights the average period it takes for each biological control agent to cause significant impact on the respective weed. The last column of the table shows the available information on the previously estimated control costs and BCRs on each of the four weeds. There has been no success in finding CBA research on *Pistia stratiotes* (Water lettuce) and *Myriophyllum aquaticum* (Parrot's feather) to which an assumption was made that such studies have not yet been done. This is represented by the 'Not Applicable' (N/A) entry in the last column of the two weeds.

Table 3.1 Summary of the Four Selected Aquatic Weeds in South Africa

Weed	Main Control Method	Supplementary Control Method	Where	Control	Estimated costs and CBA Range
Pistia stratiotes (Water lettuce) has a CARA 2002 – Category 1 NEMBA – Category 1b; it was initially an exotic but mi-	Biological control – *Neohydronomus affinis*, it is a leaf and stem borer and has extensive status (Hill and Coetzee, 2017:4).	Chemical control – Terbutryn herbicide (Cilliers *et al.*, 2003:171).	KZN, EC and MP	Complete biological control usually in a period between 1-2 years, however, it may require subsequent release. The agent has been proven to	N/A

nor weed (Coetzee ***et al***., 2011).				have good dispersal ability (Harley *et al*., 1990:366).	
Salvinia molesta (Salvinia), has a CARA 2002 – Category 1 NEMBA – Category 1b; it was initially second to the most important weed - water hyacinth (Coetzee *et al*, 2011: 452).	Biological control – *Cyrtobagous salvinae* (Coleoptera, Currculionidae), it is a stem borer and has to kill the stems and has considerable status (Hill and Coetzee 2017:4).	Chemical control – Diquat, Terbutryn, and Gyyphosate (Cilliers *et al*., 2003:173).	KZN, EC, MP, WC, GP and L	Complete biological control usually between 1 – 1.5 years in subtropical areas and about 3 years in cooler areas (Cilliers *et al,* 2003:173). A number of sites are substantially controlled (Martin *et al* 2018:76). It also may require subsequent releases in other areas (Coetzee *et al*, 2011: 452). The agent has been proven to not have a good dispersal ability (Martin *et al*., 2018:79)	There is by far no specific BCR in South Africa on Salvinia due to the difficulty to quantify many of the invaded sites (Martin *et al*., 2018:79). However, van Wilgen *et al* (2004:113) suggested that the results in South Africa are expected to be similar to those of Australia. Thus, the Australian BCR is 53:1 in Sri Lanka at a cost of A $16 million for a period of 25 years (Doelman 1989:13). There was also CBA study done in Tengwe in Zimbabwe that showed a BCR of Z$ 10.6:1 for a period of 4 years (Chikwenhere and Kenswani, 1987:111-112). These can be used as relative comparisons for South Africa.
Myriophyllum aquaticum (Parrot's feather) has a CARA 2002 – Category 1 NEMBA – Category 1b; it was initially posed a greater threat in the 1960s and was considered to be more important that water hyacinth (Cilliers *et al*., 2003:170).	Biological control – *Lysathia sp. (Coloptera: Chrysomelidae)*, it is a leaf feeder and has an extensive status (Hill and Coetzee 2017:4).	Chemical control – no herbicides have been registered in the country but glyphosate- based herbicide had been used experimentally (Cilliers *et al*., 2003:170).	KZN, EC, MP, WC, GP and L	Complete biological control usually takes up to 3 years (Cilliers *et al*., 2003:171). It may however also require augmented releases (Coetzee *et al*., 2011: 457).	N/A

Azolla filiculoides (Red water fern) has a CARA 2002 – Category 1 NEMBA – Category 1b; it was initially confined to small streams and farm dams for years (Cilliers *et a*l., 2003:466).	Biological control – *Stenopelmus rufinasusit* is a frond feeder and has an extensive status (Hill and Coetzee 2017:4)	Chemical control – Glyphosate, Paraquat and diquant herbicide (Cilliers *et al*., 2003:167).	EC, MP, WC, GP, L, NC, NW and FS.	Complete biological control usually takes between 10 months and a year (Cilliers *et al*., 2003:168). Subsequent release is hardly required (Cilliers *et al*., 2003:168), this is because the agent is effective in that it has strong dispersal ability, making the weeds to have the most success weed control in the aquatic system (Coetzee *et al*., 2011: 457).	The weed is said to have costed an estimated value of US 36 million (in 2000 dollars) / R400 million in control efforts, in South Africa in the last 20years. (Hill 2003: 20). In the year 2000 it has a BCR of 2.5:1, in 2005 an estimated 13:1 and 2010 an estimated 15:1. The respective NPV is said to be US $206 million after 1995, rising up to about US $2.9 billion after taking into account the sensitivity test. (McConachie *et al*., 2003:29-30). Cilliers *et al*., (2003:168) suggested an average BCR of 70:1 five years after the first release.

3.5 CONCLUSION

Comparing the results found by Doeleman (1989) and Chikwenhere and Keswani (1997) on S. molesta, to those found by McConnachie *et al*. (2003) on A. filiculoides as well as by van Wyk and van Wilgen (2002) and Fraser *et al*., (2016) on E. crassipes; it is reasonable to conclude that biological control is indeed cost-effective, economically beneficial and a sustainable management programme on these weeds. As much as there are issues within conventional CBA that can limit the usefulness of the framework as a tool for evaluation is it however the most ideal approach. In most cases, the issue of understated benefits is a common limitation as well as giving monetary values to environmental impacts, costs and or benefits.

The information acquired in this chapter is detrimental to the rest of this study in that it will help align the methods, results, analysis and conclusion properly. This chapter will be a gate to how appropriate assumptions have been made in evaluation, estimation and interpretation. For example the characteristics and behaviour of the weeds outlined in section 3.2 and 3.3 will be beneficial when making assumptions on the invasiveness of the weeds in order to assign conversion factors and estimate the potential herbicide cost of the four weeds as well as the possible cost-saving associated with the biological control of each weed. Section 3.4 will also be beneficial to our results and conclusion chapters as it will provide literature to which the results and conclusion of this study will be benchmarked against. This is to show that both the results found and conclusion made in this study are not outside the historical findings that already exist in literature.

CHAPTER FOUR: MATERIAL AND METHODS

4.1 INTRODUCTION

This chapter describes the methodological approach used in this study. The chapter provides a brief narrative of the problem, explains how the study answered its main research question and explores the main and secondary aims of the study. The data collection, data sources and data limitation, assumptions and adaptations are outlined. In view of the research design this chapter discusses the respective methodological and analytical procedures followed to quantify the costs of differing control options for aquatic weeds. Ethical requirements involved in the study are also disclosed.

4.2 AIMS OF STUDY

With the context of research explored in the previous chapters, there are four main factors that emphasize the need for such a study in South Africa especially at a national scale. Most of the economic analysis in literature focus on terrestrial IAPs rather than on aquatic IAPs. The studies on aquatic weeds have focused on quantifying either the water loss saving and or avoided costs of impact or control (when conducting a Cost Benefit Analysis (CBA)) due to the difficulty to quantify the respective non-monetary benefits of clearing aquatic weeds. Most of the economic evaluation work done on the big bad five aquatic weeds have been on water hyacinth than on the four aquatic weeds selected in this study. The main gap that this study addressed is that of the lack of retrospective economic return analysis on the biological control of the four weeds. This is because, since the weeds are under complete biological control, no such economic study has been done apart from McConnachie *et al*. (2003) study on *A. filiculoides*.

Such a retrospective study is important for economic return evaluation purposes and to it an investigation of the cost-saving that biological control has provided relative to the alternative control method (chemical control) should be added. This is imperative as it will help reveal the relative cost-effectiveness of this programme especially considering the legislative need for the Working for Water (WfW) programme to invest in cost-effective approaches to ensure that every

Rand spent on investment produces the best possible returns (Kraaij *et al.*, 2017). To do this, a full CBA is the best and most comprehensive approach.

4.3 STUDY DESIGN

This study engaged the positivist research paradigm approach, with a qualitative, objective and review nature (Guba and Lincoln, 1994). It tracked the following stages in its approach: data collection and representation using tables and graphs, study limitations, adaptations and assumptions, as well as the analytical procedure for estimating the monetary values integrated within this research.

4.4 DATA COLLECTION AND SOURCES

4.4.1 Primary data

The study will have no primary data as it uses already existing data sources.

4.4.2 Secondary data

There are three main data sources for this study, the Department of Environment, Fishery and Forestry (DEFF): Natural Resource Management (NRM) programme (WfW), Rhodes University Centre of Biological Control (CBC) as well as the Southern African Plant Invaders Atlas (SAPIA). The type of data used was the historical cost of clearing the big bad five aquatic weeds in South Africa and the historical number of hectares cleared with that cost (as incurred and documented by those key data sources). The data used in this study was obtained between 2018 and 2019 and were presented as per annum figures over the life of each project and expressed as cost per hectare where possible. Careful attention was given to the data for inconsistencies; as such corrections were done and disclosed where necessary.

In terms of the type of data included in the total cost of each control method; Table 4.1 below shows the type of costs incorporated for biological control and chemical control. For chemical control, the respective cost categories were included and varied according to the type of spray approach used. For example, they varied with regards to the type of data obtained for the DEFF: NRM programme on the spray by boat, bakkie (a light truck), knapsack and aerial. The biological control data was obtained from CBC and chemical control data was obtained from the DEFF: NRM programme. No ethical clearance was needed to obtain this data (confirmed by Rhodes University Ethics Committee).

Table 4.1 Types of costs included in each control method and spray approach

Control approach	**Costs included**
Biological control	Exploration costs, quarantine costs, establishment trails, post release evaluation costs and implementation costs
Boat	Herbicide cost per ha and cost of person day per ha
Bakkie	Herbicide cost per ha and cost of person day per ha
Knapsack	Herbicide cost per ha and cost of person day per ha
Aerial	Herbicide cost per hectare, helicopter cost per ha, accommodation and meals per ha, and, support veh/equipment per ha.

4.4.3 Sample and presentation

Economic evaluation studies have tended to evaluate the WfW programme considering site specific evaluation as proxy for the economic position of the whole programme (SANBI National Status Report, 2017). This may be due to the nation-wide evaluation difficulty caused by the prevailing gaps in adequate documentation. This study, however, attempted to look at the overall costs of all relevant sites covered by and documented in the SAPIA database as at July 2019. The SAPIA database "catalogues localities, abundance and habitats of alien plant species growing outside cultivation" (Invasive Species South Africa, 2019). This database reflected the nation-wide site-specific information for each of the four weeds and has been used (in this study) to estimate the total hectarage cleared for the periods disclosed.

4.4.4 Analytical procedure

The main analytical procedure presented in this section will be that of the CBA framework, particularly the technique of the environmental CBA. Environmental CBA mainly considers policies and or projects that aim to improve environmental services, actions or factors that produce any form of direct and indirect ecological, economic and social consequences (Atkinson and Mourato, 2008). The main objective of this technique is to estimate monetary values of those ecological changes that result from the project under evaluation, especially as it relates to non-market or non-monetary values. It also has the benefit of discounting which is a principle of assigning lower weights to a specific unit of future costs and benefits relative to present ones. This discounting principle incorporates both time considerations and a discount rate (Hosking and du Preez, 2004). The time consideration factor seeks to accommodate inflation and pure change in prices. CBA techniques have an added benefit in that they can help make direct implications on economic efficiency and is best useful for public sector project evaluation (Atkinson and Mourato, 2008). Moreover, the framework is a useful way to evaluate a particular decision based on the consequences it has (Dreze and Stern, 1987). It can also employ a sensitivity analysis to evaluate the degree of sensitivity of the data and assumptions used in the main method application of the study.

4.4.5 Limitations, assumptions and adaptations

The main limitation faced in conducting this study relates to poor documentation, which affected data collection, availability, accuracy and reliability. Although our respective data sources are reliable and well recognised, some assumptions, exclusions and adaptations needed to be done (especially as it related to data on the number of hectares cleared as well as on the cost of clearing using herbicide control method). Actual historical annual costs of clearing using biological control could not be accessed, as such, the most recent (available) costs were used as proxy for previous years.

For cost of clearing using herbicides, the main limitation was that there was no historical herbicide control data on the four selected aquatic weeds due to the use of biological control since as early as 1985. As such, *E. crassipes* (water hyacinth) herbicide clearing costs were used, following an assumption that this weed was the most suitable surrogate for the four selected aquatic weeds in South Africa. To these surrogate costs, conversion factors were employed to take into account the biological realities and differences between the five weeds. Although obtained through expert opinion, these conservation factors took into account the invasiveness of each weed such as weed competitiveness, growth rate and reproductive capacity.

With regards to the number of hectares cleared, the SAPIA database as at July 2019 was the primary reference for compiling data on the historical number of hectares cleared. The database has a record of all the sites where the four weeds have been identified. However, a limitation was encountered when using this database, which included only coordinates of the sites and not the actual number of hectares cleared. As such, a manual calculation of the area of these sites was done and will be explained in more detail in the next section.

For our ideal framework, although it will remain the main framework used, it will not follow the traditional approach of conducting the benefit cost ratios (BCRs) based on the costs and benefits of clearing the weeds using the two control methods as would be preferred. This is mainly because it is difficult to quantify or give a monetary value to the benefits of clearing these weeds – especially at a national-scale. As a result, the avoided costs of herbicide clearing were used as the main benefit when conducting the BCR of using biological control instead of chemical control.

Due to these core limitations, assumptions and adaptations, the data used in this study is therefore sensitive. Compelling the need for a sensitivity analysis to see the degree of sensitivity of the data and to check if the results of the study would maintain robustness with the variation of some key assumptions.

4.5 QUANTIFYING RESPECTIVE VALUES AND ESTIMATES: SCENARIO ONE

4.5.1 Estimated number of hectares cleared

For the number of hectares cleared, the coordinates on the SAPIA datasheet were used to calculate the total area of a site using Google Earth and Google Maps ruler option. The calculated area was then adjusted based on expert opinion to a reasonable estimate of the area of infestation because a 100% infestation for some of the larger sites would have resulted in possible overestimation. Efforts were made to clean the data as some sites were more complex to calculate and estimate – they would have led to more misleading results. Table 4.2 below outlines some of the exclusions and assumptions made in this regard.

Table 4.2 Site data exclusion category and assumptions

Exclusion category	Assumptions
Sites with no coordinates (where coordinates were zero or not given). Sites that were complex water bodies (rivers). Sites that were not observable (where there were no water bodies around the point, or the water body had dried up and the boarders of that body were not visible; those that were visible were included). Sites that were outside South Africa (such as those in Namibia) and 2019 sites were excluded.	Multiple entries of the same site were considered to be either secondary invasion or subsequent release of the biological agent. If there were more than one water bodies around a point (given by the coordinates), the site nearest to the pointed was included. All historical sites from the earliest record were included (unless they fell under the exclusion categories).

4.5.2 Estimated cost of clearing: Biological control

The cost of clearing using biological control was the sum of the cost-types explained in Table 4.1. These cost types were incurred during the specific periods taken into consideration. For each year, only the types of costs incurred in that year were summed up to get the total costs incurred in that year. For example, *S. molesta* costs for the years 2000 would be R237,000.00 which is a sum of R40,000.00 + R100,000.00 + R15,000.00 + R40,000.00 + R20,000.00 + R22,000.00. This total cost per year was then discounted respectively with an appropriate discount factor. The primary costs obtained from CBC are shown in Table 4.3 below.

Table 4.3 Cost of Clearing using biological control

Biological Control Costs per year	***P. stratiotes***		***S. molesta***		***A. filiculoides***		***M. aquaticum***	
	Cost	Period	Cost	Period	Cost	Period	Cost	Period
1. Exploration costs								
a. Overseas contracts	0		0		0	0	0	0
b. Scientist years for exploration	0		0		0	0	0	2 weeks (1991)
c. Technician years for exploration	0		0		150000	Half a day (4 hours) 1995	0	0
d. Overheads	0		0		0	0	0	0
e. Running costs	0		0		0	0	0	2 weeks (1991)
2. Quarantine cost								
a. Scientist years for host specificity	250000	1985	0		200000	1996, 1997	80000	1991, 1992,1993,1994
b. Technician years for host specificity	150000	1985	0		40000	1996, 1997	80000	1991, 1992,1993,1994
c. Glasshouse space	50000	1985	0		14976	1995;1996;1997	7200	1991, 1992,1993,1994
d. Normal running costs	20000	1985	0		17656	1996, 1997	8000	1991, 1992,1993,1994
3. Establishment trials								
a. Scientist years for rearing	40000	1985-1990	40000	1985 - 2002	40000	1997	80000	1994, 1995
b. Technician years for rearing	100000	1985-1991	100000	1985 - 2002	20000	1997	40000	1994, 1995, 1996
c. Running costs	15000	1985-1991	15000	1985 - 2002	8500	1997	7500	1994, 1995, 1996
d. Overheads					12250	1997		
4. Post release monitoring cost								
a. Scientist years for sampling and analysis	40000	1986-1990; 2006-2012	40000	1990 - 2018	50000	1998-2018	40000	1995-2008

b. Technician years for sampling and analysis	20000	1986-1990; 2006-2018	20000	1990-2018	20000	1998-2018	20000	1995-2008
c. Running costs	22000	1986-1990; 2006-2018	22000	1990-2018	3750	1998-2018	10000	1995-2008
d. Overheads								
e. Sub-contracts								
5. Implementation costs								
a. Scientist oversight of mass-rearing	40000	2006-2018	40000	2006-2018	40000	1997	40000	2010-2018
b. Technician years of mass-rearing and releasing	120000	2006-2018	120000	2006-2018	120000	1997	120000	2010-2018
c. Tunnel space	440	2006-2018	440	2006-2018	2200	1997	440	2010-2018
d. Running costs	20000	2006-2018	20000	2006-2018	20000	1997	20000	2010-2018

Raw costs data obtained from Rhodes University Centre for Biological Control (CBC)

For discounting, because these costs were obtained in 2018 Rands, discounting was necessary to make the value of money relatable over the period of years under review. However, due to the different time periods involved between the cost recording of the four weeds, different time periods were applied for appropriate discounting. For example, costs associated with *P. stratoites* and *S. molesta* were discounted from the year 1985 while *A. filiculoides* was discounted from 1995 and *M. aquaticum* from 1991. These start-up years were based on when the biological control agent of each weed was realised in South Africa. Table 4.4 below shows the periods used for each weed.

Table 4.4 Discounting periods used for each weed

Weeds	Starting Period	Discounting period
P. stratiotes	1985	33 years
S. molesta	1985	33 years
A. filiculoides	1995	23 years
M. aquaticum	1991	27 years

The discounting process was done using the formula below to calculate the Present Value (PV) which is in this case a cost.

Equation 1 $$PV = {}^{IV}/_{(1+r)}{}^{n}$$

Where,

PV = present value (cost)

IV = initial value (cost)

R = the discount rate

N = number of years covered in the period

At the start of the period, n was set as n=x and would decrease leading to a positive n=0. This is shown on the timeline below

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PV= FV/(1+r) ^ x PV= FV/(1+r) ^ 0

4.5.3 Estimated cost of clearing: Chemical control scenario one

Chemical control costs of clearing *E. crassipes* (water hyacinth) were used as there were good datasets for these. However, *E. crassipes* being a larger statured weed and far more aggressive, would have required more herbicide application than the other four weeds that are smaller in stature. For example, *P. stratiotes* plants can grow up to 1kg in biomass, in comparison to 1.5 kg to 2.5 kg for *E. crassipes* (Nueunschwander *et al*., 2009), thus it would require only about 80% as much application in comparison to *E. crassipes. A. filiculoides* (McConnachie *et al*., 2004) and *S. molesta* (Julien *et al*., 2009) are relatively small plants ranging from 0.05kg to 0.5kg and would require only about half the herbicide application of *E. crassipes*. *M. aquaticum* is attached to the substrate of the water body and this requires the herbicide to translocate down the plant (Cilliers 1999); although the emergent parts are far smaller in surface area than *E. crassipes*, it requires more herbicide than either *A. filiculoides* or *S. molesta*. These (*E. crassipes)* costs were thus adjusted for – using conversion factors to make them reasonable per ha cost estimates of the four selected aquatic weeds under study. The respective conversion factors applied were as presented in Table 4.5 below. Table 4.6 shows the cost of clearing *E. crassipes* using herbicides obtained from the DEFF: NRM.

Table 4.5 Conversion factors in terms of the surrogate weed water hyacinth

WEED	CONVERSION FACTOR
E. crassipes	100%
P. stratiotes	80%
S. molesta	50%
A. filiculoides	50%
M. aquaticum	70%

Table 4.6 Water hyacinth clearing costs and conversion factors

Spray approach	Costs of clearing water hyacinth					
	Herbicide cost per ha	Person days costs per ha	Helicopter cost per ha	Accommodation and meals per ha	Support vehicle equipment per ha	Total cost per ha
Boat	482.88	1244				1726.88
Bakkie	482.88	2615.51				3098.39
Knapsack	482.88	10104.39				10587.27
Aerial	373.75		1621.5	86.25	164.02	2245.52

These costs were presented under four possible spray approaches, spray by boat, bakkie, knapsack and aerial. However, aerial spray was excluded because none of the sites included in this study were big enough to could have required the use of aerial spray (all the helicopter surveys were excluded). Table 4.7 below shows a summary of converted costs of each weed by various spray approaches. These cost estimates were derived per equation 2 below:

Equation 2: Estimated cost per ha per month (pm) = water hyacinth clearing cost per ha pm * conversion factor

Table 4.7 Converted cost estimates of clearing (per hectare) the four selected weeds in 2018 Rands

WEED	CONVERSION FACTOR	SPRAY METHOD			
		BOAT	BAKKIE	KNAPSACK	AERIAL
E. crassipes	**100%**	**1726.88**	**3098.39**	**10587.27**	**2245.52**
P. stratiotes	80%	1381.50	2478.71	8469.82	1796.42
S. molesta	50%	863.44	1549.20	5293.64	1122.76
A. filiculoides	50%	863.44	1549.20	5293.64	1122.76
M. aquaticum	70%	1208.82	2168.87	7411.09	1571.86

These costs were assumed to be given as monthly figures because they were an average of the latest 12-month period. As such, each monthly figure was multiplied by 12 months to get the full annual cost per hectare (Equation 3). The total annual costs of clearing for each year was then derived using (Equation 4) below; within which, the total annual number of hectares cleared in each year was calculated using Equation 5 below. These annual estimated costs of clearing using herbicide control (derived using equation 4) were then discounted and the present value (cost) was calculated using the present value (cost) formula expressed in the previous biocontrol section.

Equation 3: annual cost per ha = cost per ha per month *12 months

Equation 4: total annual cost of clearing = annual cost per ha * annual number of ha cleared

Equation 5: annual number of ha cleared = sum of all number of ha (sites) cleared in a year

For the annual number of ha cleared (equation 5 above), certain assumptions were made with regards to the historical account of the annual and accumulated number of hectares cleared. The number of hectares recorded before the start of the discounting period of each weed were accumulated and the sum was considered to be the total cost number of hectares at the start of the period. Moreover, because it is often unlikely that the initial weed cover would remain the same after herbicides spray application, it was further assumed that the degree of infestation (weed cover) of each weed would go down to zero by the end of each year as a result of spray effort. However, due to the regrowth capacity of each weed, it was further assumed that the cleared catchments would most likely suffer a weed regrowth in the following subsequent years. Thus, regrowth (recovery) estimates were made for each weed and set at 100%, 50%, 50% and 30% for *P. stratiotes, S. molesta, A. filiculoides and M. aquaticum* respectively (Hill and Coetzee 2017). These estimated growth rates were based on the potential growth rate, seed germination and reproductive reality as well as herbicide uptake of each weed. As such, part of the initial cover would be carried over to the following year and the subsequent cover (hectarage) would be an accumulated value. For example:

Year 1: y1 = 100%

Year 2: y2 = (y1*100%) + y2 *P. stratiotes*

Y2 = (y1+50%) + y2 *S. molesta*

Y2 = (y1+50%) + y2 *A. filiculoides*

Y2 = (y1+30%) + y2 *M. aquaticum*

Although the study persisted to use this data; the gaps, limitations, exclusions and assumptions presented significantly concerning implications. The first and principal implication is on the accuracy and reliability of the hectarage included in the study - both of which are compromised. The second is that the estimates and results of the study are highly sensitive to the method employed and as such the results may be taken as the best possible results under the current documentation.

4.5.4 Estimated cost of clearing: Chemical control scenario two

Because scenario one excluded the possibility of a follow-up incentive, the second scenario of the study took into account such possibility. This scenario was grounded by the fundamental assumptions made in the first scenario of the study; however, it included the distinct incorporation of the probability of a follow-up clearing requirement. This incorporation was driven by an assumption that: all four weeds will require an initial clearing and a subsequent follow-up clearing

– due to the common responses of aquatic weeds to herbicide application (expressed in literature) as well as the perceived effectiveness and thus success of herbicide application on aquatic weeds (also expressed in literature). Upon interrogating the question of the effectiveness and success of the initial clearing, possible changes on the plant cover (number of hectares) needed to be addressed considering the subsequent follow-up incentive was consideration.

To this, an assumption was made that the initial clearing would be about 90% successful on all weeds and a follow-up clearing would be done later on the remaining 10%. In our method application, to quantify the initial clearing cost - cost per ha of each weed was applied on 100% cover of the weed (see equation 6 below). This is because, the initial clearing would ideally be done on the total cover although producing a 90% success rate. To quantify the follow-up clearing cost, 10% of the initial cover was calculated to which a cost per ha was applied (see equation 7). To this, the PV representing the present cost was calculated and an 8% discount rate for the period variations expressed in scenario one.

Equation 6: initial clearing cost = (initial plant cover *100%) * cost per ha

Equation 7: follow-up clearing cost = (initial plant cover * 10%) * cost per ha

Equation 8: discounting using formula

$$PV = {}^{IV}/_{(1+r)}{}^{n}$$

4.5.5 Cost benefit analysis

With an 8% discount rate employed throughout, the total cost of clearing for both control methods was calculated as the sum of all discounted values represented as the Net Present Cost (NPC) of each control method on each of the four weeds. These values were used to calculate the prevailing cost-saving of using biological control instead of chemical control- see Equation 9 below. These cost-savings were calculated for each weed as well as for the overall programme on the four aquatic weeds – for each chemical control approach. Due to the difficulty of quantifying the monetary value of benefits associated with clearing aquatic weeds, the avoided cost concept was used and presented as the prevailing cost-saving of using one method (biological control) instead of the other (herbicide control). The decision to do so in terms of biological control was motivated by the complete biological control status of the four weeds in South Africa.

Equation 9: cost-saving = NPC of clearing using herbicides – NPC of clearing using biological control

= Avoided cost

An avoided cost is the excess amount that would have been spent had the alternative control method (herbicides) been applied. The excess being the amount avoided by using the chosen method (biocontrol). This avoided cost was then used as the main benefit flowing from the successful use of biological control on these weeds and injected into the formula below (equation 10) to calculate the benefit-cost ratio (BCR).

Equation 10: BCR = benefits/cost

= cost-saving/cost

= avoided cost/cost

4.6 SENSITIVITY ANALYSIS

To cater for the sensitivity of the data used in the study, the study was only able to vary the discount rate to see if the results of this study maintains robustness. This (discount rate) variable holds the highest power on the results of this study. As such, this rate was varied from an 8% discount rate to a lower limit of 5% and upper limit of 10% for both scenario one and two. Although other variables would have been interesting to vary, they ground the main assumptions of the study and to avoid complications were not varied in this case.

4.7 CONCLUSION

In Conclusion, due to prevailing limitations, *E. crassipes* herbicide clearing costs were used for surrogacy to aid assumptions on the costs of clearing the four selected aquatic weeds using herbicides. The avoided cost of using biological control instead of chemical control were used as the main benefits in the benefit-cost analysis; this avoided cost was the prevailing herbicide cost-saving. To quantify the respective benefit cost ratios, an 8% discount rate was employed and was varied to 5% and 10% to under a sensitivity test. Two scenarios were incorporated in this analysis; one focused on purely the initial clearing of both control methods while the second included one follow-up clearing. The results presented in the next chapter (Chapter 5) are based on the assumptions employed in this study and may differ upon changes in the assumptions thereof. They should be considered carefully and within context.

CHAPTER FIVE: RESULTS

Following the methods explained in the previous chapter, this chapter presents the results of the data analysis. Considering all the data, limitations, assumptions, adaptations and estimates, this chapter indicates the quantitative results of this study considering its goals and objectives. These include a primary presentation of the estimated number of hectares cleared for each weed, the estimated costs of clearing using biological and chemical control methods. For each scenario, the chapter outlines the Net Present Costs (NPC) of each control method, the prevailing cost-saving and thus avoided cost of using biological control instead of chemical control. Additionally, the chapter presents the benefit-cost ratios (BCR) of using biological control instead of chemical control. As well as the sensitivity test results with a variation in the discount rate for both scenarios.

5.1 SCENARIO ONE

5.1.1 Primary estimate of the study

Table 5.1 below shows the estimated total number of hectares incorporated within the study for the four selected weeds. These estimates are a sum of all sites throughout the years recorded as per the limitations, exclusion, assumptions and adaptations made in Chapter 4 section 4.4.5. They are the initial estimates and not the accumulated number of hectares derived for the chemical control regrowth assumption when calculating the estimated chemical control cost (see chapter 4 section 4.4.3). Of the four selected aquatic weeds, the weed with the least number of hectares included was *P. stratiotes*, this was followed in ascending order by *S. molesta, A. filiculoides* and *M. aquaticum*. There could have been possible underestimation of the number of hectares due to some data cleaning as explained in section 4.5.1 of chapter 4.

Table 5.1 Estimated number of hectares historically cleared for each weed

Weed	Sum of all estimated number of hectares cleared
P. stratiotes	347.74
S. molesta	456.10
A. filiculoides	3975.23
M. aquaticum	8248.25

The estimated cost of control considered all the limitations, assumptions and method application expressed in the previous chapter. Appendix 1 shows the estimated annual cost of the biological control while Appendix 2 shows the estimated annual net present cost of the biological control method.

5.1.2 Estimated Net Present Cost (NPC)

From the table and figure below, three main findings can be observed. These observations are based on a ranking from the least-costly individual project and overall programme to the most-costly project and overall programme using the relative NPC values.

- On the overall sum of all four weeds, the biological control management programme is the least-costly management programme relative to each of the three chemical control approaches. See Table 5.2 and Figure 5.1 below.
- On the individual weed project basis, under the biological control management programme, the least-costly weed project was on *A. filiculoides, M. aquaticum, P. stratiotes* and *S. molesta* at a cost of R957,140, R1,662,796, R2,237,379 and R2,985,891 respectively. This resulting in a total biological control programme cost of about R7,843,205 million on all the four selected weeds. See Table 5.2 below.
- Under the chemical control method however, *S. molesta* would have been the cheapest project (the least-costly) followed by *A. filiculoides, P. stratiotes* and *M. aquaticum* respectively for all three spray approaches. Overall, the total programme cost of all the four weeds was an estimate of about R149,580,142, R268,264,839 and R881,711,739 for all three approaches boat, bakkie and knapsack respectively. See also Table 5.2 below.

Table 5.2 Total NPC of biological control and chemical control

Weed	**Net Present Cost**			
	Biological Control	**Chemical control**		
		Boat	**Bakkie**	**Knapsack**
P. stratiotes	R2,237,379	R45,397,340	R81,452,462	R242,981,469
S. molesta	R2,985,891	R8,605,893	R15,440,740	R52,761,461
A. filiculoides	R957,140	R30,649,371	R54,877,824	R187,906,766
M. aquaticum	R1,662,796	R64,927,538	R116,493,813	R398,062,042
Total	R7,843,205	R149,580,142	R268,264,839	R881,711,739

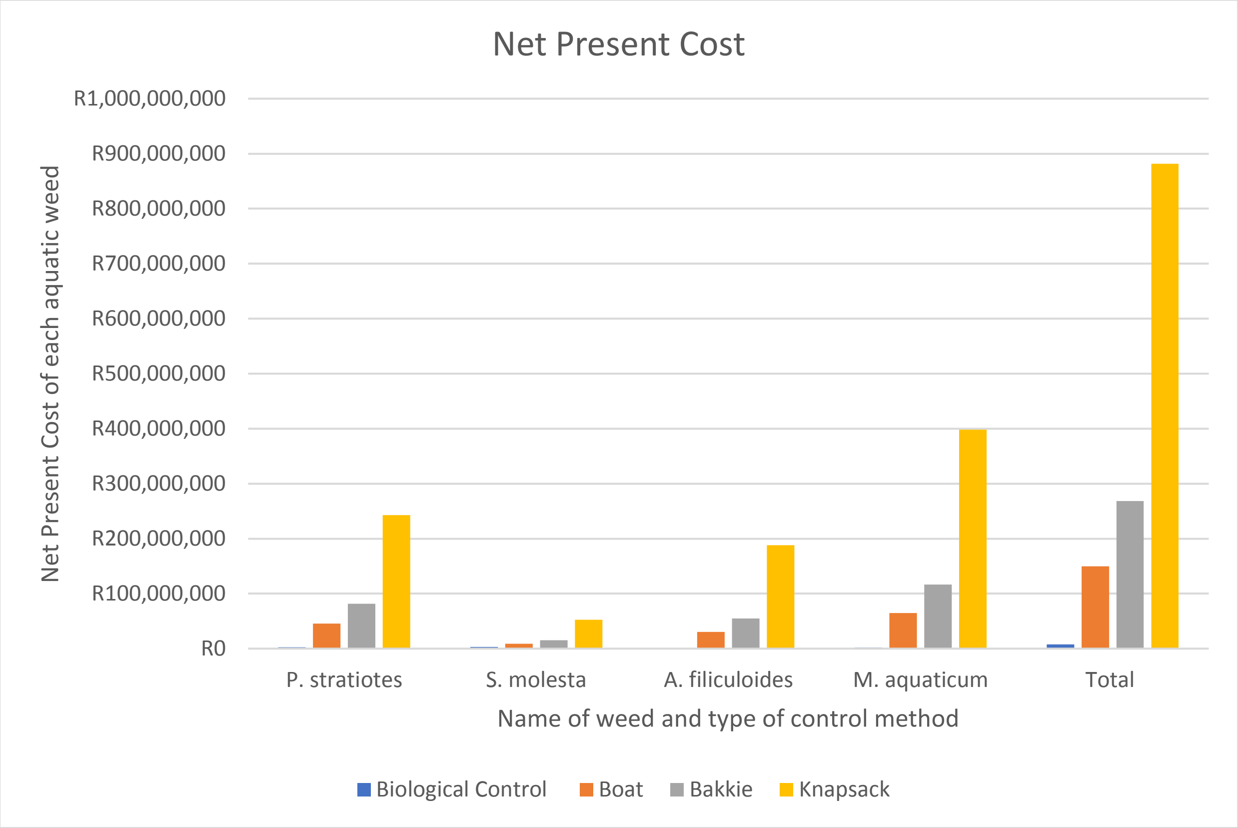

Figure 5.1: Discounted cost (NPC) of biological and chemical control methods on the four selected aquatic weeds.

5.1.3 Cost-saving (Avoided cost)

Using the relative cost-saving results to deduce on the relative cost-effectiveness of each individual project and overall programme, the following observations were made:

- The overall biological control management programme indicate positive total cost-savings in relation to all three chemical control spray approaches. With the lowest total cost saving of about R141,736,937 using the boat approach was followed by a cost-saving of about R260,421,633 for the bakkie approach and the highest cost-saving of about R873,868,533 using the knapsack approach. See Table 5.3 below.
- On an individual weed project basis, biological control management programme indicate positive relative cost-savings for all four weeds. *S. molesta* producing the lowest (but positive) cost-saving, followed by *A. filiculoides, P. stratiotes and M. aquaticum* producing the highest relative cost-saving. This cost-saving order was the same under all three possible spray approaches. See also Figure 5.2 below.

Table 5.3 Estimated cost-saving and avoided cost of using biological control

Weed	**Cost-Saving**		
	Chemical control		
	Boat	**Bakkie**	**Knapsack**
P. stratiotes	R43,159,961	R79,215,083	R240,744,091
S. molesta	R5,620,002	R12,454,849	R49,775,570
A. filiculoides	R29,692,231	R53,920,684	R186,949,626
M. aquaticum	R63,264,742	R114,831,017	R396,399,246
Total	R141,736,937	R260,421,633	R873,868,533

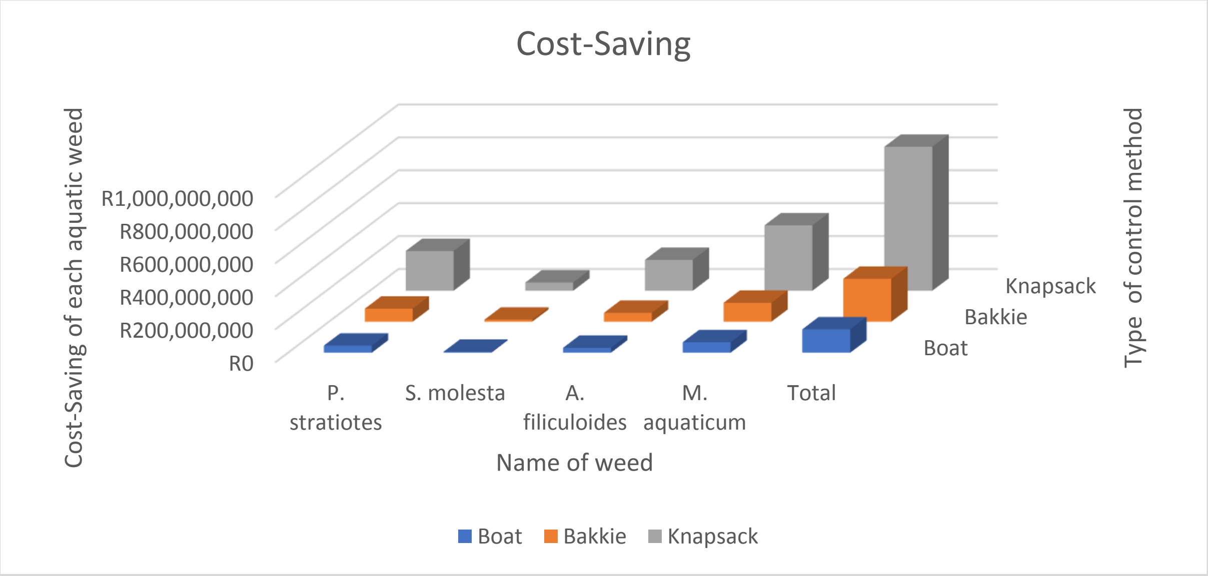

Figure 5.2 Estimated cost-saving that flow of the use of biological control instead of chemical control.

5.1.4 Benefit Cost Rations (BCRs)

Following the results interpreted above, benefit cost ratios (BCRs) were calculated and used to observe the relative return on investment on each weed project as well as the overall control management programmes. The following observations were made:

- The overall biological control programme on the selected weeds produced positive BCRs of 90.24:1, 164.97:1 and 557.99:1 across the three chemical control approaches – boat, bakkie and knapsack respectively. This indicating that the overall biological control programme has a positive return on investment.
- On an individual weed project basis, the biological control management programme maintains positive relative BCRs for all four weeds. The lowest return yielding from the project on *S. molesta, P. stratiotes, A. filiculoides* and *M. aquaticum* respectively. This is the same across all three spray approaches.
- *S. molesta* has a BCR of between 1.88:1 and 16.67:1, while *P. stratiotes* has a BCR of between 190.29:1 and 107.60:1 and *A. filiculoides* of between 31.02:1 and 195.32:1, with the highest return ratio of between 38.05:1 and 238.39:1 for *M. aquaticum.* As shown in Table 5.4 and Figure 5.3 below.

Table 5.4 BCR of using biological control instead of chemical control

Weed	Benefit cost ratios		
	Chemical control		
	Boat	**Bakkie**	**Knapsack**
P. stratiotes	19.29	35.41	107.60
S. molesta	1.88	4.17	16.67
A. filiculoides	31.02	56.34	195.32
M. aquaticum	38.05	69.06	238.39
Total	90.24	164.97	557.99

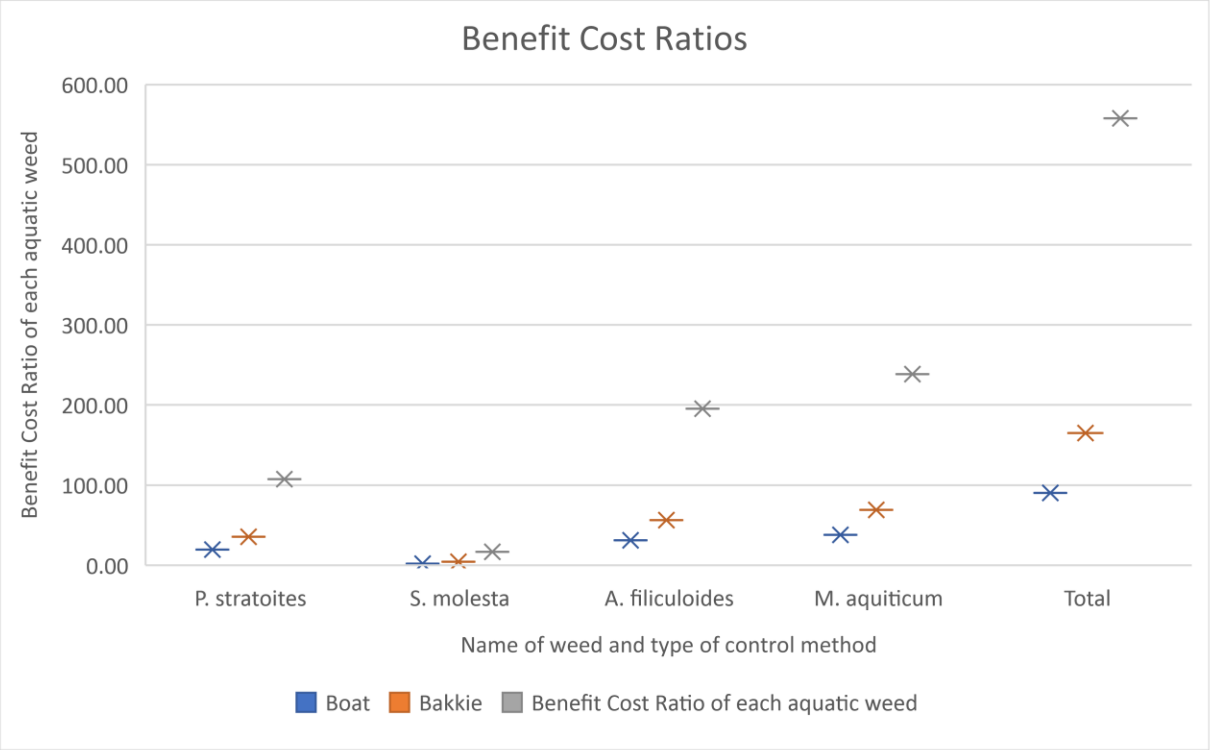

Figure 5.3 A distribution of the BCR of using biological control method on the four selected aquatic weeds using the three alternative chemical control spray options.

5.2 SCENARIO TWO

The results presented here are of the second scenario method application expressed in the previous chapter (chapter 4 section 4.5.4). The method held some common assumptions with scenario one but had additional assumptions that relate to the incorporation of a follow-up clearing requirement. As such, the results on the primary estimates of the study (Table 5.1 and Appendix

1) were maintained in Scenario two as they were presented in scenario one – unless were specified otherwise.

5.2.1 Estimated cost of clearing, cost-saving and BCRs

The key findings (results) under scenario two corresponded with those of scenario one. As with the findings in scenario one, the overall biological control management programme is the least-costly management programme with positive cost-savings and BCRs relative to the chemical control programme. The total programme cost (of all the four weeds) under biological control was an estimated R7,843,205 while the total chemical control programme costs were an estimated R164,538,052, R295,216,121 and R1,008,761,000 respectively for boat, bakkie and knapsack approach. See Figure 5.4 below.

In terms of individual weed projects, *A. filiculoides M. aquaticum, P. stratiotes and S. molesta* showed to be cheaper under biological control than under chemical control in that order from the least costly project to the most costly. However, as with scenario one, the cheapest project under chemical control was *S. molesta, A. filiculoides, P. stratiotes* and *M. aquaticum* respectively (see Table 5.5 and Figure 5.4). These costs resulted in positive cost-savings for *S. molesta, A. filiculoides, P. stratiotes* and *M. aquaticum* respectively; producing total cost-saving of about R156,694,847, R287,372,915 and R1,000,917,795 under the boat, bakkie and knapsack approach (see Table 5.6 and Figure 5.5). Like the results found in the first scenario, there are positive return on investment on all four weeds under biological control as well as on the overall programme. This is shown by positive BCRs of about 99.67:1, 182.00:1 and 631.56:1 for the boat, bakkie and knapsack approach respectively. In terms of return (BCRs), *S. molesta* has the lowest BCR followed by *P. stratiotes, A. filiculoides and M. aquaticum* (see Table 5.7 and Figure 5.6). The NPCs under scenario two are higher than those under scenario one for both control methods. And the prevailing cost-savings are also larger for scenario two than for scenario one. Resulting in larger returns on investment for scenario two than scenario one.

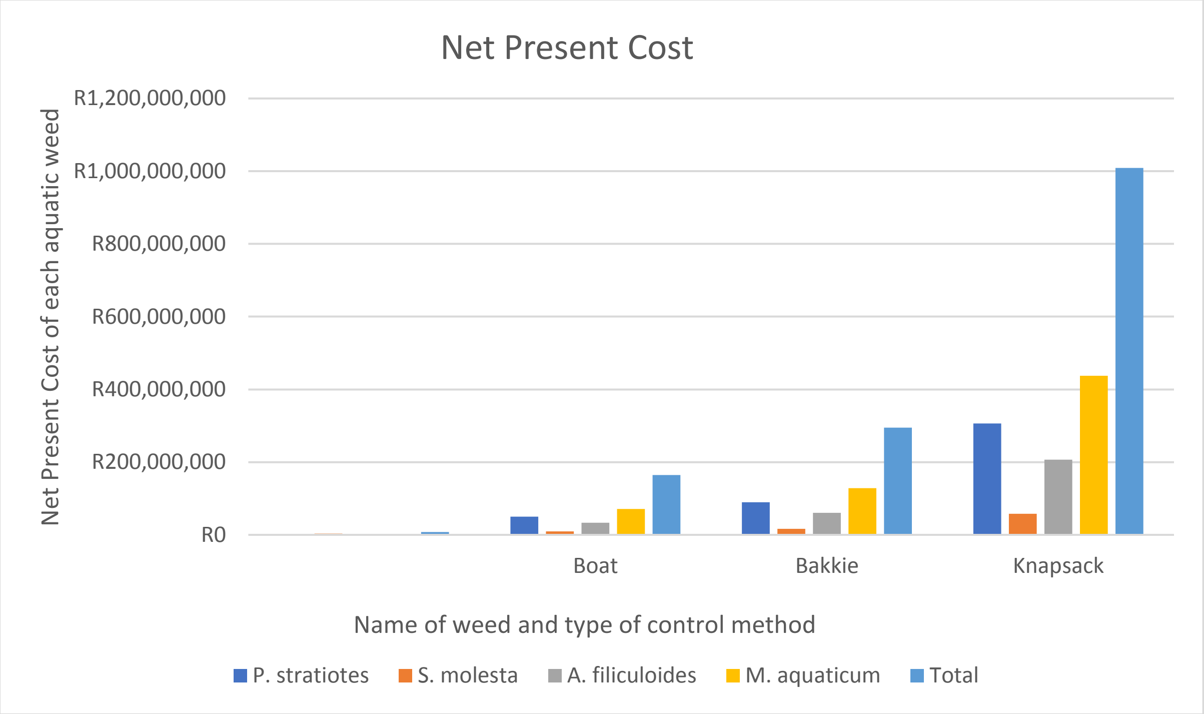

Figure 5.4 estimated cost of clearing including follow-up clearing costs.

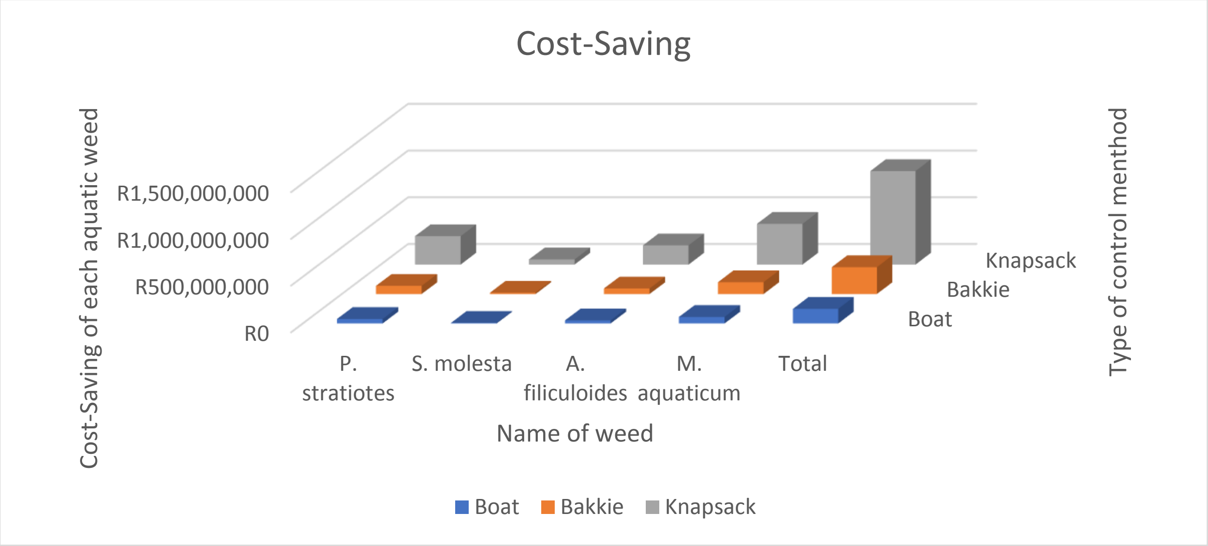

Figure 5.5 Estimated cost-saving that flow of the use of biological control instead of chemical control when including follow-up cost.

Table 5.5 Total NPC of biological and chemical control

Weeds	Biological Control	Chemical control								
		Initial Clearing Cost			Follow-up Clearing Cost			Total NPC		
		Boat	**Bakkie**	**Knapsack**	**Boat**	**Bakkie**	**Knapsack**	**Boat**	**Bakkie**	**Knapsack**
P. stratiotes	R2,237,379	R45,397,340	R81,452,462	R242,981,469	R4,539,720	R8,145,372	R49,937,060	R49,937,060	R89,597,834	R306,157,552
S. molesta	R2,985,891	R8,605,893	R15,440,740	R52,761,461	R860,588	R1,544,049	R5,276,179	R9,466,481	R16,984,789	R58,037,641
A. filiculoides	R957,140	R30,649,371	R54,877,824	R187,906,766	R3,064,848	R5,499,038	R18,790,795	R33,714,219	R60,490,303	R206,697,561
M. aquaticum	R1,662,796	R64,927,538	R116,493,813	R398,062,042	R6,492,754	R11,649,381	R39,806,204	R71,420,292	R128,143,194	R437,868,246
Total	R7,843,205	R149,580,142	R268,264,839	R881,711,739	R14,957,910	R26,837,840	R113,810,238	R164,538,052	R295,216,121	R1,008,761,000

Table 5.6 Estimated cost-saving and avoided cost of using biological control

Weed	Cost-saving		
	Chemical control		
	Boat	**Bakkie**	**Knapsack**
P. stratiotes	R47,699,681	R87,360,455	R303,920,174
S. molesta	R6,480,590	R13,998,898	R55,051,750
A. filiculoides	R32,757,079	R59,533,163	R205,740,421
M. aquaticum	R69,757,496	R126,480,398	R436,205,450
Total	R156,694,847	R287,372,915	R1,000,917,795

Table 5.7 BCR of using biological control instead of chemical control

Weed	Benefit cost ratios		
	Chemical control		
	Boat	**Bakkie**	**Knapsack**
P. stratiotes	21.32	39.05	135.84
S. molesta	2.17	4.69	18.44
A. filiculoides	34.22	62.20	214.95
M. aquaticum	41.95	76.06	262.33
Total	99.67	182.00	631.56

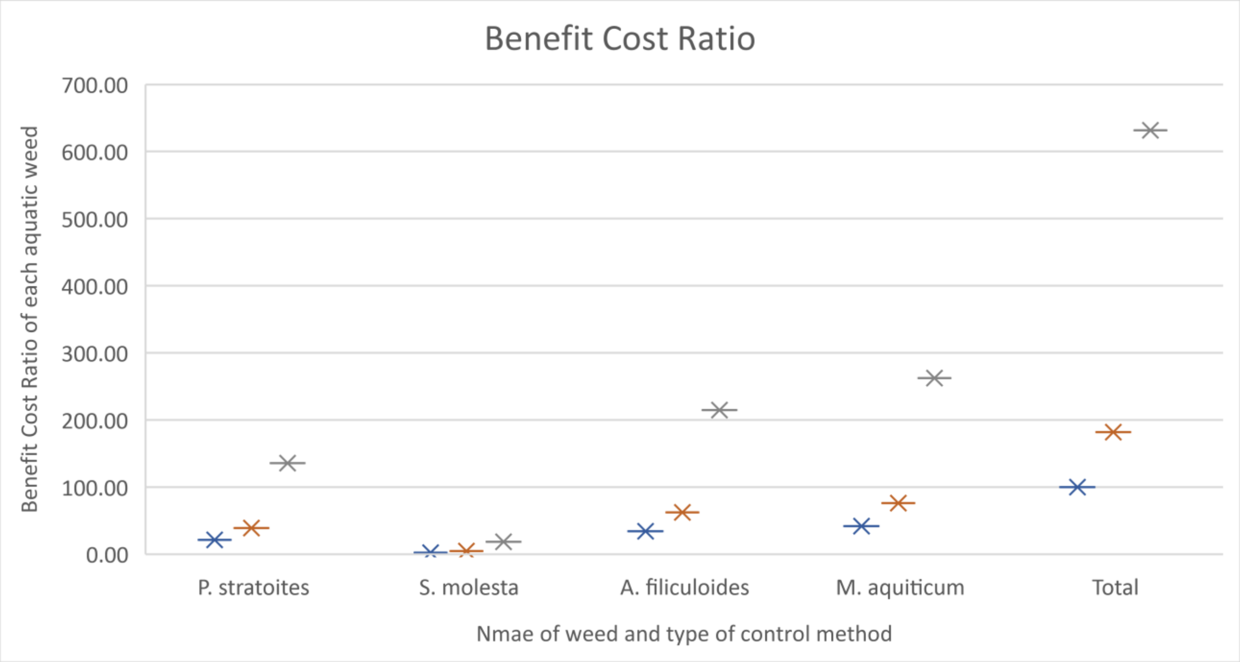

Figure 5.6 A distribution of the benefit cost ratios of using biological control method on the four selected aquatic weeds using the three alternative chemical control spray options including follow-up cost.

5.3 SENSITIVITY ANALYSIS

When varying the discount rate to 5% and 10% under both scenario one and scenario two, the results were as presented below. Only the discount factors were varied under this sensitivity test.

5.3.1 With a 5% discount rate

The NPC results under the 5% discount rate confirm that indeed the overall biological control programme is the least-costly relative to the three chemical control options. Like the main results, the individual NPCs reveal that all four weeds *A. filiculoides M. aquaticum, P. stratiotes* and *S. molesta* are the least-costly under biological control than with chemical control respectively; in that order from the least-costly to the most-costly. Although relatively higher under a lower discount rate, the overall estimated cost of the biological control method was about R10,258,585. Likewise, the individual weed project with the least cost was on *S. molesta* followed by *A. filiculoide*s, *P. stratiotes* and *M. aquaticum*. The overall estimated cost of the three spray approaches (boat, bakkie, knapsack) under chemical control were higher than those estimated under the main results (8% discount rate) with estimated costs of about R199,544,816, R357,911,976 and R1,188,038,253 for scenario one and of about R219,499,153, R393,827,951 and R1,345,720,235 for scenario 2. As expected, cost estimates under scenario two are higher than under scenario 1.

The estimated cost-saving and BCRs were also positive and relatively higher than those estimated under the main results. Here, the estimated cost-saving was about R189,286,231, R347,653,391 and R1,177,779,668 for the boat, bakkie and knapsack approach in scenario one while for scenario two the estimated cost-saving was about R209,240,567, R383,569,366 and R1,335,461,649 respectively. These results-maintained robustness with the main results where the lowest cost-saving was for the project on *S. molesta* followed by *A. filiculoides, P. stratiotes* and *M. aquaticum* producing the highest cost saving. The prevailing BCRs revealed similar weed results as previously where *S. molesta* has the lowest BCR followed by *P. stratiotes, A. filiculoides and M. aquaticum* under all three control methods. Producing overall positive BCRs of about 94.39:1, 172.45:1 and 586.89:1 under scenario one and of about 104.23:1, 190.19:1 and 659.56:1 under scenario two for the boat, bakkie and knapsack approach respectively. These results (figures) are higher than those estimated under the main results with an 8% discount rate.

Table 5.8 NPC of both biological and chemical control methods under a 5% discount rate analysis

Weed	**Net Present Cost**						
	Biological Control	**Chemical Control scenario 1**			**Chemical Control Scenario 2**		
		Boat	**Bakkie**	**Knapsack**	**Boat**	**Bakkie**	**Knapsack**
P. stratiotes	R2,862,599	R53,739,513	R96,420,091	R294,126,212	R59,113,448	R106,062,249	R362,416,780
S. molesta	R3,979,668	R10,560,262	R18,947,279	R64,743,406	R11,616,286	R20,841,976	R71,217,787
A. filiculoides	R1,290,408	R43,832,042	R78,530,244	R268,727,777	R48,215,120	R86,507,927	R295,600,724
M. aquaticum	R2,125,910	R91,413,000	R164,014,363	R560,440,858	R100,554,300	R180,415,800	R616,484,943
Total	R10,258,585	R199,544,816	R357,911,976	R1,188,038,253	R219,499,153	R393,827,951	R1,345,720,235

Table 5.9 Estimated cost-saving and avoided cost of using biological control under a 5% analysis

Weed	**Cost-Saving**					
	Scenario 1			**Scenario 2**		
	Boat	**Bakkie**	**Knapsack**	**Boat**	**Bakkie**	**Knapsack**
P. stratiotes	R50,876,913	R93,557,491	R291,263,613	R56,250,848	R103,199,650	R359,554,181
S. molesta	R6,580,593	R14,967,610	R60,763,738	R7,636,618	R16,862,307	R67,238,119
A. filiculoides	R42,541,635	R77,239,836	R267,437,369	R46,924,712	R85,217,519	R294,310,316
M. aquaticum	R89,287,089	R161,888,453	R558,314,947	R98,428,389	R178,289,890	R614,359,033
Total	R189,286,231	R347,653,391	R1,177,779,668	R209,240,567	R383,569,366	R1,335,461,649

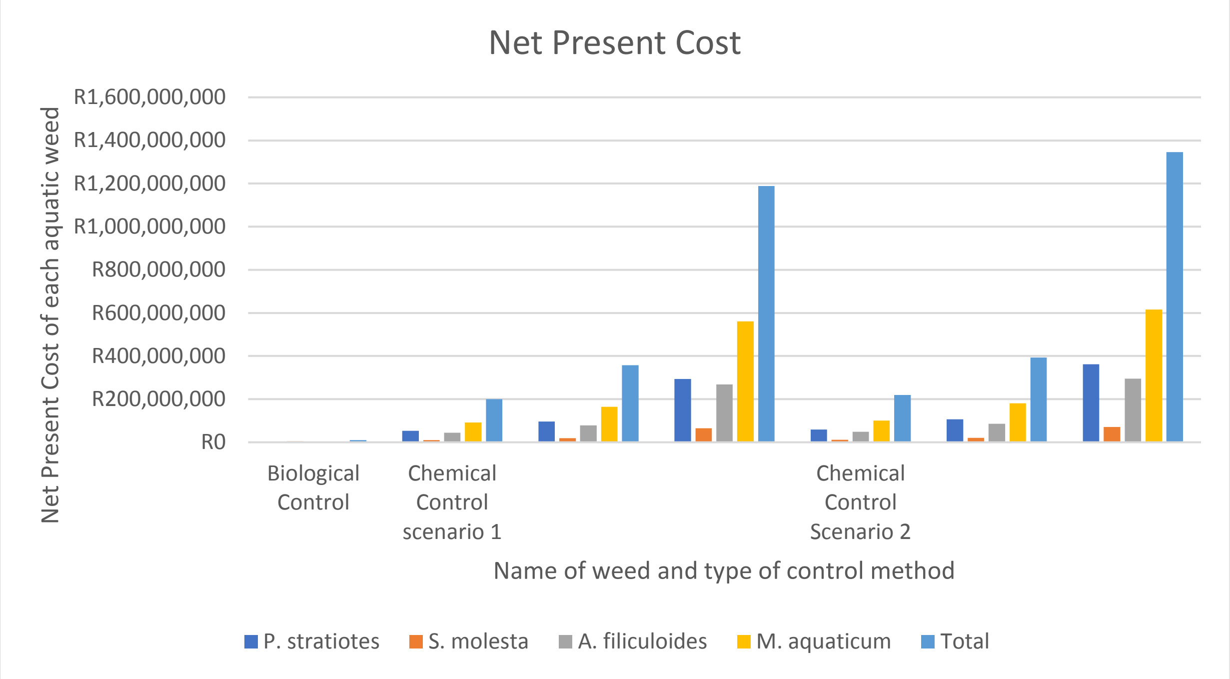

Figure 5.7 NPC of both biological and chemical control methods under a 5% discount rate analysis

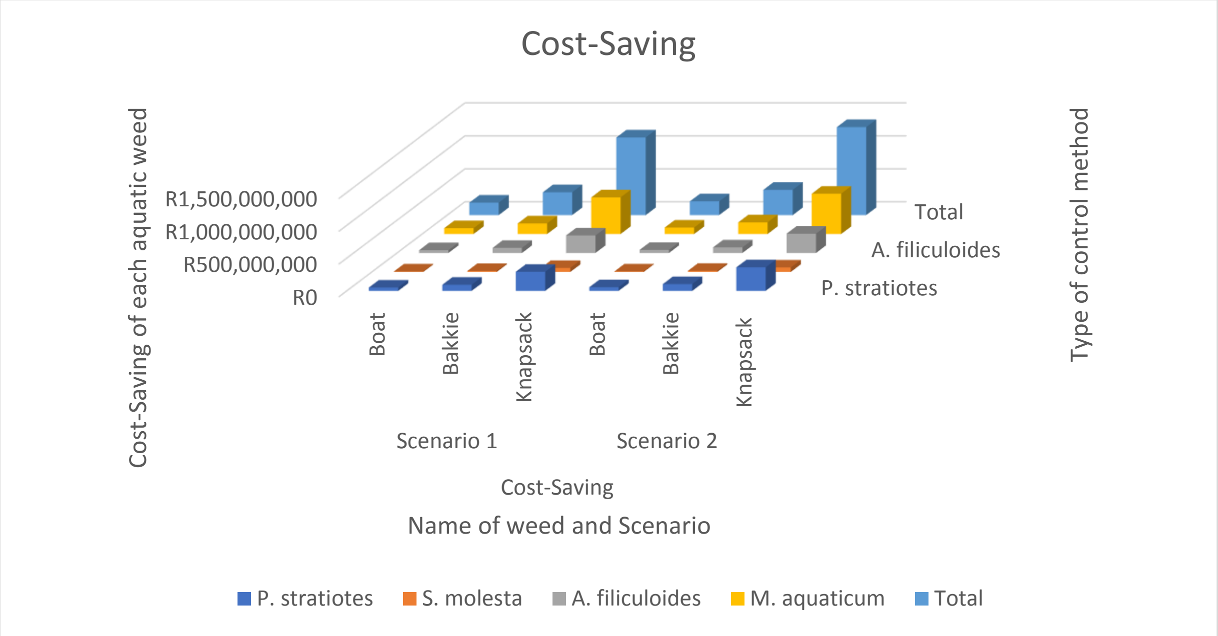

Figure 5.8 Estimated cost-saving and avoided cost of using biological control under a 5% analysis

Table 5.10 BCR of using biological control instead of chemical control under a 5% analysis

Weed	Benefit Cost Ratio					
	Scenario 1			**Scenario 2**		
	Boat	**Bakkie**	**Knapsack**	**Boat**	**Bakkie**	**Knapsack**
P. stratiotes	17.77	32.68	101.75	19.65	36.05	125.60
S. molesta	1.65	3.76	15.27	1.92	4.24	16.90
A. filiculoides	32.97	59.86	207.25	36.36	66.04	228.08
M.aquaticum	42.00	76.15	262.62	46.30	83.87	288.99
Total	94.39	172.45	586.89	104.23	190.19	659.56

5.3.2 With a 10% discount rate

At a higher discount rate, the results are still robust to the main results of the study confirming that even at a 10% discount rate, the overall biological control programme is the least-costly control method relative to the three chemical control options. With an overall programme cost estimate of about R6,802,248. The individual NPCs reveal that all four selected aquatic weeds are cheaper under biological control with that of *A. filiculoides* as the least costly project followed by *M. aquaticum, P. stratiotes* and *S. molesta;* while chemical control cost also maintained that *S. molesta* was the cheapest followed by *A. filiculoides, P. stratiotes* and *M. aquaticum* respectively. For chemical control, total costs are R127,823,596, R229,229,019 and R748,325,364 respectively for the boat, bakkie and knapsack approach (while for the second scenario, costs were R140,605,870, R252,276,728 and R862,035,957 respectively).

Overall, the prevailing chemical control cost saving were likewise; the lowest for *S. molesta* followed by *A. filiculoides, P. stratiotes* and *M. aquaticum*; although maintaining positive saving throughout. The overall relative cost-savings in favour of the biological control programme were an estimate of about R121,021,349, R222,426,772 and R741,523,116 under scenario one and about R133,803,622, R245,474,480 and R855,233,709 under scenario two – for boat, bakkie and knapsack respectively. When considering the BCRs, *S. molesta* had the lowest BCR followed by *P. stratiotes, A. filiculoides and M. aquaticum* with the highest return – like the order presented by the main results. Overall, the relative return offered by biological control was an estimated 87.56:1, 160.14:1 and 539.42:1 under scenario one and 96.72:1, 176.71:1 and 613.47:1 under scenario two for the boat, bakkie and knapsack.

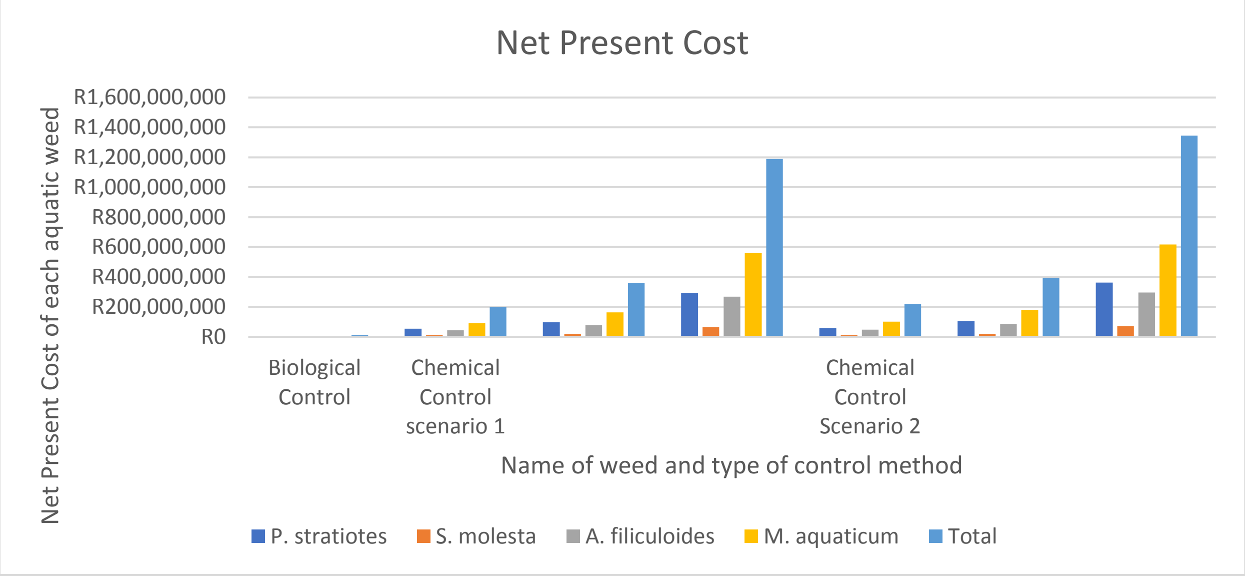

Figure 5.9 NPC of both biological and chemical control methods under a 10% discount rate analysis

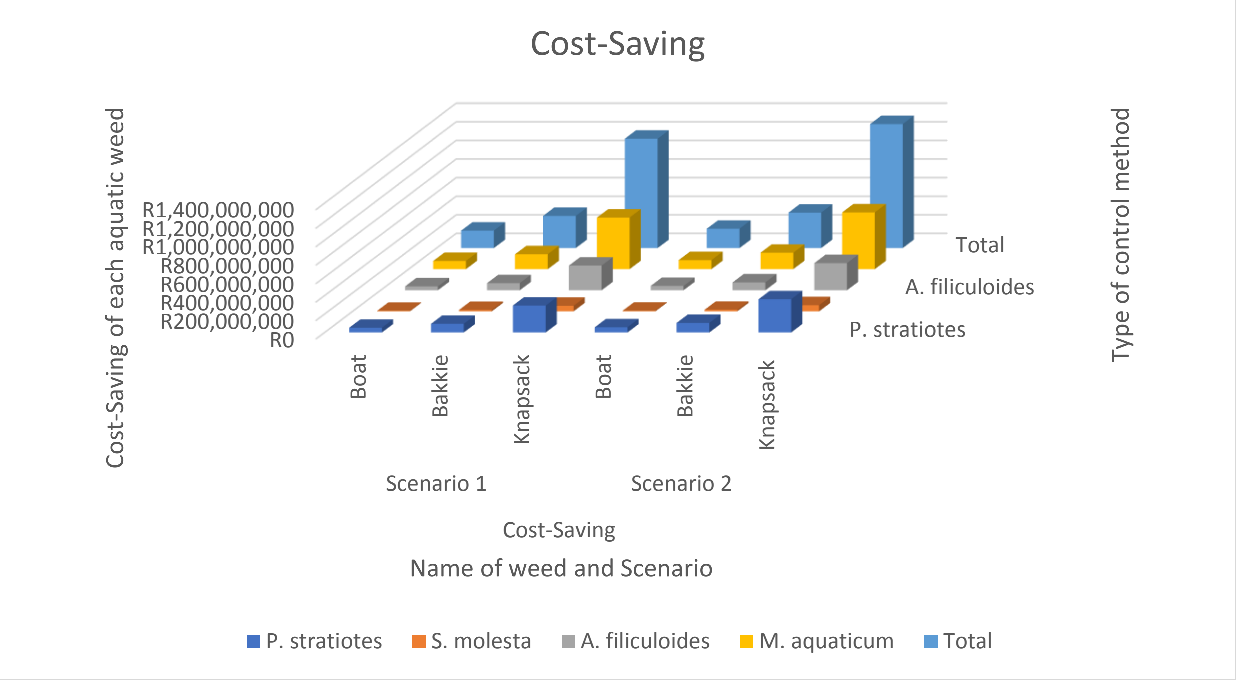

Figure 5.10 Estimated cost-saving and avoided cost of using biological control under a 10% analysis

Table 5.11 NPC of both biological and chemical control methods under a 10% discount rate analysis

Weed	**Net Present Cost**						
		Chemical Control Scenario 1			**Chemical Control Scenario 2**		
	Biological Control	**Boat**	**Bakkie**	**Knapsack**	**Boat**	**Bakkie**	**Knapsack**
P. stratiotes	R1,972,248	R41,329,287	R74,153,513	R218,040,787	R45,462,204	R81,568,979	R278,722,797
S. molesta	R2,559,333	R7,699,946	R13,815,284	R47,207,231	R8,469,939	R15,196,790	R51,927,984
A. filiculoides	R809,235	R24,806,128	R44,393,846	R152,082,708	R27,286,669	R48,957,945	R167,291,074
M. aquaticum	R1,461,432	R53,988,235	R96,866,376	R330,994,639	R59,387,059	R106,553,014	R364,094,102
Total	R6,802,248	R127,823,596	R229,229,019	R748,325,364	R140,605,870	R252,276,728	R862,035,957

Table 5.12 Estimated cost-saving and avoided cost of using biological control under a 10% analysis

Weed	**Cost-Saving**					
	Scenario 1			**Scenario 2**		
	Boat	**Bakkie**	**Knapsack**	**Boat**	**Bakkie**	**Knapsack**
P. stratiotes	R39,357,040	R72,181,265	R216,068,539	R43,489,956	R79,596,731	R276,750,549
S. molesta	R5,140,613	R11,255,951	R44,647,898	R5,910,606	R12,637,457	R49,368,651
A. filiculoides	R23,996,893	R43,584,612	R151,273,473	R26,477,434	R48,148,710	R166,481,839
M. aquaticum	R52,526,803	R95,404,944	R329,533,206	R57,925,626	R105,091,582	R362,632,670
Total	R121,021,349	R222,426,772	R741,523,116	R133,803,622	R245,474,480	R855,233,709

Table 5.13 BCR of using biological control instead of chemical control under a 10% analysis

Weed	Benefit Cost Ratio					
	Scenario 1			**Scenario 2**		
	Boat	**Bakkie**	**Knapsack**	**Boat**	**Bakkie**	**Knapsack**
P. stratiotes	19.96	36.60	109.55	22.05	40.36	140.32
S. molesta	2.01	4.40	17.45	2.31	4.94	19.29
A. filiculoides	29.65	53.86	186.93	32.72	59.50	205.73
M. aquaticum	35.94	65.28	225.49	39.64	71.91	248.14
Total	87.56	160.14	539.42	96.72	176.71	613.47

5.4 CONCLUSION

In conclusion, biological control management programme on the four selected aquatic weeds is the less expensive and thus a more cost-effective management option compared to chemical control. This was consistently found to be the case under both scenarios of the main results and the sensitivity test results. Thus, maintaining robustness across a 5%, 8% and 10% discount rate, *A. filiculoides* is the cheapest weed project under biological control method followed by *M. aquaticum, P. stratiotes* and *S. molesta* while for chemical control, the cheapest is *S. molesta* followed by *A. filiculoides, P. stratiotes* and *M. aquaticum.* Across the three discount rates*, M. aquaticum* had the highest relative cost saving followed by *P. stratiotes, A. filiculoides,* and *S. molesta* with the lowest cost saving. Leading to the concluding findings across all three discount rates that *M. aquaticum* offers the highest return on investment with the highest BCR followed b*y A. filiculoides, P. stratiotes* and *S. molesta.*

This study found that the estimated cost of the biological control method on all four aquatic weeds was about R7,843,205 while for chemical control the estimated costs would have costed for R149,580,142, R268,264,839 and R881,711,739 for the boat, bakkie and knapsack approach. These chemical control cost estimates would have increased to about R164,538,052, R295,216,121 and R1,008,761,000 for boat, bakkie and knapsack approach respectively when including a possible follow-up initiative. These would have led to positive BCRs of 90.24:1, 164.97:1 and 557.99:1 across the three chemical control approaches under scenario one (with BCR of about 99.67:1, 182.00:1 and 631.56:1 for the boat, bakkie and knapsack approach respectively under scenario two).

Table 5.14 Summary of study results

Summary of Results

Main Results					**Sensitivity Test Results**	
8% discount rate					**5% discount rate**	**10% discount rate**
Scenario 1 & 2					**Scenario 1 & 2**	**Scenario 1 & 2**
Project rank	**Biological control**	**Chemical control**	**Cost-Saving**	**Benefit cost ratio**	**Robustness**	**Robustness**
Least	*A. filiculoides*	*S. molesta*	*S. molesta*	*S. molesta*	Yes	Yes
Second-least	*M. aquaticum*	*A. filiculoides*	*A. filiculoides*	*P. stratiotes*	Yes	Yes
Second-most	*P. stratiotes*	*P. stratiotes*	*P. stratiotes*	*A. filiculoides*	Yes	Yes
Most	*S. molesta*	*M. aquaticum*	*M. aquaticum*	*M. aquaticum*	Yes	Yes

1. Least costly, least cost-saving, least BCR (return on investment)
2. Second-least costly, second-least cost-saving, second-least BCR (return on investment)
3. Second-most costly, second-most cost-saving, second-most BCR (return on investment)
4. Most costly, most cost-saving, most BCR (return on investment)

CHAPTER SIX: DISCUSSION AND CONCLUSION

This chapter includes a four-part analysis of results. The first (section 6.1), discusses the context of results and explains what they mean for the management of the four selected aquatic weeds: *Pistia stratiotes* (water lettuce), *Salvinia molesta* (salvinia), *Azolla filiculoides* (red water fern), *Myriophyllum aquaticum* (parrot's feather) in South Africa. It also reviews the limitations and assumptions of the research methodology (section 6.2) - because it is important to understand the results within the context of the assumptions made in the methods. The chapter also provides a brief qualitative review in support of the quantitative results under (section 6.3). Section 6.4 provides recommendations on: the most economically feasible control method for the four aquatic weeds, the areas of limitations in this study that make for an opportunity for future studies to enhance research results, as well as recommendations on which of the two control methods should be prioritized in future and emerging aquatic weeds such as *Iris pseudacorus*, *Nymphaea mexicana* and *Sagittaria platyphylla* in South Africa (Hill and Coetzee, 2017).

6.1 DISCUSSION

Biological invasions – in this context invasive alien plants (IAPs) – have a host of environmental, economic and social consequences. These consequences can be direct and indirect impacts; with an associated cost on the overall ecosystem, economy and social well-being of the nation. Most of the literature on IAPs have consisted of studies aimed at valuing the direct consequences (impacts and costs) of such IAPs. Where possible, some studies have also sought to investigate the overall success and prevailing return on individual projects - based on specific IAPs, a group of IAPs, and or, on a specific control method. Very few studies, however, have attempted to quantify the indirect impacts of IAPs, and, even fewer studies have done a comparative study on prevailing and competing control methods of a specific or group of IAPs –especially at a national scale. The literature available on the success, return and comparative analysis of the management of IAPs in South Africa is concerning; especially one that includes an evaluation of the ecological, economic and social significance of clearing these IAPs.

This study sought to provide a retrospective evaluation of the relative return on investment on the use of chemical and biological control management programmes on the four selected aquatic weeds, *P. stratiotes*, *S. molesta*, *A. filiculoides*, and *M. aquaticum* in South Africa. With the standing hypothesis that biological control is the most environmentally friendly, cost-effective and sustainable control method for IAPs relative to chemical, mechanical and manual control methods; based on the overall findings of this study we failed to reject our hypothesis for the four selected aquatic weeds under the method and assumptions made in Chapter 4 of the study.

The results from the first scenario (assuming no follow-up treatment for herbicide control), are such that the total cost of biological control on all four weeds was estimated to be R7,843,205 while the cost of the three possible chemical control spray approaches ranged between R149,580,142 and R881,711,739. The BCR ranged of between 90.24:1 and 557.99:1. These values indicate that, of the two control methods, biological control has substantial benefits making it a relatively more cost-effective control approach on the four aquatic weeds and offering the best return on investment at an increasing scale. Similarly, the results of the second scenario (assuming one follow-up treatment) are such that, the cost of biological control on all four weeds remained constant at R7,843,205 while estimated costs of the three possible chemical control spray approaches ranged between R164,538,052 and R1,008,761,000. Under this scenario, the BCRs ranged between 99.67:1 and 631.56:1.

Under the sensitivity analysis with varying discount rate of 5% and 10%, the overall results under both scenario one and two maintained robustness to those of the main results of the study. For example, at a lower discount rate of 5%, biological control had a total cost estimate of R10,258,585 (for both scenarios), while chemical control had an estimated total cost range of between R199,544,816 and R1,188,038,253 for scenario one (scenario two range was R219,499,153 and R1,345,720,235). Leading to an estimated BCR range of between 94.39:1 and 586.89:1 under scenario one and that of between 104.23:1 and 659.56:1 for scenario two. Compared to the main results, these results under a lower discount rate reveal a relatively higher return on biological control for both scenarios.

Similarly, at a higher discount rate of 10%, the total estimated cost of biological control was about R6,802,248 (for both scenarios), while chemical control has an estimated total cost range of between R127,823,596 and R748,325,364 for scenario one (scenario two range was between R140,605,870 and R862,035,957). Leading to an estimated BCR range of between 87.56:1 and 539.42:1 for scenario one and 96.72:1 and 613.47:1 for scenario two. Compared to the main results, these results under a higher discount rate reveal a relatively lower return on biological control for both scenarios however it was still positive.

Overall, these results under the sensitivity test reveal a similar trend. *Azolla filiculoides* is the least costly project under biological control followed by *M. aquaticum, P. stratiotes* and *S. molesta.* Biological control is relatively less costly overall than chemical control, and scenario one estimates are less than those of scenario two. However, with the possibility that costs and especially benefits in this study were likely to have been under-estimated, the magnitude of the relative return on investment is likely to be significantly larger than was found here. This is especially the case considering that the study only quantified the herbicide cost-saving; excluding the return associated with both the environmental cost-saving and water saving due to the difficulty to give monetary values to both additional types of return. Thus, it is reasonable to expect that both the environmental and water saving would offer a positive influence on the prevailing cost-saving and BCRs.

However, various factors such as the environmental impact and impact on water caused by the four selected aquatic weeds would need to be interrogated in order to assess (estimate) the degree of environmental cost-saving and water-saving associated with clearing water catchments off aquatic weeds under the chemical and biological control method. Hence, this section of the chapter breaks down the discussion of results into three parts to cater for a discussion around the three types of saving associated with clearing. To do this effectively, the results will be discussed based on the results of the individual weed projects.

6.1.1 Herbicide cost-saving

As discussed, the main results indicate that overall, biological control is the cheapest and more-effective method for the overall four aquatic weeds. Looking at the individual weed control management projects, the quantified herbicide cost-saving result present positive returns on all four weeds. For example, of the four aquatic weeds, *M. aquaticum* had the highest relative cost saving followed by *P. stratiotes, A. filiculoides,* and *S. molesta,* confirming that biological control offers a better herbicide cost-saving than chemical control on all four weeds. On *M. aquaticum, P. stratiotes, A. filiculoides,* and *S. molesta* biological control was initiated in the years 1991, 1985, 1985 and 1995 respectively and has now been implemented for about 27, 33, 33 and 23 years.

With respect to the herbicide saving, *M. aquaticum* had the second lowest biological control cost and the highest chemical control costs which resulted in the highest cost-saving (benefit). Thus, the highest benefit and the lowest biological control cost resulted in the highest benefit cost ratios (highest return on investment). *Azolla filiculoides* had the lowest biological control cost and the second lowest chemical control cost leading to the second lowest cost saving (benefit). As such, *A. filiculoides* with the second lowest benefit and the lowest biological control had the second highest benefit cost ratios (return on investment). *P. stratiotes* had the second most expensive biological control costs and second most expensive chemical control cost which resulted in the second highest cost saving (benefit). Hence, with the second highest benefit and second biological control cost, *P. stratiotes* had the second lowest benefit cost ratio range (second highest return on investment). *Salvinia molesta* had the highest biological control costs and the lowest chemical control cost which led to the lowest cost saving (benefit). With the lowest benefit and the highest biological control cost, the project on *S. molesta* produced the lowest benefit cost ratio range (lowest return on investment).

Looking at the associated biological control costs of the four selected weeds based on the cost data received from the Rhodes University CBC – the following observations can be made.

- *M. aquaticum* (second least costly project under biological control and most beneficial) had the lowest post release monitoring costs, the second lowest establishment trails and implementation costs, and, the most expensive exploration and quarantine costs relative to other weeds.
- *A. filiculoides* (least expensive project under biological control and second most beneficial) had the second highest post release monitoring and evaluation, the second lowest

exploration and quarantine costs as well as the lowest establishment trails and implementation costs.

- *P. stratiotes* (second most costly project under biological control and second least beneficial) had no (zero) exploration costs, had the second lowest post release monitoring and evaluation cost and the second most expensive (though a small amount) quarantine, establishment trails and implementation costs.
- *S. molesta* (the most expensive project under biological control and least beneficial) had no exploration and quarantine cost, however, the project incurred the most expensive establishment trails, post release monitoring and evaluation and implementation cost of all the four weeds with a significant difference.

In addition to the individual cost types, the ranking of the cheapest project under biological control to the most expensive also corresponds to the rank of the period of the project. For example, *P. stratiotes and S. molesta* have been in operation for 33 years and are both the most-costly while *M. aquaticum* has the second highest number of years in operation (27) and is the second cheapest project and *A. filiculoides* has the least number of years (23) and is the least expensive. Looking at the above individual cost types incurred by each weed and the period; the results on the costs of biological control on the four weeds are sensible.

In the case of chemical control costs, various factors need to be considered to investigate not only if the costs are sensible but also if the assumptions and method application makes sense of the results. This is important because, while costs under biological control were based on 'actual' incurred costs, costs under chemical control were purely hypothetical and based on assumptions.

For chemical control, estimates relied heavily on the estimated number of hectares in the study, as such, it is probable that any distortion in that estimation may lead to over/understatement of the costs themselves. Based on our estimated historical number of hectares infested by each weed, it was estimated that *P. stratiotes* had the least estimated infestation across the country followed by *S. molesta, A. filiculoides and M. aquaticum.* These estimated number of hectares have a direct impact on the result found under chemical control costs. However, the limitations encountered in this process had a much greater bearing on these results. As mentioned previously (in chapter 4 section 4.5.1), a number of sites were excluded due to the associated difficulty to use all the coordinate data recorded in the SAPIA database.

For example, the initial number of sites infested with each weed under the SAPIA database were 130 sites for *S. molesta,* 133 sites for *P. stratiotes*, 160 sites for *M. aquaticum* and 607 sites for *A. filiculoides.* Of these sites, not all were included in the area estimate; about 80% of *S. molesta* was included and about 74%, 71% and 71% of total sites were included for *A. filiculoides, P. stratiotes* and *M. aquaticum* respectively*.* Thus, because 20%, 26%, 29% and 29% of total sites for the four weeds *S. molesta, A. filiculoides, P. stratiotes* and *M. aquaticum* were excluded. It is reasonable to expect that *S. molesta* was probably the least understated followed by *A. filiculoides* with *P. stratiotes* and *M. aquaticum* being probably the most understated (Table 6.1). This order follows the weed project cost rank from the least to the most expensive under chemical control. As such, it is also reasonable to expect that, although all the four weeds could probably cost more under chemical control should all the sites be included, the degree of costs would most likely differ yet take the same order of ranking.

Table 6.1 Site inclusion for chemical control cost estimates

Weed	**Total no. of sites**	**No. of sites included**		**No. of sites excluded**		**Degree of possible underestimation**
P. stratiotes	133	95	71%	38	29%	Most-possible understatement
S. molesta	130	104	80%	26	20%	Least possible understatement
A. filiculoides	607	452	74%	155	26%	Second-least possible understatement
M. aquaticum	160	113	71%	47	29%	Most-possible understatement

Salvinia molesta and A. filiculoides were the two cheapest projects under chemical control and have had the lowest rate of sites excluded. As such, with the highest rate of inclusion, *S. molesta* is likely to have been less understated than *A. filiculoides* and because the two had the same estimated conversion factor, it is likely that *S. molesta* would have still cost less than *A. filiculoides* under chemical control. For *P. stratiotes* and *M. aquaticum*, both projects could have cost even more under chemical control especially being the two most costly projects and having the highest rate of site exclusion. They probably would have remained the most-costly projects. Therefore, with much consideration, it is likely that the cost of all weed projects under chemical control would have increased with a reasonable prospect that these costs would have still kept to the rank of *S. molesta* being the cheapest project (the least-costly) followed by *A. filiculoides, P. stratiotes* and *M. aquaticum.*

Similar to the estimated number of hectares, the estimated cost per hectare used under the chemical control boat, bakkie and knapsack approach; also have an influence on the results of this study in the same extent. For example, the estimated conversion factors used to translate *E. crassipes* (water hyacinth) cost per hectare to suit the four selected weeds were the lowest for *S. molesta* (50%) and *A. filiculoides* (50%) followed by a relatively high factor for *M. aquaticum* (70%) and the highest factor for *P. stratiotes* (80%). Evidently, the estimated costs per hectare also followed the conversion factors respectively across the three spray approaches. *S. molesta* (cheapest project under chemical control) has the lowest cost per ha and the second lowest number of hectares. This was followed by *A. filiculoides* (second cheapest project) with the second lowest cost per ha and second highest number of hectares. The third weed, *P. stratiotes* (second most-costly project) had the highest cost per hectare and lowest estimated number of hectares while *M. aquaticum* (most-costly project) had the second highest cost per hectare and the highest number of hectares estimated. So, both the estimated number of hectares and cost per hectare have a joint detrimental effect on results.

Should the cost per hectare be under or overstated, this would have an impact on the weed project costs estimated. Already, there is a possible underestimation of costs because the individual cost types given by the Natural Resource Management (NRM) programme on *E. crassipes* excluded overhead costs. As such, the inclusion of overhead costs would have led to an increase in the estimated and applied cost per hectare of each weed. These overhead costs would have thus increased the respective total cost of each weed leading to a potential increase in the prevailing cost-saving under each of the three control approaches. This would have a positive effect on the return on investment produced by the biological control management programme relative to chemical control; as it would increase the BCR ranges.

The last issue of concern with the chemical control method is that, due to poor documentation and data, the incomplete inclusion of invaded sites to get a more inclusive area estimate; caused a gap between the cost inclusion period of the two control methods on some of the weeds. For example, while period dates were fixed for biological control (due to good data keeping amongst other factors), for chemical control, period dates depended on when the earliest number of hectares (recorded in the SAPIA database) was able to be estimated and included in the estimated number of hectares for each weed. Evidently, there is a two-year gap in the chemical control cost recording for *P. stratiotes* and a 10-year gap in for *S. molesta* because the number of hectares for those years could not be estimated due to the prevailing limitations encountered in this study. As such, cost of clearing using chemical control could not be estimated for those years.

While the gap is reasonably short for *P. stratiotes* and accurately covered for *A. filiculoides* and *M. aquaticum;* it is significantly wide for *S. molesta* and may have significant effect on the chemical control cost of *S. molesta.* Although the magnitude of the effect could not be calculated, it is sensible to expect that the effect would have been positively related to the chemical control costs of *S. molesta* which would have led to a positive effect on the prevailing cost saving and return on investment in favour of biological control. Although the degree of effect on the overall chemical control project cost rank could not be evaluated credibly, it is possible that it would have remained the same (*S. molesta* maintaining the least-costly project under chemical control). This inference is derived from the quantitative gap between *S. molesta* and *A. filiculoides* (the second least-costly project under chemical control) is significantly large based on the results of the study.

The above discussion affirms that biological control is indeed the relatively more cost-effective management option compared to chemical control with respect to herbicide cost saving. The discussion further suggests that possible underestimation of the chemical control costs throughout the results of this study exists due to the above factors discussed such as possible underestimation of the number of hectares, cost per ha and prevailing period gap.

6.1.2 Environmental cost-saving

Environmental saving is saving that comes as a result of avoided environmental damage or reversal of environmental damage caused by an action. It is – in addition to other types of saving (e.g. herbicide cost saving) – detrimental to overall return on investment. IAPs have associated environmental impacts that have an associated environmental cost. Likewise, IAPs management programmes can also have environmental impacts that have environmental costs. Both sources of environmental impacts and costs can have an associated cost saving when avoided, reversed and or rectified. For example, the environmental cost caused by the presence of IAPs can result in a saving when the IAPs are cleared, and, upon the clearing of the IAPs, costs associated with the clearing process (method) can become a cost saving. As such, IAPs can have a two-part cost saving – IAP oriented and clearing method oriented.

For the IAP oriented cost saving, there exists a possible variation in the prevailing cost-saving between a group of IAPs. For example, the relative cost-saving between the four selected aquatic weeds can differ, and, that of the biological and chemical control method can differ too. As such, although it was difficult to quantify this environmental saving, a qualitative analysis will be taken, and an inference will be drawn on the possible cost saving associated with each weed project and with each control method.

Each of the four selected aquatic weeds individually produce a different measure of environmental impact. It is within reasonable expectation that the magnitude of costs will be positively related to that of impacts and possibly return. Evaluating the degree of environmental impact produced by the big bad five aquatic weeds, Hill and Coetzee (2017) found that *E. crassipes* was the most environmentally hazardous weed followed by *P. stratiotes*, *S. molesta, A. filiculoides* and *M. aquaticum*. The results of the study will be used here as a proxy for national environmental performance of such a study. While Hill and Coetzee (2017) measured only the degree of environmental impact, an inference that environmental costs would be aligned to degree of impacts will be maintained. Thus, *E. crassipes* would most-likely have the highest environmental cost followed by *P. stratiotes*, *S. molesta, A. filiculoides* and *M. aquaticum* because the greater the impact the greater the cost.

With regards to the relative environmental cost saving between the two alternative control methods. Hill and Coetzee (2017) further evaluated the degree of environmental impact post the biological control method initiative and found that post biological control *E. crassipes* still had the most environmental impact but was now followed by *M. aquaticum, P. stratiotes* and *S. molesta* - with no record of impact for *A. filiculoides*. Of the four selected aquatic weeds, *M. aquaticum* had the relatively least cost saving followed by *P. stratiotes* and *S. molesta* with *A. filiculoides* potentially producing the highest relative cost saving. Despite that the fact that, Hill and Coetzee (2017) did not focus on the chemical control method, it would not be misleading to expect that the degree of impact could potentially follow the same order (as in post biological control) but at higher degrees than biological control. However, it is also possible that, post herbicide application, *E. crassipes* would be followed by *P. stratiotes*, *M. aquaticum, S. molesta* and *A. filiculoides* – this based on the rate of herbicide application each weed requires which affects the degree of associated herbicide environmental impact and cost.

Apart from the individual weeds, the essential question is of the magnitude of the degree of impact, cost and return under chemical control relative to biological control. Qualitatively, a hypothesis that chemical control is much more environmentally harmful than biological control has proven true – (see section 6.3). As such, a priori expectation that overall, the degree of environmental impact and cost would be more for chemical control than biological control is credible. This further suggesting that the environmental saving would be significantly larger for biological control than chemical control.

6.1.3 Water saving

South Africa, being a water scarce nation with increasingly less annual rainfall, is in a position that emphasizes the need to use, save and sustain the available water in a way that will best benefit the country. With increasing water demand across all stakeholders, households, agriculture, industries and the overall economy, the water resource is critical to national capacity. IAPs – in particular aquatic weeds – have an impact on the water resource. They change the hydrological characteristics of catchments, cause soil water depletion, reduce water yield, affect water consumption and streamflow (Gorgens and van Wilgen, 2004). They also affect life under water by imposing a threat to native aquatic life, vegetation, competition, and produce. Socially, they reduce the welfare of affected communities surrounding invaded catchments as well as endanger the health of those using the invaded catchments for their livelihoods. As such, their impact on water is widespread as it has other associated externalities.

According to Monney (2005), the degree of impact of aquatic weeds on water depends on, *inter alia*, the degree of loss of moisture in water. This can be directly associated with the rate of evaporation the weed causes, the biomass of the weed and if the weed has deep roots. Although it is difficult to find studies on the evapotranspiration rates of the four selected weeds, the biomass and root level of the weeds can be useful to direct which of the four weeds could potentially cause a relatively larger impact on water than the other.

As outlined in chapter 4, of the four aquatic weeds, the weed with the largest biomass is *P. stratiotes*, *M. aquaticum, S. molesta* and *A. filiculoides* in a descending order; while the weed with the deepest root level is *M. aquaticum* followed by *P. stratiotes*, *S. molesta* and *A. filiculoides*. Although the biomass and root level do not follow the same weed order, it can also be expected that the degree of water loss may follow either one of those patterns. Thus, based on both the biomass and root level ordering, it is likely that the cost associated with water loss would be more for either *M. aquaticum* or *P. stratiotes,* followed by *S. molesta* and *A. filiculoides* possibly ranking the lowest. Moreover, it is possible that, upon clearing of these weeds, the prevailing water saving would be positively related to the degree of water loss. For example, depending on which weed causes the highest water loss, between *M. aquaticum* and *P. stratiotes*, either one would produce the highest water saving followed by the other - then by *S. molesta* and *A. filiculoides* with the least water-saving.

Similar to the inference drawn under the previous environmental cost-saving, it is expected that overall, chemical control is likely to cause a relatively larger impact on water than biological control; producing more water loss saving for biological control than chemical control. This is amongst other factors due to the induced water damage caused by chemical control relatively; considering herbicide residue and the chemical effect of the herbicide on the quality of water. The possible regrowth potential of the weeds (averaging between 100% and 30%) may lead to further damage of the water at each follow-up treatment required. This may result in temporary water yield recovery producing seasonal effects on the stakeholders dependent on the affected water catchments as well as may lead to constraints on the sustainable development of water resource. All these factors are significantly avoided under biological control and could lead to a significant cost-saving in favour of biological control relative to chemical control.

A more detailed comparative analysis of the effect of both control methods is discussed under section 6.3. However, considering the quantified results of the herbicide cost-saving, projected environmental cost-saving and water saving; overall biological control programme does indeed offer the best overall return on investment than chemical control on the four selected aquatic weeds under study in South Africa.

6.2 RESEARCH LIMITATIONS AND ASSUMPTIONS

The results in Chapter 5 should be interpreted within the context of the research method, limitations and assumptions expressed in Chapter 4. They are a step towards retrospective economic evaluation of the control efforts of the four selected aquatic weeds in South Africa; aimed at estimating the relative cost-saving of the two alternative control methods used by the DEFF NRM WfW programme. The assumptions used were due to several research limitations encountered.

For example, limitations such as poor documentation posed a significant challenge on this study. This poor documentation led to a lack of quantitative literature on the economic evaluation of the respective aquatic weeds in terms of cost-effectiveness, cost-efficiency and return; leading also to very few studies to compare the results of this study with. Another area lacking was that of poor documentation on the number of hectares invaded at each site identified to have been infested with the weeds. Although site coordinates are well recorded by the SAPIA, it was still difficult to quantify the degree of infestation at those sites; hence a lot of estimation went into that as well as expert opinion. There was also a lack of complete financial data on the control costs of the surrogate weed. For example, although the herbicide cost and application costs were obtained from the NRM, other costs such as overhead costs could not be accessed. As such, it is without doubt that there is a degree of over/underestimation in some aspects of the data used.

Apart from poor documentation, the methodology of quantifying economic benefits of clearing IAPs as well as quantifying other impacts of IAPs became a huge hindrance in this study. Although this is inherent to the economic evaluation of biological invasions, quantifying or giving monetary value to the ecological and social costs and benefits in this study was difficult; especially monetary values to benefits. Hence the traditional benefit cost ratios (BCRs) could not be calculated and the avoided herbicide costs were used as the main benefit of clearing using biological control. Also, because herbicides have never been needed on these four selected aquatic weeds since the inception of the DEFF NRM WfW programme, all chemical control cost estimates were purely based on assumption and may be unrealistic to some degree.

As such, the results provided the next best evaluation so far. Although exposed to limitations, the disadvantage of the method used is that it excludes other benefits such as secondary benefits of clearing and it does not investigate the individual return offered by the chemical control management programme. In addition to this, for adequate estimation of chemical control costs, a knowledge of the number of follow-up treatments that would have been required by each weed is essential; looking at the degree of herbicide resistance at each spray incentive. Weed regrowth capacity under chemical control would have been essential to results as well; however, this was estimated using existing literature and expert opinion and was included in the method. Within the method, the results may be sensitive to other assumptions made in the study apart from the discount rate that showed no significant sensitivity.

6.3 QUALITATIVE REVIEW

The early use of herbicides was associated with high levels of impact including threat to non-target species. Over the years, herbicide application was subject to some regulatory changes which led to changes in the legally approved herbicide compounds application rate. Although herbicide application itself had not become ineffective, they eventually became the least preferred option. Their use requires careful consideration of the related herbicide selectivity, herbicide residue behaviour and herbicide resistance development as well as an understanding of the two key processes, herbicide dispersion, degradation and binding (Gettys *et al*., 2014). For effective use, factors such as the type of herbicide preferred, dose required, application frequency, strategy and the continuous ecological changes that affect chemical components need to be considered.

According to Blackburn (1963), herbicide use is often ineffective on floating weeds and, or in, flowing water than on submerged weeds because the former has a shorter exposure period to the chemical. Thus, whether the weed is submerged, emerged or floating - affects the weed. In addition to the issue of effectiveness, herbicide use has some effects and limitations attached to their use. For example, factors such as over-spraying, misuse and malpractice enhance herbicide impact on the overall ecosystem and affect both the effectiveness and cost-effectiveness of the control effort. In some cases, herbicides may also affect or even kill non-target species, cause toxic infections to other water organisms, threaten human health, taint water (increase water treatment requirements), result in oxygen and carbon dioxide imbalance or reduction, and, they may have successful kills but suffer regrowth because some may even encourage weed bloom conditions (Pimentel *et al.*, 1992; Kolpin *et al*., 1998; Ueckermann and Hill, 2001; Hill *et al*., 2012).

Because herbicides are not completely ineffective, they have some associated benefits. For example, their use is relatively more effective than mechanical control and is likely to have a better cost-saving than mechanical control (Cooper and Dobson, 2007). They are quick and when successful, they improve the water yield (Cooper and Dobson, 2007).

According to van Klinken *et al*. (2016), weed biological control models require a six-step prioritization framework for adequate choice of biological control model and agents release. This is because for an agent to be passed and released as a control agent, it must first be proven to be classifiable as a successful agent. It must, be trusted and proven to can achieve benefits and to assure a reasonable probability to succeed. This is because, weed biological control has been "increasingly criticized for their lack of rigorous evaluation of the ultimate outcomes of deliberate introductions of exotic organisms" (Morin *et al*., 2001:1). This is criticized due to the possible threat and risk these agents may impose on native non-target species (Denslow and D'Antonio, 2005); because some agents move to prey on native species that are close to their family to either kill or reduce their richness and competitiveness (Stiers *et al*., 2011). This then results in an overall effect on the ecosystem as it affects the native species that support the structure and function of the ecosystems. Hence a post-release evaluation is essential to this control management method.

In addition, the prevailing uncertainty of outcomes at the primary levels of biological control incentives – the 50/50 chance of agent success or failure is a limitation as only a few or none of the natural enemies being tested may be a good control agent. Hence every project must have a degree of uncertainty and likelihood of success. Also, because biological control models may take long to master (van Klinken *et al*., 2016), the process of research, introduction and establishment can take months to years to get right, resulting in very high initial costs between the testing and release stage. Should there be wrong agent release and poor introduction, this may be costly as well. As such, this may work against the control method as people may generally prefer quicker, 'immediately convenient' and relatively less uncertain solution even though they may be unsustainable.

Although biological control has a long history of success rates and is considered safe, economically and ecologically sustainable (McFadyen, 1997; van Wilgen *et al*., 2004); its success is subject to some biotic and abiotic factors. Biotic factors include "host-plant quality or genotype, biological control agent density, and agent mortality factors such as predation, parasitism or disease", and abiotic factors include "climate, habitat conditions, concurrent management tactics such as mechanical harvesting or pesticide application" (Reeves and Lorch, 2011:1). The biological characteristics and make up of these weeds also affect their invasion success and thus the success of biological control in producing the desired efficacy (Stiers *et al*., 2011). Other factors that affect the success of biological control include: the advantage of a tropical climate (as it enhances the growth and population of biological control agents), simple techniques for mass-rearing (which helps with large population releases as well as with agent establishment) and large water bodies.

Like herbicide use, biological control also has benefits associated with it. Apart from the already emphasized benefit of success, safety, economic and environmental return, sustainability and effectiveness; some other benefits include the ability to control rapid invasion growth rate, successful establishments, protection against regrowth, likelihood of agent dispersal ability, and relatively less environmental and human health threats. The reproductive capacity of the control agents can reproduce making them often (not always) self-sustainable. Biological control does not cause further harm to the quality of water; causing a significant amount of avoided costs and reduction in replacement costs. Moreover, biological control aids restoration and protection (conservation) of biodiversity. Biological control is the mainstay of weed control (Zachariades, 2017), and is sustainable over time to produce long-term control benefits relative to other control methods. So much so, Mc Fadyen (2000:8) argued that “programs against floating water weeds have been the outstanding success of the last two decades”.

From this brief qualitative analysis, although both control methods have associated advantages and disadvantages one has more disadvantages than the other. This qualitative analysis show that chemical control has more disadvantages than biological control, making biological control more appealing. Qualitatively, biological control is also more appealing relative to herbicide use; agreeing with the overall qualitative result explored above.

6.4 RECOMMENDATIONS

According to Le Maitre *et al*. (2001), water is a key constraint to economic growth and needs efficient and effective management as it has become a limited resource. The externalities of ensuring effective and efficient water clearing of IAPs as well as the opportunity cost of not clearing propels the choice of the best control management option for aquatic weed management in the country. Evidently, the results and discussion of this study leads to the recommendation of the continued use of biological control on the four aquatic weeds under evaluation as well as the recommendation to invest in further biological control initiatives on other aquatic weeds – especially emerging aquatic weeds. This is primarily because while biological control proves more economically, ecologically and socially beneficial than chemical control currently, it is likely to be even more relatively beneficial considering the rising climate change effects. This climate change is expected to affect the success of biological control but by not nearly as much as it will enhance the damage of herbicide performance and as well as enhance herbicide degradation, herbicide resistance and herbicide binding alongside associated herbicide environmental degradation (impacts). Biological control benefits are significantly understated, when considering the lag effect that will produce benefits well into the future. The main downfall of herbicides is that it is a temporary solution while biological control is a long-term sustainable solution.

Understanding the research limitations discussed above and in Chapter 4 provides an opportunity for future recommendations and research areas. The gaps in literature as well as methodological pitfalls (Chapter 4) in this study may be used to conduct better refined studies and results. Because this study focused on quantifying the relative herbicide cost-saving, it is important to understand that there exists a gap in the inclusion of quantified environmental and water saving. This gap presents an opportunity for a second study in addition to this one. However, for this to be possible, other pivotal studies may be necessary. For example, studies such as those of the evapotranspiration rates of the four selected aquatic weeds in order to be able to estimate the respective water saving. In addition, studies on how to value other environmental benefits are necessary towards conducting a full cost benefit analysis. Another area of interest and inclusion is that of prevailing externalities. An evaluation of related externalities (impacts, costs, benefits) may be incorporated in further research. Such as how clearing aquatic weeds benefits the water sector as well as overall industries in the economy such as fishery and agriculture – amongst others.

These studies should be done based on individual regions and at a national level although the later will be much more difficult; as well as incorporate a multidimensional outlook on other sociological and political factors. This is important because different regions within the country face different environmental, economic, sociological and political dynamics with which this topic could have different outcomes. Perhaps, every study should have an economic incorporation so that economic literature of biological invasions would increase, and retrospective studies would have a greater literature base.

The method used in this study relied heavily on assumptions due to mainly poor documentation that affected data collection and analysis. For example, the invaded site recording by SAPIA was difficult to use; with no record of the number of hectares infested and or plant cover/density. This led to the use of expert driven estimation as well as the exclusion of treated cleared sites. Precise description or more accurate cover/density estimate is necessary as well as precise documentation of costs to aid a better and more accurate method application. Having good documentation will help with retrospective analysis studies. Such documentation should be prioritized during the life of all control management studies, projects and clearing (implementation) incentives. This is primarily because, apart from providing more accurate results, it would also help with policy decision making; especially considering the scarce state of financial resources as well as the growing need for economic evaluation integration in various policies such as the environmental policy. This study, as well as recommendations, will be extremely helpful in determining relatively smooth economic evaluation of this nature as well as of the emerging aquatic weeds such as *Iris pseudacorus*, *Nymphaea mexicana* and *Sagittaria platyphylla* in South Africa.

6.5 CONCLUSION

Under the ever-increasing biological invasion and their associated global impacts, it is important for South Africa to put in place measures that will protect the existing biodiversity by managing the existing invasion capacity and guarding against future invasions. To do this, measures that enhance sustainable water management, sustainable environmental health and sustainable economic growth will be necessary. The same measures will need also to ensure that the prevailing returns on investments are maximized. This is because, while IAPs threaten the country's ecosystems, they have also become an essential threat to the overall economy. Thus affecting not only the water resource but also the economic growth and performance of the nation. For example, the current degree of impact imposed by IAPs is expected to increase due to the increased water scarcity, rainfall declines and hazardous climate conditions. As such, IAPs need to be adequately and sustainably handled.

Using a case study of the four selected aquatic weeds *Pistia stratiotes* (water lettuce), *Salvinia molesta* (salvinia), *Azolla filiculoides* (red water fern), *Myriophyllum aquaticum* (parrot's feather) in South Africa; this study sought to investigate the relative performance of two alternative control methods used as measures of response towards the management of these aquatic weeds. The point of which was to not only see if the control methods are effective in reducing invasion but to evaluate if they are doing so effectively and efficiently; as well as to see which of the two alternative control methods is the most effective and efficient response. So that, the DEA would: (1) distribute more investment in the method that produces maximum possible return as well as (2) consider the use of that method on other emerging aquatic weeds of the same kind as the four selected here. This study was also essential in attaching quantitative values to the standing hypothesis in literature.

Having used *E. crassipes* (water hyacinth) as a surrogate weed for chemical control costs of the four selected weeds, the chemical control costs of the overall management of the four weeds were found to be relatively more costly than biological control. This was found to be the case also for the individual weed projects. Thus, because it would have been difficult to deduce on the relative cost-effectiveness by merely looking at the estimated costs; a CBA was conducted. This CBA looked at the relative return on investment of the biological control programme in light of the avoided costs of using biological control instead of chemical control captured by the prevailing cost-saving of using the former control methods relative to the latter.

As discussed earlier, the results showed that the biological control programme is more beneficial than the chemical control programme under the methods applied in the study. This was revealed by positive BCRs of 90.24:1, 164.97:1 and 557.99:1 across the three chemical control approaches – boat, bakkie and knapsack respectively. These positive BCRs confirmed that under the conditions of the first scenario, we fail to reject the hypothesis that biological control on the four selected weeds is more beneficial than chemical control. The same finding that benefits outweigh costs (in favour of biological control) is found under scenario two conditions as well as under the two sensitivity-test variation. Thus, altogether, we fail to reject the hypothesis across the study. Especially because, although the different weed projects also showed different return yields, the results of all weed projects were in favour of biological control. This comparative study is essential in that it avoids biased arguments over the two competing control programmes as it proved quantitatively which control programme is more economically beneficial. Confirming the qualitative analysis dominant in literature.

Seeing that the estimated individual weed costs and overall costs of the four weeds impose a significant loss (impact) to the economy; their control should be invested towards a management programme that will yield significant benefits (financial return). Additionally, that management programme should also ensure a reasonable degree of biodiversity conservation and should not impose further harm to the overall biodiversity (by significantly enhancing the issue while aimed at reducing it). Already, several catchments across the country have dried up since the 1980s while some have declined in size. Making it important that the remaining catchments need to be adequately preserved and sustainably protected. Ensuring that, previous cleared or uninvaded catchments may not be subject to possible (re)invasion; either by the same weeds or by new invasions. This adequate preservation and sustainable protection is essential because, soon, the impacts of aquatic weeds will cost significantly more than they do currently - under current geographic and climate conditions. Thus, with complete biological control status, these four selected weeds are expected to produce even better return in the future.

As such, the findings of this study led to the recommendation that the environmental policy - on the management of aquatic weeds - should continue to prioritize economic evaluation. This is to avoid the continued use of economically ineffective and inefficient policy implementation actions. Moreover, apart from the quantitative results of this study, this economic analysis is useful in contextualizing these issues more broadly to aid towards holistic decision making. That said, this study agrees with the continued use of biological control methods on the four selected aquatic weeds. It further discourages the use of chemical control on these weeds as the approach proves to results in waste. This study also encourages similar studies to be conducted for the emerging aquatic weeds identified. Early research on these emerging weeds will help aid decision making as well as maximize return on investment.

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APPENDIX

Appendix 1: The estimated annual cost of biological control

BIOLOGICAL CONTROL COSTS				
Years	*P. stratiotes*	*S. molesta*	*A. filiculoides*	*M. aquaticum*
1985	R625,000.00	R155,000.00		
1986	R237,000.00	R155,000.00		
1987	R237,000.00	R155,000.00		
1988	R237,000.00	R155,000.00		
1989	R237,000.00	R155,000.00		
1990	R237,000.00	R237,000.00		
1991	R115,000.00	R237,000.00		R235,160.00
1992	R115,000.00	R237,000.00		R175,200.00
1993	R0.00	R237,000.00		R175,200.00
1994	R0.00	R237,000.00		R302,700.00
1995	R0.00	R237,000.00	R15,536.00	R197,500.00
1996	R0.00	R237,000.00	R272,632.00	R117,500.00
1997	R0.00	R237,000.00	R535,582.00	R70,000.00
1998	R0.00	R237,000.00	R73,750.00	R70,000.00
1999	R0.00	R237,000.00	R73,750.00	R70,000.00
2000	R0.00	R237,000.00	R73,750.00	R70,000.00
2001	R0.00	R237,000.00	R73,750.00	R70,000.00
2002	R0.00	R237,000.00	R73,750.00	R70,000.00
2003	R0.00	R82,000.00	R73,750.00	R70,000.00
2004	R0.00	R82,000.00	R73,750.00	R70,000.00

2005	R0.00	R82,000.00	R73,750.00	R70,000.00
2006	R262,440.00	R262,440.00	R73,750.00	R70,000.00
2007	R262,440.00	R262,440.00	R73,750.00	R70,000.00
2008	R262,440.00	R262,440.00	R73,750.00	R70,000.00
2009	R262,440.00	R262,440.00	R73,750.00	R0.00
2010	R262,440.00	R262,440.00	R73,750.00	R180,440.00
2011	R262,440.00	R262,440.00	R73,750.00	R180,440.00
2012	R262,440.00	R262,440.00	R73,750.00	R180,440.00
2013	R222,440.00	R262,440.00	R73,750.00	R180,440.00
2014	R222,440.00	R262,440.00	R73,750.00	R180,440.00
2015	R222,440.00	R262,440.00	R73,750.00	R180,440.00
2016	R222,440.00	R262,440.00	R73,750.00	R180,440.00
2017	R222,440.00	R262,440.00	R73,750.00	R180,440.00
2018	R222,440.00	R262,440.00	R73,750.00	R180,440.00
	R5,211,720.00	R7,513,720.00	R2,372,500.00	R3,667,220.00

Appendix 2: The estimated annual net present cost of biological control at an 8% discount rate

BIOLOGICAL CONTROL NET PRESENT COSTS				
Years	*P. stratiotes*	*S. molesta*	*A. filiculoides*	*M. aquaticum*
1985	R49,118.37	R12,181.36		
1986	R20,115.74	R13,155.86		
1987	R21,725.00	R14,208.33		
1988	R23,463.00	R15,345.00		
1989	R25,359.00	R16,585.00		
1990	R27,492.00	R27,492.00		
1991	R14,375.00	R29,625.00		R29,395.00
1992	R15,525.00	R31,995.00		R23,652.00

1993	R0.00	R34,602.00		R25,579.20
1994	R0.00	R37,446.00		R47,826.60
1995	R0.00	R40,290.00	R2,641.12	R33,575.00
1996	R0.00	R43,608.00	R50,164.29	R21,620.00
1997	R0.00	R47,163.00	R106,580.82	R13,930.00
1998	R0.00	R50,955.00	R15,856.25	R15,050.00
1999	R0.00	R54,984.00	R17,110.00	R16,240.00
2000	R0.00	R59,250.00	R18,437.50	R17,500.00
2001	R0.00	R63,990.00	R19,912.50	R18,900.00
2002	R0.00	R69,204.00	R21,535.00	R20,440.00
2003	R0.00	R25,830.00	R23,231.25	R22,050.00
2004	R0.00	R27,880.00	R25,075.00	R23,800.00
2005	R0.00	R30,176.00	R27,140.00	R25,760.00
2006	R104,188.68	R104,188.68	R29,278.75	R27,790.00
2007	R112,586.76	R112,586.76	R31,638.75	R30,030.00
2008	R121,509.72	R121,509.72	R34,146.25	R32,410.00
2009	R131,220.00	R131,220.00	R36,875.00	R0.00
2010	R141,717.60	R141,717.60	R39,825.00	R97,437.60
2011	R153,002.52	R153,002.52	R42,996.25	R105,196.52
2012	R165,337.20	R165,337.20	R46,462.50	R113,677.20
2013	R151,481.64	R178,721.64	R50,223.75	R122,879.64
2014	R163,493.40	R192,893.40	R54,206.25	R132,623.40
2015	R176,617.36	R208,377.36	R58,557.50	R143,269.36
2016	R190,631.08	R224,911.08	R63,203.75	R154,637.08
2017	R205,979.44	R243,019.44	R68,292.50	R167,087.44
2018	R222,440.00	R262,440.00	R73,750.00	R180,440.00
Total	R2,237,378.51	R2,985,890.95	R957,139.98	R1,662,796.04

Appendix 3: The estimated annual net present cost of the boat, bakkie and knapsack approach under the chemical control method – Scenario 1 at 8% discount rate

CHEMICAL CONTROL NET PRESENT COST												
Years	SCENARIO ONE											
	P. statoites			*S. molesta*			*A. filiculoides*			*M. aquaticum*		
	Boat	Bakkie	Knapsack	Boat	Bakkie	Knapsack	Boat	Bakkie	Knapsack	Boat	Bakkie	Knapsack
1985	R0.00	R0.00	R0.00	R0.00	R0.00	R0.00						
1986	R0.00	R0.00	R0.00	R0.00	R0.00	R0.00						
1987	R303.93	R545.32	R1,863.36	R0.00	R0.00	R0.00						
1988	R328.25	R588.94	R2,012.43	R0.00	R0.00	R0.00						
1989	R6,563.25	R11,775.86	R40,238.41	R0.00	R0.00	R0.00						
1990	R7,115.30	R12,766.36	R43,622.94	R0.00	R0.00	R0.00						
1991	R7,667.35	R13,756.85	R47,007.48	R0.00	R0.00	R0.00				R8,522.15	R15,290.55	R52,248.18
1992	R10,518.77	R18,872.91	R64,489.18	R0.00	R0.00	R0.00				R3,740.32	R6,710.93	R22,931.39
1993	R11,375.86	R20,410.70	R69,743.86	R0.00	R0.00	R0.00				R3,331.37	R5,977.19	R20,424.19
1994	R12,310.86	R22,088.30	R75,476.23	R0.00	R0.00	R0.00				R8,805.31	R15,798.60	R53,984.17
1995	R52,194.33	R93,647.71	R319,996.45	R4,632.54	R8,311.72	R28,401.40	R74,666.64	R133,967.28	R457,770.12	R15,640.68	R28,062.71	R95,890.92
1996	R166,702.24	R299,099.20	R1,022,029.06	R96,648.96	R173,408.09	R592,540.52	R85,580.90	R153,549.71	R524,683.85	R4,695,534.59	R8,424,787.72	R28,787,693.68
1997	R239,707.66	R430,086.42	R1,469,615.51	R54,346.49	R97,508.77	R333,190.33	R969,246.52	R1,739,027.29	R5,942,307.24	R10,087,213.65	R18,098,606.67	R61,843,355.89
1998	R304,888.58	R547,034.81	R1,869,230.94	R38,380.13	R68,861.84	R235,302.93	R1,232,190.51	R2,210,802.83	R7,554,378.06	R3,289,745.61	R5,902,503.31	R20,168,989.77
1999	R397,956.75	R714,018.87	R2,439,819.45	R27,918.89	R50,092.21	R171,166.56	R2,161,549.29	R3,878,263.31	R13,252,139.42	R1,072,295.96	R1,923,927.01	R6,574,102.92
2000	R428,832.71	R769,416.89	R2,629,115.79	R15,042.50	R26,989.34	R92,223.36	R1,164,627.85	R2,089,581.53	R7,140,161.32	R346,647.40	R621,959.16	R2,125,248.79
2001	R489,995.77	R879,156.39	R3,004,098.29	R38,364.48	R68,833.75	R235,206.95	R2,656,172.35	R4,765,718.66	R16,284,600.35	R357,647.32	R641,695.35	R2,192,687.80
2002	R609,068.27	R1,092,797.74	R3,734,115.85	R203,787.96	R365,637.45	R1,249,393.90	R1,436,300.60	R2,577,018.24	R8,805,746.86	R116,036.69	R208,194.49	R711,405.38
2003	R668,635.86	R1,199,674.63	R4,099,316.73	R109,919.88	R197,218.83	R673,902.53	R774,716.93	R1,390,001.28	R4,749,675.10	R37,552.97	R67,378.01	R230,232.22
2004	R721,702.20	R1,294,886.91	R4,424,659.33	R89,019.40	R159,719.08	R545,764.77	R418,735.31	R751,297.15	R2,567,204.37	R14,625.99	R26,242.14	R89,670.01
2005	R781,136.50	R1,401,524.65	R4,789,043.04	R48,175.20	R86,436.21	R295,355.05	R226,609.70	R406,584.34	R1,389,310.60	R4,749.15	R8,520.98	R29,116.38
2006	R842,693.45	R1,511,970.89	R5,166,440.45	R25,985.81	R46,623.88	R159,315.16	R122,233.76	R219,312.48	R749,397.16	R1,537.02	R2,757.74	R9,423.26

2007	R910,618.36	R1,633,842.60	R5,582,878.98	R14,040.19	R25,190.99	R86,078.34	R74,177.53	R133,089.71	R454,771.46	R56,380.68	R101,158.92	R345,662.38
2008	R1,179,822.19	R2,116,851.39	R7,233,331.51	R226,476.44	R406,345.24	R1,388,493.61	R6,831,540.18	R12,257,186.02	R41,883,163.89	R79,909.27	R143,374.23	R489,913.04
2009	R1,283,058.18	R2,302,078.67	R7,866,257.53	R122,287.49	R219,408.88	R749,726.57	R3,711,842.30	R6,659,807.35	R22,756,756.92	R25,888.53	R46,449.53	R158,719.13
2010	R2,336,778.93	R4,192,677.33	R14,326,478.06	R1,349,215.94	R2,420,770.47	R8,271,843.66	R3,834,217.00	R6,879,372.69	R23,507,018.14	R13,588,603.01	R24,380,843.88	R83,309,905.15
2011	R2,522,855.77	R4,526,538.67	R15,467,290.21	R728,326.75	R1,306,767.76	R4,465,263.75	R2,116,884.12	R3,798,124.83	R12,978,303.86	R4,401,197.53	R7,896,684.44	R26,983,152.61
2012	R2,726,242.09	R4,891,456.88	R16,714,224.41	R393,521.32	R706,058.05	R2,412,621.07	R1,143,771.01	R2,052,160.07	R7,012,291.11	R1,426,803.32	R2,559,988.61	R8,747,540.04
2013	R3,875,060.17	R6,952,680.33	R23,757,473.92	R2,256,155.77	R4,048,006.77	R13,832,157.78	R696,361.98	R1,249,416.39	R4,269,292.44	R17,115,970.99	R30,709,692.25	R104,935,725.81
2014	R4,182,333.66	R7,503,994.19	R25,641,326.48	R1,217,528.99	R2,184,497.05	R7,464,490.43	R385,309.50	R691,324.37	R2,362,275.63	R5,541,955.36	R9,943,446.61	R33,976,986.11
2015	R4,577,291.78	R8,212,632.87	R28,062,761.69	R657,631.31	R1,179,925.61	R4,031,840.41	R208,119.55	R373,409.22	R1,275,950.24	R1,796,045.94	R3,222,488.41	R11,011,317.13
2016	R4,940,477.40	R8,864,264.95	R30,289,403.99	R354,905.56	R636,773.46	R2,175,873.57	R150,143.65	R269,388.54	R920,508.54	R581,566.01	R1,043,453.11	R3,565,503.32
2017	R5,338,252.13	R9,577,957.23	R32,728,107.46	R191,740.11	R344,021.13	R1,175,530.30	R111,147.10	R199,420.72	R681,426.45	R188,516.96	R338,239.53	R1,155,772.25
2018	R5,764,851.11	R10,343,366.34	R35,343,528.57	R341,841.28	R613,333.45	R2,095,778.38	R63,226.64	R113,441.57	R387,633.16	R61,074.61	R109,580.84	R374,440.26
	R45,397,339.64	R81,452,461.82	R242,981,469.02	R8,605,893.39	R15,440,740.05	R52,761,461.33	R30,649,370.90	R54,877,823.99	R187,906,766.26	R64,927,538.39	R116,493,812.93	R398,062,042.15

Appendix 4: The estimated annual net present cost of the boat, bakkie and knapsack approach under the chemical control method – Scenario 2 at 8 % discount rate

SCENARIO TWO											
P. statoites			*S. molesta*			*A. filiculoides*			*M. aquaticum*		
Boat	Bakkie	Knapsack	Boat	Bakkie	Knapsack	Boat	Bakkie	Knapsack	Boat	Bakkie	Knapsack
R0.00	R0.00	R0.00	R0.00	R0.00	R0.00						
R0.00	R0.00	R0.00	R0.00	R0.00	R0.00						
R334.32	R599.85	R2,049.70	R0.00	R0.00	R0.00						
R361.07	R647.84	R2,213.67	R0.00	R0.00	R0.00						
R7,219.57	R12,953.47	R44,262.25	R0.00	R0.00	R0.00						
R7,826.83	R14,043.01	R47,985.25	R0.00	R0.00	R0.00						
R8,434.08	R15,132.56	R51,708.24	R0.00	R0.00	R0.00				R9,374.37	R16,819.61	R57,473.00
R11,570.65	R20,760.23	R70,938.12	R0.00	R0.00	R0.00				R4,114.35	R7,382.02	R25,224.53
R12,513.44	R22,451.81	R76,718.26	R0.00	R0.00	R0.00				R3,664.51	R6,574.91	R22,466.61

R13,541.94	R24,297.16	R83,023.87	R0.00	R0.00	R0.00				R9,685.84	R17,378.46	R59,382.59
R57,413.75	R103,012.63	R351,996.16	R5,095.79	R9,142.88	R31,241.56	R82,133.08	R147,363.79	R503,547.42	R17,204.75	R30,868.98	R105,480.01
R183,372.41	R329,009.58	R1,124,232.17	R106,313.84	R190,748.62	R651,794.94	R94,138.74	R168,904.43	R577,152.56	R5,165,088.05	R9,267,266.49	R31,666,463.05
R263,678.36	R473,095.72	R1,616,577.35	R59,781.13	R107,259.49	R366,509.58	R1,066,168.36	R1,912,927.22	R6,536,541.70	R11,095,935.01	R19,908,467.34	R68,027,691.48
R335,377.34	R601,739.14	R2,056,154.41	R42,218.14	R75,747.91	R258,833.37	R1,355,406.00	R2,431,879.54	R8,309,820.62	R3,618,720.18	R6,492,753.64	R22,185,888.74
R437,752.31	R785,421.86	R2,683,801.88	R30,710.77	R55,101.35	R188,283.33	R2,377,697.96	R4,266,083.39	R14,577,361.71	R1,179,525.56	R2,116,319.71	R7,231,513.21
R471,715.85	R846,359.77	R2,892,027.89	R16,546.75	R29,688.23	R101,445.76	R1,281,087.26	R2,298,536.31	R7,854,181.95	R381,312.14	R684,155.08	R2,337,773.67
R538,995.19	R967,073.39	R3,304,508.71	R42,200.92	R75,717.02	R258,727.79	R2,921,781.89	R5,242,282.84	R17,913,070.64	R393,412.05	R705,864.89	R2,411,956.58
R669,974.92	R1,202,079.21	R4,107,528.18	R224,166.72	R402,200.61	R1,374,334.07	R1,579,926.50	R2,834,715.90	R9,686,327.09	R127,640.35	R229,013.94	R782,545.91
R735,499.24	R1,319,643.95	R4,509,249.21	R120,911.84	R216,940.40	R741,293.21	R852,186.38	R1,528,999.16	R5,224,645.60	R41,308.27	R74,115.81	R253,255.44
R793,872.20	R1,424,377.60	R4,867,126.13	R97,921.32	R175,690.73	R600,341.59	R460,607.63	R826,425.65	R2,823,926.42	R16,088.59	R28,866.36	R98,637.01
R859,249.91	R1,541,679.28	R5,267,948.29	R52,992.71	R95,079.69	R324,890.74	R249,270.01	R447,242.11	R1,528,242.53	R5,224.06	R9,373.08	R32,028.02
R926,962.54	R1,663,170.31	R5,683,085.52	R28,584.38	R51,286.19	R175,246.77	R134,456.79	R241,243.37	R824,337.34	R1,690.72	R3,033.51	R10,365.59
R1,001,679.92	R1,797,229.38	R6,141,167.97	R15,444.21	R27,710.04	R94,686.23	R81,595.06	R146,398.47	R500,248.89	R62,018.74	R111,274.82	R380,228.61
R1,297,804.05	R2,328,539.80	R7,956,666.08	R249,124.04	R446,979.11	R1,527,343.84	R7,514,674.42	R13,482,884.84	R46,071,506.66	R87,900.20	R157,711.65	R538,904.34
R1,411,363.61	R2,532,290.10	R8,652,884.83	R134,516.22	R241,349.41	R824,699.70	R4,083,015.78	R7,325,777.34	R25,032,446.95	R28,477.39	R51,094.49	R174,591.04
R2,570,456.12	R4,611,951.55	R15,759,128.69	R1,484,137.27	R2,662,843.61	R9,099,033.23	R4,217,627.60	R7,567,298.86	R25,857,734.75	R14,947,463.31	R26,818,928.27	R91,640,895.67
R2,775,140.59	R4,979,199.54	R17,014,022.27	R801,159.29	R1,437,442.43	R4,911,792.94	R2,328,566.40	R4,177,931.18	R14,276,142.42	R4,841,317.28	R8,686,352.88	R29,681,467.88
R2,998,865.47	R5,380,610.14	R18,385,650.14	R432,873.37	R776,662.72	R2,653,884.69	R1,258,144.79	R2,257,372.76	R7,713,524.63	R1,569,483.65	R2,815,987.47	R9,622,294.05
R4,262,565.02	R7,647,959.12	R26,133,225.99	R2,481,770.91	R4,452,800.91	R15,215,382.27	R765,996.16	R1,374,356.02	R4,696,224.37	R18,827,568.09	R33,780,661.48	R115,429,298.39
R4,600,565.77	R8,254,405.22	R28,205,464.17	R1,339,281.66	R2,402,943.22	R8,210,944.18	R423,839.33	R760,455.69	R2,598,504.68	R6,096,150.90	R10,937,791.27	R37,374,684.72
R5,035,019.58	R9,033,908.86	R30,869,043.38	R723,394.31	R1,297,916.27	R4,435,026.99	R228,930.90	R410,749.54	R1,403,546.06	R1,975,650.54	R3,544,737.25	R12,112,448.84
R5,434,523.65	R9,750,705.16	R33,318,350.35	R390,396.05	R700,449.78	R2,393,462.30	R165,157.58	R296,326.96	R1,012,559.97	R639,722.61	R1,147,798.42	R3,922,053.65
R5,872,075.73	R10,535,767.77	R36,000,924.64	R210,914.08	R378,422.69	R1,293,084.07	R122,261.49	R219,362.47	R749,569.52	R207,368.66	R372,063.48	R1,271,349.48
R6,341,334.48	R11,377,718.97	R38,877,888.38	R376,025.34	R674,665.81	R2,305,357.54	R69,549.12	R124,785.54	R426,396.72	R67,182.07	R120,538.92	R411,884.28
R49,937,059.91	R89,597,833.97	R306,157,552.12	R9,466,481.07	R16,984,789.14	R58,037,640.68	R33,714,219.25	R60,490,303.37	R206,697,561.21	R71,420,292.23	R128,143,194.22	R437,868,246.37

Appendix 5: Estimated number of hectares cleared based on coordinate database received from SAPIA as at July 2019 – grouped per year.

YEAR	Estimated number of hectares cleared by annual grouping			
	P. stratiotes	S. molesta	M. aquaticum	A. filiquloides
1972			1	
1973				
1974				
1975			1	
1976			1.7	
1977				
1978			1	
1979				
1980				1
1981				
1982				
1983				
1984				
1985				
1986				
1987	0.2			
1988				
1989	3.5			
1990				
1991				1
1992	1		0.5	
1993			1	
1994			3.37	37.39
1995	13.82	2.63	5.19	3
1996	36.13	49.38	1757.34	42.77
1997	18.01	1.01	2966.66	447.63
1998	12.88	4.05	6.5	318.09
1999	17.93	3	2.18	622.65
2000				
2001	6	10.81	62.64	724.66
2002	16.35	60.5		
2003	2.22			
2004		8.43	0.5	0.18
2005				
2006				

2007			8.98	1.83
2008	25.67	45.63	9.18	1415.7
2009	1.08			4.46
2010	106.24	229.34	1733.69	327.04
2011				7.8
2012				
2013	82.21	18.32	1685.82	11.08
2014				1.25
2015	4.5			
2016				4.26
2017				3.13
2018		23		0.31
	347.74	456.1	8248.25	3975.23

Appendix 6: Exact of the site data received from SAPIA used to estimate the number of hectares cleared – using P. stratiotes sheet

SAPIATaxID	Record_number	Date	1/4 Deg Sq	Lat Degs	Lat Min	Lat Sec	Long Degs	Long Min	Long Sec	Dec Lat	Dec Long	Acc	Locality\Route	Notes
Pistia stratiotes L.	21828	1998-07-00	1535AA	15.00	0.00	0.00	35.00	14.00	0.00	-15.00	35.23	1 min	Liwonde	
Pistia stratiotes L.	6566	1995-01-00	2531AC	25.00	28.00	11.00	31.00	6.00	20.00	-25.47	31.11	1 min	Nelspruit Dist; near Karino; Crocodile River	None seen in July 1996 after floods (observation L Henderson)
Pistia stratiotes L.	6549	1995-01-00	2531AC	25.00	27.00	35.00	31.00	7.00	30.00	-25.46	31.13	1 min	Nelspruit Dist; near Tekwane Estate, dam site	None seen in July 1996; dam dry; wall broken by floods
Pistia stratiotes L.	5538	1995-01-00	2531BD	25.00	27.00	0.00	31.00	58.00	0.00	-25.45	31.97	1 min	Crocodile River (Malelane), Kruger Nat Park	
Pistia stratiotes L.	5541	1995-01-00	2531BD	25.00	20.00	0.00	31.00	54.00	0.00	-25.33	31.90	1 min	Crocodile Bridge, Kruger Nat Park	
Pistia stratiotes L.	5557	1995-01-00	2531BB	25.00	7.00	0.00	31.00	54.00	0.00	-25.12	31.90	1 min	Lower Sabie, Sabie River, Kruger Nat Park	
Pistia stratiotes L.	5527	1995-01-00	2431DD	24.00	47.00	0.00	31.00	51.00	0.00	-24.78	31.85	1 min	Tshokwane, Kruger Nat Park	
Pistia stratiotes L.	5556	1995-01-00	2431DD	24.00	47.00	0.00	31.00	54.00	0.00	-24.78	31.90	1 min	Orpen Dam, Kruger Nat Park	
Pistia stratiotes L.	7178	1996-08-00	2231AD	22.00	23.00	0.00	31.00	16.00	0.00	-22.38	31.27	1 min	Dakamila & Nhlangaluwe Pans, Limpopo R floodplain	In Kruger National Park
Pistia stratiotes L.	9466	1996-10-00	2531BB	25.00	6.00	0.00	31.00	54.00	0.00	-25.10	31.90	1 min	Sabie River at Lower Sabie, Kruger National Park	