Aquatic weeds: To control or not to control. The case of the Midmar Dam, KwaZulu-Natal, South Africa

T. Vundla*
ASSET Research, Pretoria. E-mail: thuli.vundla@gmail.com

J.N. Blignaut
Department of Economics, University of Pretoria, Pretoria; South African Environmental Observation Network, Pretoria. E-mail: jnblignaut@gmail.com

D.C. Crookes
ASSET Research, Pretoria; Department of Economics, University of Pretoria, Pretoria. E-mail: d_crookes@hotmail.com

* Corresponding author

Abstract

The Midmar Dam within the uMngeni Catchment, KwaZulu-Natal is important for water provisioning and recreational use. In 2014, an estimated 60 ha of the dam was infested with Egeria densa*, which can spread at a rate of 50% per annum under optimal conditions.* E. densa *limits access to, and the recreational use of, the dam. We use the travel cost method to estimate the recreational value of the Midmar Dam, informing the maximum desirable cost of control. The model estimates that the most likely extent of the invasion would be between 233 ha and 771 ha. The estimated cumulative NPV is R684 million for the best-case scenario, which allows for clearing operations and a spread rate of 15%. If no clearing is done, the cumulative NPV is reduced to an estimated -R20 million. This study therefore suggests that management of the problem is imperative, but that control efforts should not exceed R687.8 million over 30 years. Doing so will constitute a net loss to society.*

Key words: aquatic weed; *Egeria densa*; Midmar Dam; opportunity costs; travel cost method

1. Introduction

The role of indigenous vegetation in a natural environment is important, as indigenous vegetation enhances ecosystem functioning and the provisioning of ecosystem goods and services (Rodriguez 2006; Pejchar & Mooney 2009). The spread of invasive alien plants (IAPs), however, can limit the functioning of ecosystems (Pejchar & Mooney 2009; Vilà *et al*. 2011). In South Africa, aquatic weeds frequently invade freshwater systems, forming dense monocultures that outcompete and replace indigenous vegetation, thus reducing indigenous species and altering ecosystem functioning (Bunn & Arthington 2002; Strayer 2010; Chamier *et al*. 2012). Aquatic weeds flourish in eutrophic waters and alter the pH, dissolved oxygen and sediment load, as well as various other chemical properties of the water (D'Antonio & Vitousek 1992; Gordon 1998). In dense infestations, feeding by certain predatory fish is hampered, leading to the growth of insectivores and altering community structure and biodiversity (Dibble *et al*. 1997). This has significant impacts on the provisioning of recreational services derived from the freshwater ecosystem (Dibble *et al*. 1997; Gordon 1998; Schultz & Dibble 2012).

South Africa has several aquatic weeds that have invaded and became established in their environment of introduction. Some of the more successful aquatic invaders include water hyacinth

(*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), Kariba weed (*Salvinia molesta*) and parrot's feather (*Myriophyllum aquaticum*) (Van Wilgen *et al*. 2001). Their competitive advantage, as a result of having no natural predators, and the high nutrient load of the water are the main drivers for the successful invasion by these species. The most devastating aquatic species invading South African waters are emergent or floating (Van Wilgen *et al*. 2001; Hill 2003). There are, however, submerged aquatic invasive alien plants, such as *Hydrilla verticillata* and *Egeria densa*, which are invading fresh water in South Africa. The latter is a prominent invader in the Midmar Dam. The Midmar Dam is the main water source in the uMngeni catchment, which serves the uMgungundlovu District Municipality and eThekwini Metropolitan Municipality. In addition to its value as a source of water, the Midmar Dam is a major tourist attraction, attracting many local and, to a lesser extent, international visitors.

E. densa is a submerged macrophyte IAP, originating from South America, and it currently invades certain parts of the Midmar Dam (Darrin 2009; Coetzee *et al*. 2011). It is globally distributed as an aquarium species and, as a result, it has been introduced into many parts of the world and has become an aquatic IAP. The introduction of *E. densa* into the Midmar system is believed to be mainly through the discarding of aquarium waste into the local river system (Coetzee *et al*. 2011). Even though this species has officially been identified as an IAP in South Africa, making it illegal to discard into the natural environment, it is still being sold in pet shops nationally (Coetzee *et al*. 2011; Martin & Coetzee 2011). The advanced reproductive ecology of *E. densa* allows it to spread sexually and asexually. Its most common mode of spreading is asexually, especially in South Africa, where only female plants have been recorded (Henderson & Cilliers 2002). Through vegetative spread, fragments of *E. densa* have successfully invaded freshwater ecosystems (Coetzee *et al*. 2011). As a submerged species, its invasion is limited by access to light, and hence water depth. It therefore concentrates in shallow waters.

The impacts of *E. densa* on ecosystem functioning are not minimal. Dense stands can have disastrous effects on ecosystem functioning (Michelan *et al*. 2010). The aquatic invader displaces native plants, limits photosynthesis and accelerates the depositing of silt (Michelan *et al*. 2010), and the siltation results in limits to water storage capacity (Patterson *et al*. 1996). Table 1 outlines the negative impacts of *E. densa* invasion, and contrasts these with the benefits, or uses, thereof. The negative impacts of aquatic weeds are not well researched in South Africa and research is mostly based on undocumented observations, with only a few systematic studies currently available (Van Wyk & Van Wilgen 2002; Richardson & Van Wilgen 2004; Coetzee *et al*. 2014).

Table 1: The effects and benefits of *E. densa* on freshwater systems

Impacts/costs	**Uses/benefits**
Increases sedimentation	Aquarium trade market
Reduces dam capacity through sedimentation	Increases oxygen in water
Shades phytoplankton from sunlight	
Limits recreation (swimming and boating)	
Increases flood risk	
Restricts water movement	
Traps sediment	
Causes fluctuations in water quality	

The main economic concern with *E. densa* in the Midmar Dam is the limits on both the recreational benefit derived from the dam and the value of water lost as a result of invasion. There are several techniques available for the estimation of the costs and benefits of invasive aquatic weeds. Specifically, the estimation of avoided costs, control costs and recreational benefits are some of the techniques. The estimation of recreational benefits has been described by Rockwell (2003) as being the most commonly applied method for the estimated benefits of invasive aquatic weed control. Horsch and Lewis (2009) applied a different methodology in quantifying the economic impacts of invasive aquatic weeds. Their study applied a hedonic approach to quantify changes in property values. The study concluded that, following invasion, property values decreased by 13%. The role of recreation was identified as crucial in attracting home buyers, thus the loss in recreational benefits drove the decrease in property values.

Many studies have made use of the travel cost method to estimate the economics of recreational activities (Garrod & Willis 1999; Rolfe & Prayaga 2007). The travel cost method is described as the oldest and simplest approach for the estimation of services associated with freshwater systems (Wilson & Carpenter 1999). There are a limited number of studies in developing countries that have investigated the recreational value of the environment, and even fewer in freshwater systems. However, there are an oversaturation of such studies in developed countries (e.g. Shivlani *et al*. 2003; Loomis 1996; 2006). Uehara *et al*. (2016), Costanza and Ruth (1998) and Costanza *et al*. (1993) vouch for the application of systems dynamics in modelling ecological processes. However, not a lot of literature has applied this technique with systems dynamic modelling. In South Africa, Van Wyk and Van Wilgen (2002) estimated the cost of controlling water hyacinth. Their study, however, focused primarily on quantifying the financial costs, thus there is a need to build further upon such research. This study therefore aims, through the estimation of the recreational value of the Midmar Dam, to i) quantify the opportunity costs of not managing *E. densa* in the Midmar Dam, and ii) determine the maximum desirable costs of controlling IAPs, after which control efforts will incur a societal loss. The travel cost method (TCM) was used to determine the recreational value of the Midmar Dam. The TCM is mainly used to estimate the costs associated with the recreational use of nature reserves, national parks and so on. This method uses travel time, together with the entry cost, to estimate how much a person pays for the recreational use of the area as a proxy for the area's recreational value. A systems dynamics approach was then utilised to examine the dynamics of the cost and benefits of controlling invasive aquatic weeds over time. Systems modelling has been proven to be an invaluable tool in ecosystem studies and the valuation of ecosystems (Costanza & Ruth 1998; Ford 1999). Systems dynamics is able to illustrate long-term trends and interaction, especially when long-term experiments are not feasible (Evans *et al*. 2012) This has led to increased applications of systems modelling to illustrate ecological and economic interactions (Costanza & Voinov 2001; Costanza *et al*. 1993). This study uses a simple dynamic model to assess the impact of invasion on tourism and presents a framework model for assessing the impacts of aquatic weeds in recreational fresh waters.

2. Methodology

2.1 Midmar Dam's physical environment

This study was conducted on the Midmar Dam, a major dam within the uMngeni catchment located in the uMngeni local municipality in the KwaZulu-Natal (KZN) province of South Africa. The dam is a major source of water for KZN (providing water to almost half the province's population), and also provides recreational benefits to the local population. The importance of the Midmar Dam is related to serving communities in both the uMsuduzi local municipality and the eThekwini Metropolitan Municipality, which are the capital city and the economic hub of KZN respectively. The uMngeni local municipality considers the dam to be of high touristic value, but with more potential than what is currently realised. The adjacent land use includes commercial agriculture and human settlement (the Mpophomeni township and the town of Howick). The areas surrounding the dam are part of a provincially proclaimed nature reserve that supports various game and plant species. The dam is approximately 35 km from Pietermaritzburg, and spans an area of 2 857 ha, including the nature reserve. The surface area of the dam only is 1 880 ha.

The climate in the area is characterised by warm, wet summers and cool, dry winters, with a mean rainfall of 992 mm per annum. The dam is within a grassland ecozone, part of which is in a mist belt, which is a critically endangered grassland type in South Africa. The areas therefore is of high biodiversity and conservation importance. The geology of the area is characterised by weathered dolerite that is overlain by Ecca shales (EKZNW 2009).

The dam is of high recreational benefit to local and international visitors. Some of the recreational benefits of the Midmar Dam include camping, overnight stays, day visits, tennis, birding and boating, as well as the famous Midmar Mile swimming race (http://www.midmarmile.co.za/) (EKZNW 2009).

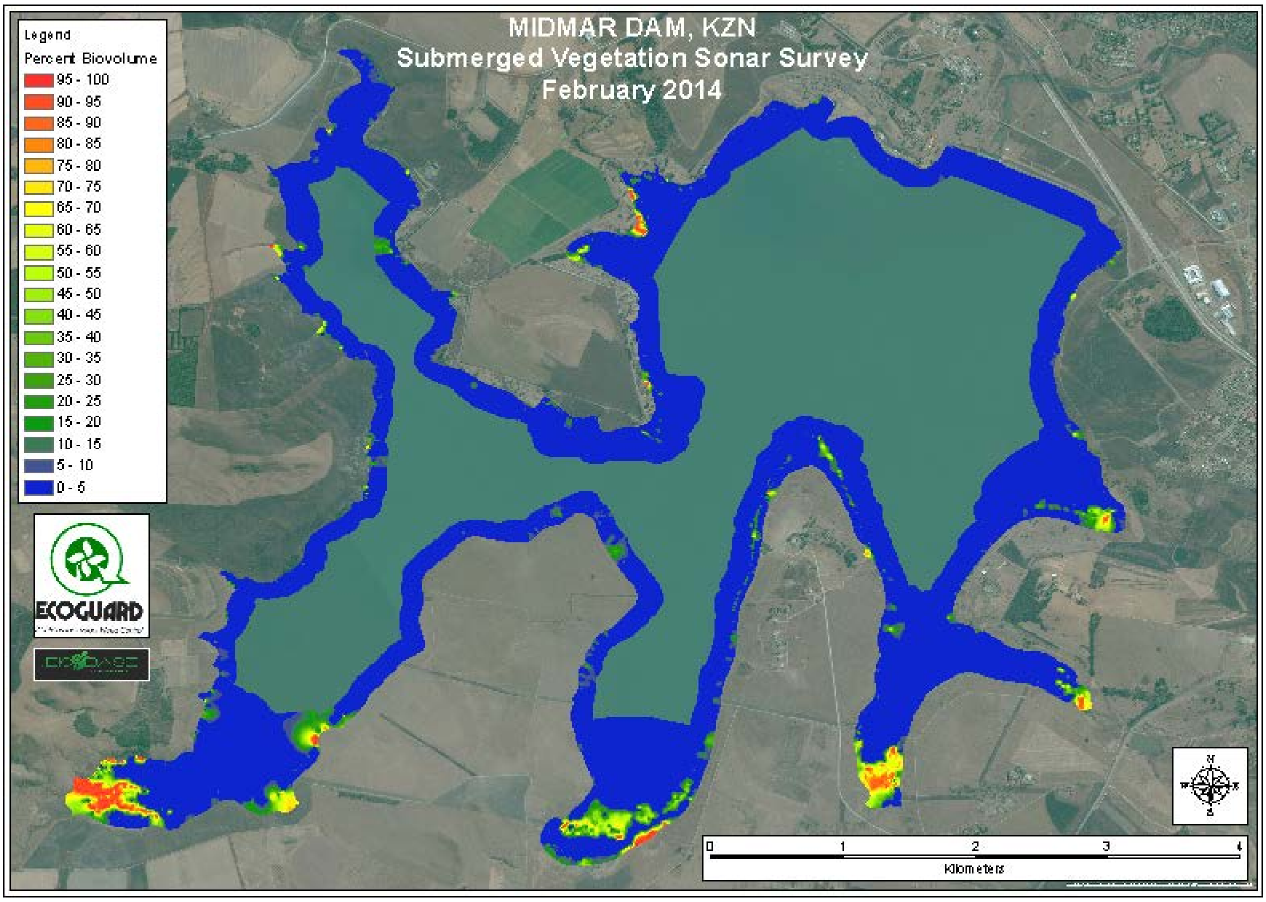

Figure 1: Areas invaded by *E. densa* within the Midmar Dam
Source: Department of Environmental Affairs ([DEA: NRM] 2016)

Figure 1 shows the extent of invasion within the study area. Areas most affected by *E. densa* are brightly highlighted in Figure 1. There are clear *E. densa* hotspots that are attributed to various attributes of that specific site, including, but not limited to, the presence of slipways and sewage spills. The deep parts of the dam, indicated in the image in dark green, are not susceptible to invasion.

2.2 Data

Data for this study was sourced from both primary and secondary sources, including site visits (meetings with the Department of Environmental Affairs (DEA) site project managers), telephonic interviews, meetings with experts, an extensive desktop analysis, Statistics South Africa, the database of the Natural Resource Management programme of the DEA (DEA: NRM), municipal documents and municipal websites. The data collected is discussed in the following sections, in conjunction with a description of the model.

2.3 System dynamics modelling

To quantify the benefits of controlling *E. densa* in the Midmar Dam, a system dynamics model was developed using Vensim® software (Ventana Systems 2007). Vensim® is modelling software that allows for non-linear simulation. Through causal loops and stock and flow diagrams, Vensim® allows for the conceptualisation and simulation of the model for analysis. Various validation tests (see sections below) were used to test the stability and enhance the confidence of the constructed model.

The model was developed and run for a period of 30 years, that is from 2014 to 2044. The developed model consisted of four sub-models, namely a land use sub-model, a recreational value sub-model, a water value sub-model and an economic sub-model. The stock and flow diagrams form the building blocks of the developed system dynamics model. The stocks in this model are denoted by rectangular boxes. The value of the stock variable is affected by the flow variable, denoted with an arrow in the land-use model (Figure 2), and the nature of this relationship is determined by the underlying equation used.

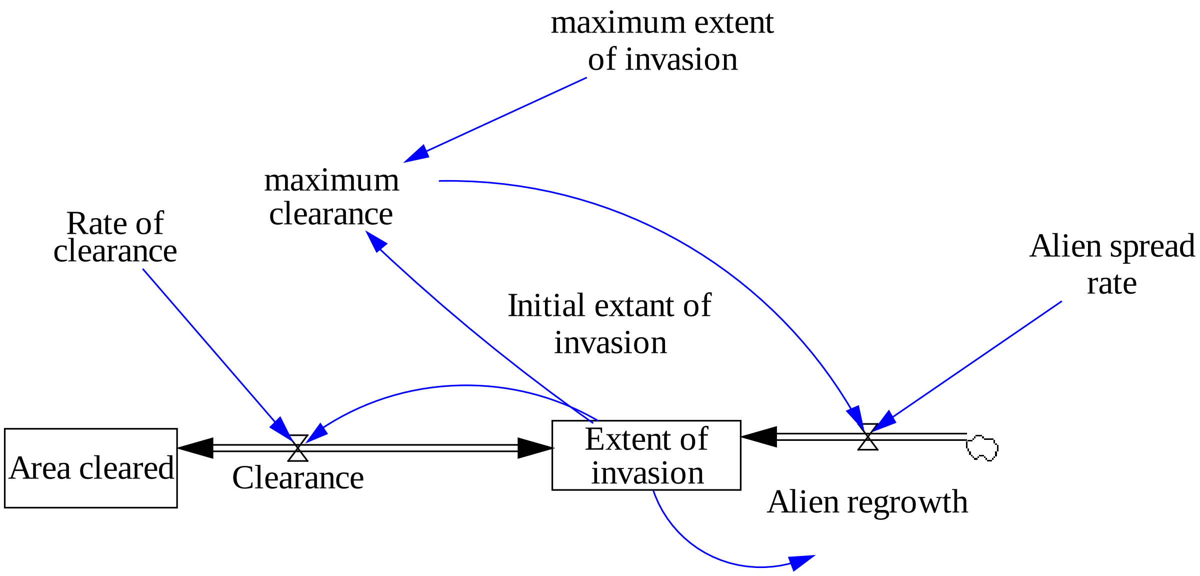

Figure 2: Land-use sub-model

The extent of invasion and the spread of *E. densa* within the Midmar Dam are outlined in the land-use sub-model (Figure 2). The two variables that affect the stock of *E. densa* are clearance and alien regrowth. Currently, there are no ongoing control activities, and therefore the stock is not controlled. However, we made provision for this in the model and base the rate of clearance on the current rate of clearance of *Eichhornia crassipes* (water hyacinth) over a period of 10 years (derived from data reported in Appendix A). The use of the long-term clearance rate of *E. crassipes* allows for an estimate of the rate of clearance of aquatic weed. The formulas applied for this land-use sub-model are outlined in Appendix B, and selected variables used in the model are found in Table 2. Values that are one-dimensional, i.e. have no units, are denoted as dmnl (dimensionless).

Table 2: Variables used in the land-use sub-model

Variable	Value	Units	Data source
Initial extent of invasion	56.58	ha	DEA: NRM (2016)
IAP spread rate: Low*	15	dmnl	Wells & Clayton (1991)
IAP spread rate: High*	50	dmnl	Wells & Clayton (1991)
Maximum invasion	925	ha	DEA: NRM (2016)

*Scenarios used in the model

Reduction in dam capacity is one of the negative impacts of aquatic weed invasion. There is, however, very little research on this topic at present. The maximum reduction in invasion was assumed to be 2%, based on the estimated impact of *Egeria* in other water bodies (Getsinger 1982). Furthermore, the proportion of water lost was assumed to be at a maximum of 1%. The water lost sub-model (see Figure 3) quantifies the value of the water lost due to invasion. The amount of water lost, coupled with the price of water, is used to estimate the value of water lost as a result of the invasion. The equations to estimate the various variables are outlined in Appendix B, while Table 3 shows the exogenous variables used in the sub-model.

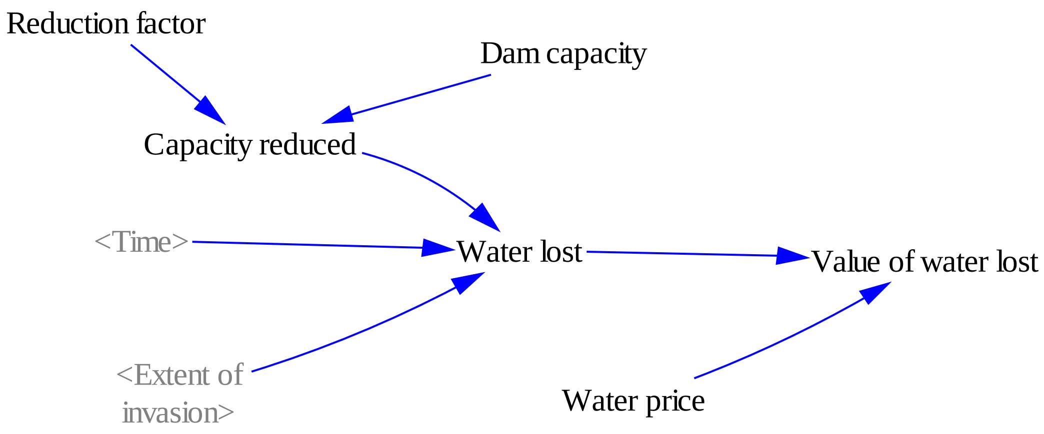

Figure 3: Sub-model of value of water lost

Table 3: Variables used in the sub-model of value of water lost

Variable	Value	Units	Data source
Reduction factor	0.01	dmnl/year	Based on McCully (1996)
Price of water	2	R/m^3	Department of Water Affairs ([DWA] 2016)
Dam capacity	235 400 000 000	m^3/ha	Umgeni Water (2016)

A major benefit or use of the Midmar Dam is the recreational use derived from it. To estimate this value (TC), a travel cost method was used, based on Equation 1 below.

TC = (round trip distance x transport costs) + (round trip distance x value of visitors' time/average speed) + (entrance fee x number of visitors) (1)

There are both day and overnight visitors (with the overnight visitors depicted by the preface ON in Figure 4) to the Midmar Dam. Since Ezemvelo KZN Wildlife does not currently collect information on the origin of the visitors, the model assumes that day visitors are from the uMgungundlovu District Municipality (UDM) only, and as such the municipality has been stratified into three zones of distances for the purpose of this study. This is based on the time it takes to get to the Midmar Dam and the time spent there. Also, it is assumed that overnight visitors are from KZN only, since the Midmar Dam is not a national destination, with the exception of the Midmar Mile event. This is an assumption made in the model as a result of the lack of quantitative data detailing the origin of the visitors. In addition, the number of international visitors was assumed to be insignificant, at less than 1% (EKZNW 2016). The uMgungundlovu municipality was divided into three distance-based zones and KwaZulu-Natal into four distance-based zones (see Figure 5, which was developed using GIS ArcMap 10.3), and the TC formula (Equation 1) was then applied. This approach is conservative, given the exclusion of national and international visitors as both day and overnight visitors. Total population and household income statistics were used to determine the population densities, thus proportioning the number of visitors according to population densities. This was done for the analyses of both the overnight (provincial) and day (district) visitors (Table 4). The asymmetric pattern observed with respect to value is due to the asymmetric levels of income distribution of populations relative to distance from the dam.

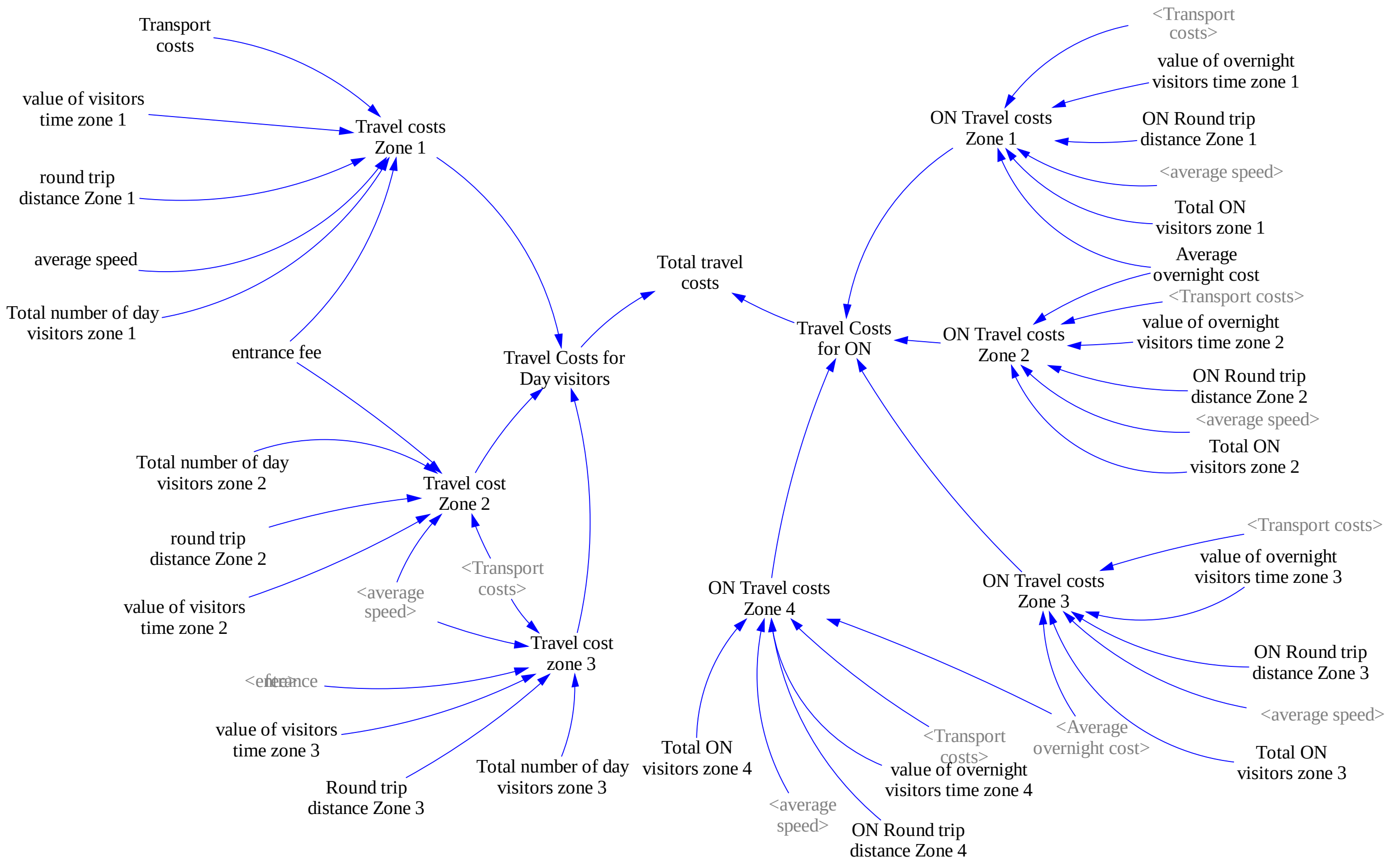

Figure 4: Recreational value of the Midmar Dam (ON = overnight)

To estimate the travel costs, the travel cost sub-model was constructed (Figure 4). The sub-model formulas are provided in Appendix B, and selected variables used in this sub-model are shown in Table 4. For NPV, this study applied a discount rate of 6%. This is based on a suite of discount values currently applied by government.

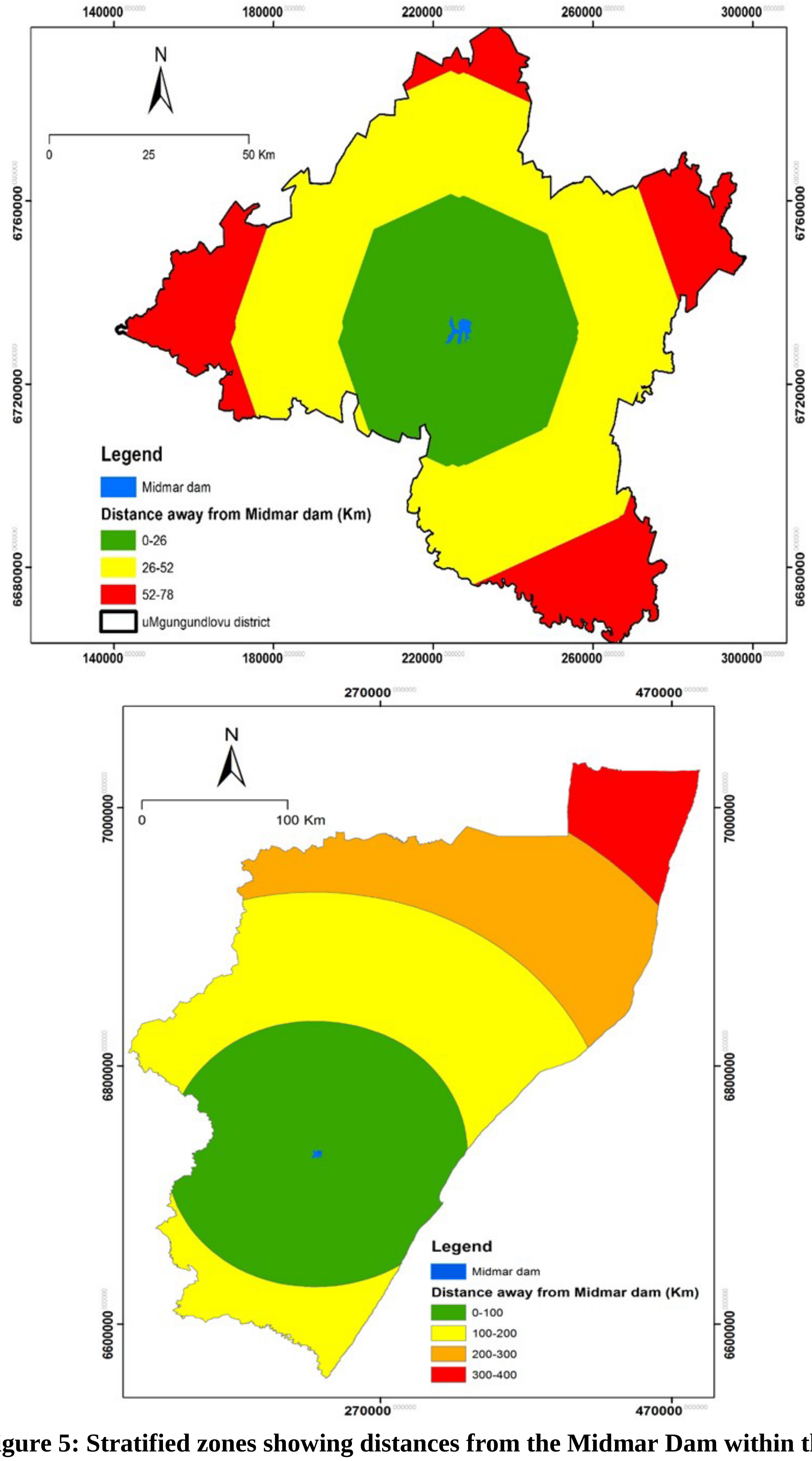

Figure 5: Stratified zones showing distances from the Midmar Dam within the uMgungundlovu District Municipality (UDM) (top) and KwaZulu-Natal (bottom)

Table 4: Variables used in the travel costs method

Variable	Value	Units	Data source
Transport costs	4.24	R/km	Automobile Association ([AA] 2016); based on generic 1.6 l car
Round trip distance	Based on Table 5 below	Km	
# of day visits	89 836	Person	EKZNW (2016)
Value of visitors time zone 1	59	R/hr	Statistics South Africa ([Stats SA] 2012)
Value of visitors time zone 2	26	R/hr	Stats SA (2012)
Value of visitors time zone 3	26	R/hr	Stats SA (2012)
Value of overnight visitors time zone 1	54	R/hr	Stats SA (2012)
Value of overnight visitors time zone 2	28	R/hr	Stats SA (2012)
Value of overnight visitors time zone 3	35	R/hr	Stats SA (2012)
Value of overnight visitors time zone 4	25	R/hr	Stats SA (2012)
Entrance fee	20	R/person	EKZNW (2016)
Average speed	80	Km/hr	Assumption based on observations

Table 5: Zones used for provincial and district analyses of the travel costs

Distance from Midmar (km)				
	Zone 1	**Zone 2**	**Zone 3**	**Zone 4**
UDM	0-26	26-52	52-78	
KZN	0-100	100-200	200-300	300-400

There are many generalisations that are implied in system dynamics modelling. Swanson (2002) and Sterman (2002) strongly emphasise that models are simplistic versions of the real world. However, confidence in the model can be increase through a string of validation tests. Sterman (2010) describes the importance of model validation and emphasises that no model can be fully validated. The confidence in the model, however, improves when the model passes through a string of validation tests. Balci (1994) further stresses the importance of model validation and verification, particularly in the case of large-scale simulation. In this study, the model accuracy was tested through the structural validity test. Structural validity seeks to verify the internal structure of the model, based on real-world scenarios and knowledge of the system (Barlas 1996). This study applied four validity tests to improve the accuracy of and confidence in the model simulation. These were the structural, dimensional consistency, parameter verification and the extreme condition tests. Structural verification was tested using the developed causal loop diagram. Since the causal loop diagrams are based on the available literature, and they informed the model, the application of the causal loops diagram is a form of validation test (Zebda 2002). In addition, testing for model structural validity was conducted by comparing the model equations with real-world scenarios. Based on the literature and the units of measurement, the model was found to be dimensionally consistent. The scaling factors furthermore are realistic based on the literature and expert interviews. The model parameters were verified through the parameter verification test. This test assesses the consistency of the parameters to real-life scenarios. For this study, the model parameters are based on data from DEA: NRM and a well-documented literature base. In the tables in Section 2.3, the model parameters used for the model and their sources are set out.

The final validity test was the extreme condition test, which tests whether the model simulates outputs that would follow real-world cases and are logical. This study ran an extreme condition test. Since the outputs demonstrated logical behaviour, the model passed this test. The output of this test is seen in Figure 6 below.

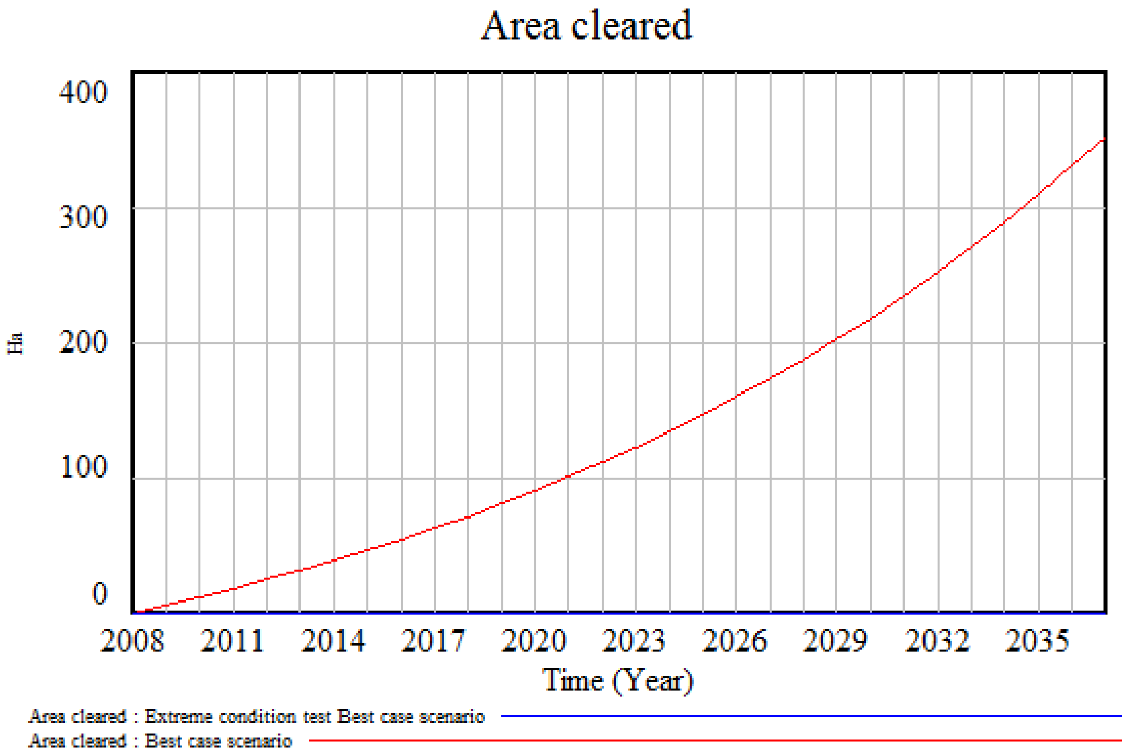

Figure 6: Results of extreme condition test

2.4 Model scenarios

We considered the four scenarios described in Table 6. These scenarios are based on the rate of clearance (either 0% (based on current control efforts for *E. densa*) or 10% (as derived in Annexure B)) and the spread rates of *E. densa* (either 15% or 50%).

Table 6: Model scenarios used to estimate the desirable costs of control of *E. densa*

Scenario name	Variables	Description
Do nothing 15%	0% clearance and 15% spread rates	No clearing and 15% p.a. spread rate
Do nothing 50%	0% clearance and 50% spread rates	No clearing and 50% p.a. spread rate
Clearing 15%	10% clearance and 15% spread rates	Clearing of 10% of invasion and spread rate at 15% p.a.
Clearing 50%	10% clearance and 50% spread rates	Clearing of 10% of invasion and spread rate at 50% p.a.

3. Results

Table 7 presents a summary of the main findings of this study. The extent of invasion is highest for the “do nothing” scenario, at both the 15% and 50% spread rates, reaching 877 ha and 925 ha respectively. In contrast, the lowest extent of invasion is 233 ha under the clearing scenario with 15% spread rate. The mean economic value of the Midmar Dam, which is a function of the travel cost and the value of water lost, is also the highest for this scenario, while it is the lowest for the “do nothing” with 50% spread rate scenario. The simulation model outputs are depicted in Figures 7 and 8, showing the temporal variations in the estimated values.

Table 7: Summary of the findings from the model

Variable	Units	Do nothing 15% 0% clearance and 15% spread rates	Do nothing 50% 0% clearance and 50% spread rates	Clearing 15% 10% clearance and 15% spread rates	Clearing 50% 10% clearance and 50% spread rates
Area cleared	ha	-	-	1 801.73	352.622
Extent of invasion	ha	877.176	925	232.891	770.833
Mean economic value	Rand/year	48 481 77.33	48 844 778.67	50 317 319.6	49 547 842.8
Cumulative NPV	Rand	678 031 616	667 887 040	684 636 736	671 548 096

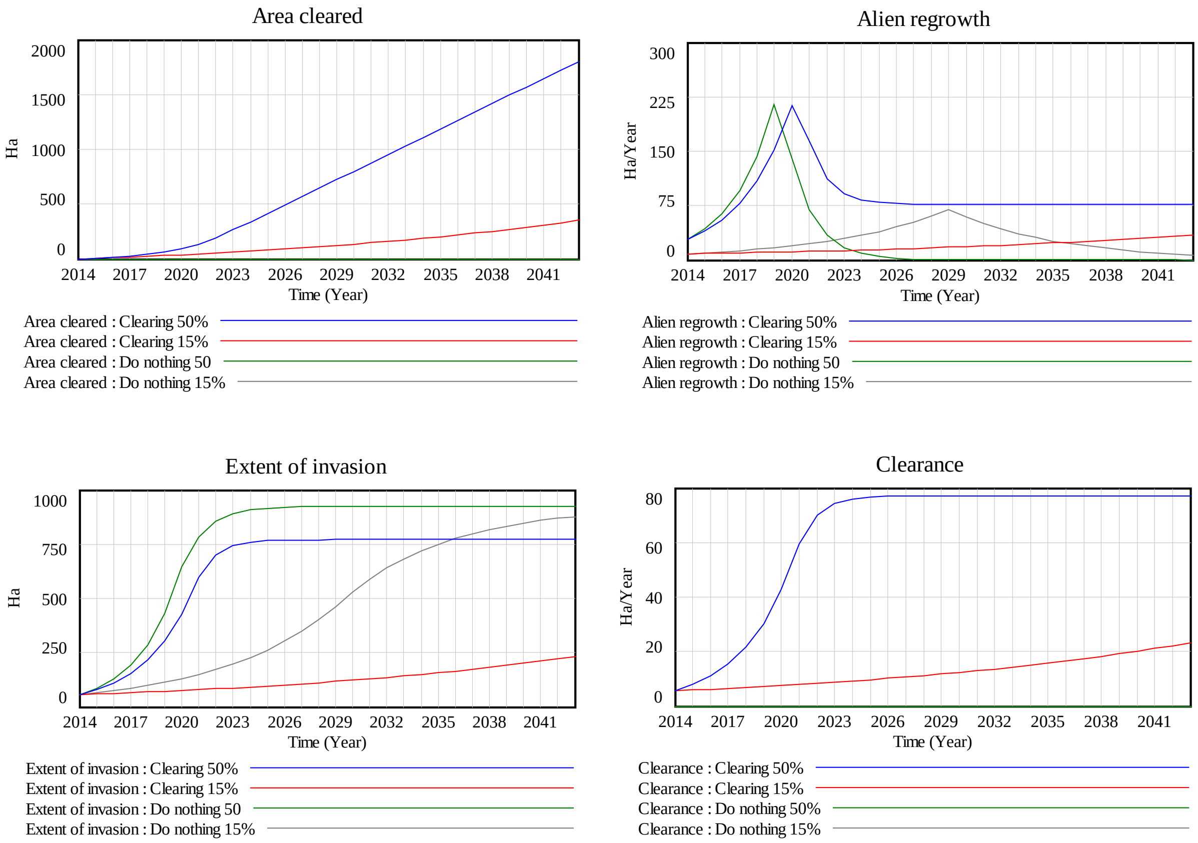

Figure 7: Model simulations of the area cleared (top left), alien regrowth (top right), extent of invasion (bottom left) and the annual clearance (bottom right) in the Midmar Dam

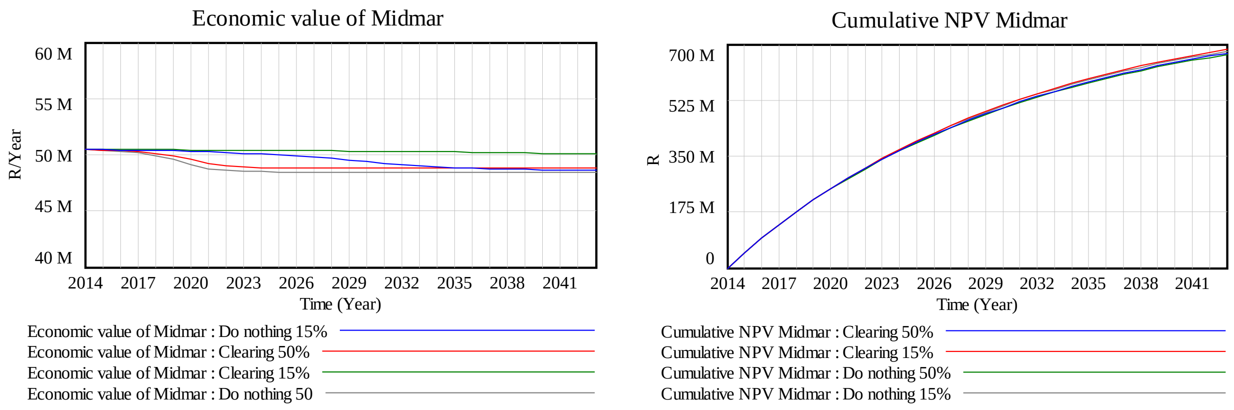

Figure 8: The total economic value per annum (left) and cumulative NPV (right) of the Midmar Dam

3.1 The "do nothing" scenario

The regrowth of *E. densa*, coupled with the spread rates, is the driver of the extent of invasion that is presented in Figure 7. Initially, a linear relationship is seen for the "do nothing" scenario, which reaches an asymptotic trend as the extent of invasion reaches its limit of 925 ha. Figure 8 presents the economic analysis of the dam, with the total economic value (TEV) and the cumulative NPV respectively. The mean economic value of the dam is lowest for the "do nothing" and 50% spread rate scenario, which is indicative of the water that is lost from the dam. For both the 15% and 50% spread rates, the general trend for the TEV declines slightly over time. This assumes that the recreational value of the dam has not been compromised by the extent of invasion.

3.2 The 15% clearing scenario

Under this scenario, we assumed a control effort that amounts to 10% of the invaded area per year. The results of the model simulation estimate that the hectares invaded for the scenario that assumes a 15% spread rate, in conjunction with the control effort, are much reduced compared to the "do nothing" scenario, at 233 ha (Figure 7). This mirrors the lower extent of invasion and reduced regrowth of *E. densa*. This scenario does not have a spike in regrowth, as seen with all the other scenarios. The mean annual regrowth is estimated at 18.8 ha/year over the 30-year period. The model clearance, which is in ha/year, was also run for a 30-year period and the model simulated it to be a mean of 12.53 ha/year for this scenario.

3.3 The 50% clearing scenario

As with the previous scenario, here we assumed a control effort that amounts to 10% of the invaded area per year, but at a higher spread rate of 50% per annum. This naturally translates into higher extents of invasion and hence area cleared (Figure 7). Mean annual regrowth increases rapidly during the first few years, with a rapid drop in 2020 as clearance operations commence. The annual regrowth drops until it stabilises at approximately 750 ha/year. The extent of invasion of *E. densa* is still lower when compared to the "do nothing" scenario. In this scenario, clearance begins to stabilise at 77 ha/year, which is higher than the initial extent of invasion. The total economic value initially is R50 million per year, but this drops steadily. The mean economic value over the 30-year period is R49 million per year (Figure 8).

3.4 The opportunity cost of not controlling *E. densa* in the Midmar Dam

The aforementioned results show that the "do nothing" with 50% spread scenario yields the lowest economic returns, and thus would likely have the highest detrimental impacts on the recreation values. The TEV and cumulative NPV were re-estimated with changes in the recreation value according to the effects of invasion. Table 8 describes the second set of scenarios for modelling TEV and cumulative NPV for 30 years, inclusive of the impacts on recreation.

Table 8: Scenario investigating the economic value lost as a result of reduction in recreation in the Midmar Dam

Scenario name	Description
Clearing 15%	Clearing interventions of 10% of invasion and spread rate at 15%, with total recreation value realised
Do nothing 50% - 100%	Do nothing at 50% spread rate, with recreation completely lost
Do nothing 50% - 90%	Do nothing at 50% spread rate, with 90% of recreation lost
Do nothing 50% - 10%	Do nothing at 50% spread rate, with 10% of recreation lost

The model simulations show than even a 10% drop in the recreation value of the Midmar Dam would have significant impacts on both TEV and cumulative NPV (Figures 9(left) and 9(right)). The mean economic value of the Midmar Dam is estimated at R44 million per year (10% drop) and R3.3 million per year (90% drop), with a negative value estimated should the economic value of recreation in the Midmar Dam be lost completely (-R1.8 million) and no clearance takes place. The model derived cumulative NPV at R599.1 million, R48.9 million and -R19.9 million for the 10%, 90% and 100% drop in recreational value respectively. This translates into the opportunity costs of not clearing the Midmar Dam being R68.7 million, R619 million and R687.8 million at 10%, 90% and 100% loss of recreational value respectively.

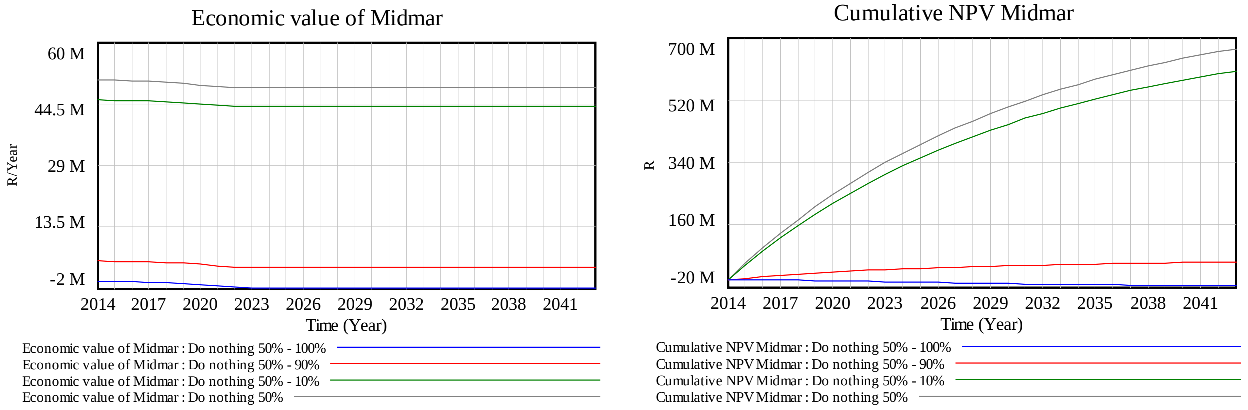

Figure 9: Economic implications of reduction in recreational value of the Midmar Dam

4. Discussion and conclusions

The findings of this study show that, with no interventions, the Midmar Dam becomes infested with *E. densa* to the maximum level within 30 years. Since this species primarily infests shallow waters, it has severe consequences for recreational use as it impedes access to the dam. It is for this reason that we placed great emphasis on the recreational benefit derived from the Midmar Dam. The model further indicates the benefits of clearing, specifically for the scenario that assumes a 10% control effort and a 15% spread rate (or best-case scenario), where the regrowth is moderate and the extent of invasion is significantly reduced. Thus clearing initiatives would control invasion, even at high spread rates.

The economic loss due to invasion, even with the recreation value remaining constant, is significant. This is shown in the "do nothing" scenario, in which there are no clearing interventions and there is a drop in the cumulative NPV. To further investigate the implication of the "do nothing" scenario, the model was run with the "do nothing" scenario at 50% spread rates and by changing the impact of invasion on recreation, reducing the economic returns from recreation by 10%, 90% and 100%. The findings of this study show that, should the recreational value of the Midmar Dam be compromised, the economic implication of this would be significant. The worst case scenario is a complete loss of the recreation value of the Midmar Dam, which would amount to a loss of R687.8 million.

Future planning and operations should heed the fact that this study suggests that the desirable costs of clearing the Midmar Dam should be no more than R687.8 million over a period of 30 years. Any amount spent on reducing *E. densa* that is less than that while maintaining the economic benefits is likely to lead to a net social gain. Therefore, the benefits of clearing earlier rather than later have the potential to maintain the dam for recreational and water-provisioning purposes. Systems dynamic modelling has been able to successfully demonstrate the recreational benefits of clearing aquatic weeds. There is also a need for further research, including using other variables such as extreme climatic events, which are crucial in the spread of aquatic weeds and thus in their control. The study furthermore has demonstrated the application of system modelling to inform decision making.

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Appendix A: Clearance data for aquatic weeds

Year	**Area cleared per contract for various years: *Eichhornia crassipes* (ha)**
2003	19 727.6
2003	3 432.32
2004	67.7
2004	5 206.64
2004	17 419.8
2004	99.72
2005	1 246.56
2006	634.38
2006	27.67
2007	34
2007	32.65
2007	51.25
2008	37.15
2009	230.26
2009	161.42
2010	45.44
2010	45.22
2011	32.46
2011	57.24
2011	31.75
2011	35.34
2011	94.17
2011	34.45
2011	50.69
2011	61.24
2011	39.72
2011	73.55
2011	162.69
2011	19.56
2011	91.01
2012	64.37
2012	41.1
2012	19.94
2012	48.41
2012	88.38
2012	42.19
2012	57.89
2012	30.76
2012	47.01
2012	17.66
2012	6.46
Grand total	49 747.82
Rate of clearance (ha/year)	5 527.54
Percentage clearance (Dmnl)	11.11

Appendix B: Model equations

Description	Formula/value	Unit
Clearance	Extent of invasion*Rate of clearance	Ha/year
Maximum clearance	MAX(maximum extent of invasion-Extent of invasion, 0)	Ha
Alien regrowth	MIN(Extent of invasion*Alien spread rate, maximum clearance* Alien spread rate)	Ha/year
Area cleared	Clearance	Ha
Extent of invasion	Alien regrowth-Clearance	Ha
Capacity reduced	Reduction factor*Dam capacity	m^3/ha
Water lost	XIDZ(Capacity reduced*Extent of invasion, Time, 0)	m^3/year
Value of water lost	Water price*Water lost	R/year
Travel costs Zone 1	((round trip distance Zone 1*Transport costs+Round trip distance Zone 1*value of visitors time zone 1/average speed)*Total number of day visitors zone 1)+(entrance fee*Total number of day visitors zone 1)	R/year
Travel costs Zone 2	((round trip distance Zone 2*Transport costs+Round trip distance Zone 2*value of visitors time zone 2/average speed)*Total number of day visitors zone 2)+(entrance fee*Total number of day visitors zone 2)	R/year
Travel costs zone 3	((Round trip distance Zone 3*Transport costs+Round trip distance Zone 3*value of visitors time zone 3/average speed)*Total number of day visitors zone 3)+(entrance fee*Total number of day visitors zone 3)	R/year
ON Travel costs Zone 1	((ON Round trip distance Zone 1*Transport costs+ON Round trip distance Zone 1*value of overnight visitors time zone 1/average speed)*Total ON visitors zone 1)+(Average overnight cost*Total ON visitors zone 1)	R/year
ON Travel costs Zone 2	((ON Round trip distance Zone 2*Transport costs+ON Round trip distance Zone 2*value of overnight visitors time zone 2/average speed)*Total ON visitors zone 2)+(Average overnight cost*Total ON visitors zone 2)	R/year
ON Travel costs Zone 3	((ON Round trip distance Zone 3*Transport costs+ON Round trip distance Zone 3*value of overnight visitors time zone 3/average speed)*Total ON visitors zone 3)+(Average overnight cost*Total ON visitors zone 3)	R/year
ON Travel costs Zone 4	((ON Round trip distance Zone 4*Transport costs+ON Round trip distance Zone 4*value of overnight visitors time zone 4/average speed)*Total ON visitors zone 4)+(Average overnight cost*Total ON visitors zone 4)	R/year
Total travel costs	(Travel costs for day visitors+Travel costs for ON)	R/year
Economic value of Midmar	Total travel costs-Value of water lost	R/year
NPV factor	((Conversion factor+Discount rate)^Year of cost(Time))	Dmnl
NPV rate	Economic value of Midmar/NPV factor	R/year
Cumulative NPV Midmar	NPV rate	R