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Robben Island Penguin Pressure Model:
A Decision Support Tool for an Ecosystems
Approach to Fisheries Management

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Dissertation presented for the degree of Master of Science
in the Department of Statistical Sciences
University of Cape Town

May 13, 2012

Abstract

The African penguin (*Spheniscus demersus*) population in southern Africa has declined from approximately 575 000 adults at the start of the 20th century to 180 000 adults in the early 1990s. The population is still declining, leading to the International Union for the Conservation of Nature upgrading the status of African penguins to Endangered on the Red List of Threatened Species.

This dissertation uses a systems dynamics approach to produce a model incorporating all important pressures. The model is stochastic and spatially explicit, and uses expert opinion where data are not available. The model has been produced and revised with the help of the Penguin Modelling Group, based at the University of Cape Town. The modelling process culminated in a workshop where participants experimented with the model themselves.

The model in this dissertation is only applicable to the penguin population on Robben Island and, as such, conclusions drawn cannot necessarily be applied to other penguin colonies.

The workshop showed that as the model is graphically displayed on a computer, it is useful for conveying the potential impact of decisions to fishery and conservation scientists as well as managers. Sensitivity analysis found that the penguin population is particularly sensitive to oiling and to food abundance and that future research should focus on these factors.

Plagiarism Statement

I know the meaning of plagiarism and declare that all of the work in the dissertation, save for that which is properly acknowledged, is my own.

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Acknowledgements

The financial assistance of the National Research Foundation, the Charl van der Merwe Trust, BirdLife South Africa and the University of Cape Town towards this research is acknowledged. Opinions expressed in this dissertation and the conclusions arrived at are those of the author, and are not necessarily to be attributed to the National Research Foundation, the Charl van der Merwe Trust, BirdLife South Africa or the University of Cape Town.

I would further like to thank my supervisors Leanne Scott, Theodor Stewart and Astrid Jarre for their support and guidance. Thank you also to the Penguin Modelling group, in particular Lynne Shannon, for their patience, support and input.

Finally, a big thank you to my family for their support and particularly to my husband, Christopher, for always being there for me throughout these last two years. I couldn't have done this without you.

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Chapter 1

Introduction

1.1 Background information

In 2010 African penguins were upgraded to Endangered status on the IUCN (International Union for the Conservation of Nature) Red List of Threatened Species (IUCN, 2010). This was after ten years of classification as Vulnerable. The justification provided by the IUCN states that “recent data has revealed that it [African penguin population] is undergoing a very rapid population decline, probably as a result of commercial fisheries and shifts in prey populations. This trend currently shows no sign of reversing, and immediate conservation action is required to prevent further declines.”

Whittington *et al.* (2000) tells us that in 1910 there were 1.4 million adult penguins on Dassen Island alone. By the early 1990s the overall population was estimated to be only 179 000 adult penguins. In 2009 it was estimated that only 26 000 breeding pairs remained (Sherley, 2010).

The Ecosystems Approach to Fisheries (EAF) is an approach built on numerous voluntary and binding agreements, conventions and codes that directly or indirectly affect fisheries. The FAO-Iceland Conference on Responsible Fisheries in 2001 highlighted the need for guidelines from the FAO (Food and Agriculture Organization) to help fisheries. The World Summit on Sustainable Development, held in Johannesburg in September 2002, further encouraged the application of an EAF by 2010 (Garcia *et al.*, 2003).

Key to this approach is the consideration of not only the target stock, but also the prey and predators of that stock. To this extent, the pelagic fishing

community needs to consider the plight of the penguins for whom pelagic fish are an important source of food. One of the current efforts to understand and perhaps prevent further decline of penguin populations is to close the areas around various penguin colonies to fishing. This is an attempt to verify if fishing does in fact have a negative effect on penguin survival and population growth. This experiment is currently under way with areas around colonies closed for three year periods according to a predetermined schedule.

An Ecosystems Approach to Fisheries also has to take into account various stakeholders. These range from commercial and subsistence fishers, fishery-dependent communities and society at large. A preventative measure such as closing an area to fishing to protect wildlife is seen as a positive step from an ecological perspective. However, it can negatively impact the commercial success of a fishing concern, or deprive subsistence fishers of food, and thus the tug-of-war between economic necessity and/or gain and the need to conserve endangered species begins. One could argue the relative importance of stability in the fishing industry, the needs of stakeholders and the desire to preserve African penguins but that is better left to a formal problem structuring project. This dissertation will take the stance that protecting African penguins is a priority in light of their conservation status.

The stock assessment models currently used to evaluate the effect of fishing on the stocks of anchovy and sardine as well as the related effect on penguins (as predators) are statistical models that concentrate on the data that are available and fit for use. Factors for which sufficient data are not available are not used as parameters in these models. As such there is likely to be resistance to a systems dynamics approach to modelling the situation, as used in this dissertation, and in particular to the use of expert opinion where data are not available or of sufficient standard.

Another factor that could impair the acceptance of a different paradigm is that the stock assessment models are currently, and have been used in the past, to determine the Operational Management Procedure (OMP). The OMP determines the Total Allowable Catch (TAC) for each fish species and is revised every five years. In order for an alternative model to be considered for inclusion in the decision making process it would need to not only be accepted scientifically but also accepted by the fishing industry and management. The model developed in this dissertation is intended to start the process of developing an alternative and complementary approach to aid decision making.

The last major attempt at a model of penguin populations based on biolog-

ical understanding was the Vortex model that was used at the African Penguin Population and Habitat Viability Assessment workshop in April 1999. At that stage African penguins were classified as Near Threatened (2004 Classification) but, the very next year, moved up to Vulnerable as a result of the Conservation Assessment and Management Plan (CAMP) in 1996 (Whittington *et al.*, 2000). The details of the Vortex model and the factors considered at the workshop will be described in chapter 2.

1.2 Research objectives

1. Create a model to assess the combined effects of multiple pressures on the African Penguin population of Robben Island
 - Model should be stochastic, stage-specific and spatially explicit
 - Pressures should be modelled explicitly, and separately if possible
 - Should stay in line with current biological understanding
2. Explore possible management strategies that could be beneficial to the Robben Island penguins
3. Ensure that the model could be extended to other penguin colonies

1.3 Delineation and limitations

This dissertation focuses on the model of the penguin population of Robben Island. As many factors identified for this island are either not factors for other islands or affect the penguins on those islands more or less strongly, the results obtained in this dissertation should not be assumed to apply equally to other penguin colonies.

As hard data are not available for all aspects of the model, qualitative relationships are used based on expert opinion. Sensitivity analyses have been performed to determine the effect of these relationships as different experts may have differing opinions. The approach to modelling is such that differences in opinion can be taken into account and the model parameters adjusted in order to explore the effects. The Penguin Modelling Group consists of representatives from the University of Cape Town, BirdLife SA, the Department of Environmental Affairs, Cape Nature and the South African National Biodiversity Institute.

This dissertation, for the most part, uses the opinions of the penguin biologists of the Penguin Modelling Group.

1.4 Definition of terms and concepts

A description of the following words is provided for ease of understanding:

biomass the total quantity or weight of an organism in a given area or volume

bycatch unwanted marine creatures caught whilst fishing for a different species

pelagic fish that inhabit the upper layers of the sea e.g. sardine and anchovy

recruit a juvenile fish that has survived long enough to become a part of a population

spawner a mature female fish

1.5 Significance of this dissertation

African penguins are in danger of extinction. The Ecosystems Approach to Fisheries recognises the importance of determining the impact of fishing on top predators like sea birds. African penguins feed on pelagic fish such as sardine and anchovy so it is important that the pelagic fishing industry, from managers to fishers, are aware of the impact their activities may have on the penguin colonies.

It is vitally important that other factors influencing the penguin population are also considered and, especially, the effect of all factors combined. This ensures that research efforts can be focused on the most important factors. As there is not currently a model that takes into account all these factors in a stochastic and spatially explicit manner, this dissertation is significant in that it can provide scenarios based on a holistic view of the penguin population and the potential causes of decline.

1.6 Chapter overviews

This chapter has provided an introduction to the plight of the African Penguin and provided general information on how conservation of penguins fits into the

Ecosystems Approach to Fisheries. It further outlined the research objectives and provided a rationale for this study.

Chapter 2 is a review of the available literature in order to provide a more detailed background to African Penguins and the EAF. Chapter 3 outlines the research methodology used and details of the data used as well as the various meetings and presentations used to gather information.

Chapter 4 details the initial model built for the Penguin Modelling Group while chapter 5 provides a description of the final model. Chapter 6 discusses the results obtained from the model. This is followed by the results of the sensitivity analysis in chapter 7.

Chapter 8 deals with the workshop that various stakeholders were invited to participate in. It examines how user friendly the model actually is and if it has fulfilled the requirement that it can be used to explore management strategies.

This dissertation concludes with chapter 9 which contains general conclusions and suggestions for further research.

Chapter 2

Literature Review

2.1 Introduction

This literature review first attempts to acquaint the reader with the species *Spheniscus demersus*, otherwise known as the African or Jackass penguin. Familiarity with the life stages and behaviour of the African penguin is important as it informs and underlies the structure and assumptions of the systems dynamic model that is discussed in chapters 4 and 5. Additionally, a short description of the penguin population on Robben Island is given to familiarise the reader with the basic demographic parameters. Following that is a review of literature that describes and attempts to identify the reasons behind the rapid decline of the penguin population.

The importance of conserving penguins as a top predator is examined in terms of the Ecosystems Approach to Fisheries and the role that the fishing industry plays in the conservation of its target stock, as well as the predators and prey of that stock, is highlighted.

Finally, similar system dynamics models and previous attempts at modelling African penguin populations are described.

2.2 The African penguin: *Spheniscus demersus*

African penguins are endemic to Southern Africa and breed at 29 sites in South Africa and Namibia (Crawford *et al.*, 1995; IUCN, 2010). Breeding is focused around three main locations - southern Namibia, Western Cape and Eastern

Cape. The majority of colonies are found on offshore islands or rocky outcrops (Sherley, 2010).

2.2.1 Life stages

Eggs Eggs can be laid all year round but egg laying reaches a peak between February and May in South Africa (Sherley, 2010). The modal clutch size is two eggs with nests of one egg occurring far more frequently than nests of three eggs. (Crawford *et al.*, 1999, 2010). Eggs are incubated for a period of 38 to 41 days. Should a clutch be lost, for whatever reason, the breeding pair may choose to lay a second clutch (Crawford *et al.*, 2010).

Chicks Chicks fledge when they are between 55 and 130 days old. Until then they are dependent on their parents for food and, for the first 21 to 25 days, temperature regulation. The second chick to hatch (in a two egg clutch) often lags behind the first chick in terms of growth. The last hatched chick is also more likely to die (Crawford *et al.*, 2010). Chicks that are born to parents who have previously been oiled (and rehabilitated) have a lower fledging success rate as their parents appear to have a reduced ability to fulfill the needs of the chicks, especially as the chicks mature (Barham *et al.*, 2007; Wolfaardt *et al.*, 2008). Breeding pairs that lose their brood or that successfully fledge their chicks may choose to lay a second clutch (Crawford *et al.*, 2010).

Immature penguins Penguins are categorized as immature or juvenile after they have fledged and before they have moulted into their adult plumage. Immature penguins will leave their birth colony and spend between one and two years at sea, sometimes up to 1 900km away from their natal colony (IUCN, 2010). They then return, usually to their natal colony, to moult into adult plumage (Randall *et al.*, 1987).

Adult penguins On average, adults penguins live until the age of 20 (15 to 27 years old in the wild). Adult penguins start breeding between the ages of two and six years old with a modal age-of-first-breeding of four years old (Crawford *et al.*, 1999). First time breeders have the flexibility to emigrate to other colonies and can thus take advantage of shifts in the long term distribution of prey. Once a pair has bred at a specific colony they usually remain faithful to that colony, and to each other (Crawford *et al.*, 2001, 2010).

2.2.2 Feeding

Penguins generally feed on pelagic fish such as sardine (*Sardinops sagax*) and anchovy (*Engraulis encrasicolus*). While not breeding, adult penguins can travel up to 120 km in search for food but this range is limited to 30 to 40km (approximately 16 to 20 nautical miles) when breeding (Sherley, 2010).

2.3 Demographic parameters of Robben Island population

African penguins recolonized Robben Island in 1983 with 9 breeding pairs (Crawford *et al.*, 1999). The colony had been extinct since the 1800s. Subsequently there was rapid growth with a peak of just over 8 000 breeding pairs in 2004. The number of breeding pairs then started to fall until just under 2 500 breeding pairs were estimated to exist on Robben Island in 2009 (Crawford *et al.*, 2010). The growth of the colony was found to be strongly correlated with the growth of the sardine stock (Crawford *et al.*, 2001).

At Robben Island, most adults moult from November to January. The peak laying season is February to April with the first clutches laid in January and the last in August. Adult annual survival rates vary between 81% and 89% without oiling events. Immature (first year at sea) survival rates vary from 17% to 44% (Crawford *et al.*, 2010).

Most penguins on Robben Island breed for the first time aged 4. The proportion of sexually mature birds that choose to breed each year varies between 0.7 and 1, and is positively related to sardine spawner biomass. The mean clutch size ranges from 1.81 to 1.92 (proportion of 2 egg nests range from 0.81 to 0.92) and the mean number of chicks fledged per pair ranged from 0.32 to 0.59. The mean number of chicks fledged per pair was found to be significantly related to the anchovy spawner biomass in Crawford *et al.* (1999).

2.4 Decline of the African Penguin

It is estimated that only 26 000 breeding pairs exist - 5 000 pairs in Namibia and 21 000 pairs in South Africa (IUCN, 2010). At the start of the 20th century there were approximately 575 000 adults. Over the next 50 years numbers halved and the decline continued until there were only around 180 000 adults in the early

1990s (Crawford *et al.*, 1995). The penguin population has decreased to less than one-tenth of what it was just over a hundred years ago, and seven islands now support 80% of the population (IUCN, 2010).

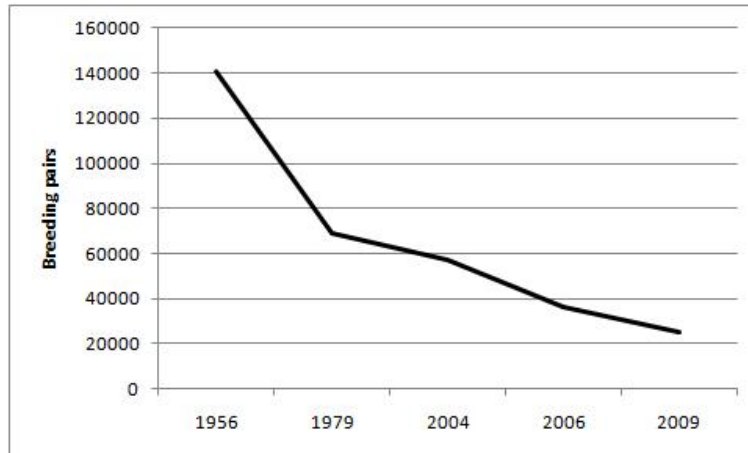


Figure 2.1: Rapid decline of the penguin population in the last 55 years

2.5 Factors thought to contribute to that rapid decline

Whittington *et al.* (2000) states the following: “Primary threats to African penguins include competition for food with seals and commercial fisheries, predation by seals, oiling, and loss of habitat from interspecific competition for nesting sites”. In addition to these threats, African penguins are affected by climate change, disease, flooding, other predators and humans. The following paragraphs illustrate specific examples of these factors as well as general comments from literature.

2.5.1 Predators

Seals At Hollams Bird Island in Namibia, penguins experience severe competition for space from the South African fur seals and at Mercury Island (Namibia), seals displaced more than 1 000 nesting pairs of penguins in the 1980s. Breeding space at Seal Island (South Africa) is severely restricted by fur seals (Crawford *et al.*, 1995). Furthermore, competition for breeding space may be the cause of

cessation of breeding at a total of five colonies. Increased numbers of seals not only decrease food availability but also prey directly on penguins (Whittington *et al.*, 2000).

Cape Gannets Cape Gannets may have displaced breeding penguins on Malgas Island in South Africa. The area occupied by the breeding gannets doubled over a decade and extended over areas where 250 pairs of penguins previously nested (Crawford *et al.*, 1995).

Sharks According to Randall *et al.* (1988), predation by sharks has been recorded for a number of penguin species and an African penguin was even found in the stomach of a great white shark. The article concluded that great white sharks are probably the most common predator, and although the injuries inflicted by these sharks were an important cause of natural mortality, oil pollution appeared to be more significant in terms of total known mortality.

Land predators The number of occupied nests at Stony Point, South Africa, dropped from 140 in 1990 to 84 in 1994. The reasons behind this are thought to be predation of adult penguins by caracal and predation of eggs by mongoose or large-spotted genet, all predators common to the area (Crawford *et al.*, 1995).

2.5.2 Natural disasters and disease

Flooding and extreme weather events Flooding can occur due to rain, spring tides or rough seas depending on the location of nests and the topography of the island (Kemper *et al.*, 2007).

de Villiers (2002) states that “extreme weather events such as heat waves and heavy rainfall may also influence the breeding output of a colony”. The article points out that the effect may be increased due to the physical location of the colony, and that the timing of weather events would also play a role. The article further describes how a severe storm flooded burrows, washed eggs out to sea and resulted in chicks drowning or dying from hypothermia.

Whittington *et al.* (2000) further states that heat stress can cause parents to abandon nests and take to the sea to cool off and prevent further dehydration. Eggs and chicks are then vulnerable to predators.

Disease Penguins living in temperate or sub-Antarctic climates are susceptible to avian malaria (Brossy *et al.*, 1999). This disease affects adult and

juvenile penguins and, as it does not normally occur in wild penguins, tends to be transmitted from penguins that have been captured and kept in confined areas. Mortality can range from 50 to 75% in captive penguins (Graczyk *et al.*, 1994, 1995).

2.5.3 Man-made disasters and human interference

Oiling South Africa experiences both catastrophic oil spills and chronic oiling. Over a ten year period, 44% of the penguin deaths on St Croix Island were attributable to oil pollution (Whittington *et al.*, 2000). Between 1953 and 2000, 15 oil spills affected penguins at various breeding colonies around South Africa (Wolfaardt *et al.*, 2009). Wolfaardt *et al.* (2009) further states that the African penguin has suffered more from oiling than any other seabird species, worldwide, based on the proportion of population affected. 5 of the world's 50 major oil spills have occurred off the coast of South Africa (Whittington *et al.*, 2000) and since oiling can have an effect on breeding success (Barham *et al.*, 2007), it should be considered a major factor in the decline of the penguin population.

Human interference Penguins would naturally burrow in accumulations of sea bird guano to make their nests. Human excavation and collection of guano has meant that penguins have had to nest on the surface where they are vulnerable to predators and weather. Commercial exploitation of eggs led to severely reduced recruitment into the adult population. Between 1900 and 1930, more than 450 000 eggs per year were harvested from Dassen Island (Wolfaardt *et al.*, 2009).

2.5.4 Food availability

Sardine stocks off South Africa collapsed in the 1960s and off Namibia in the 1970s. The reduced prey availability caused a decrease in the number of penguins between Cape Town and Lüderitz. The number of penguins at Possession Island (southern Namibia) decreased from 23 000 pairs in 1956 to fewer than 500 pairs in 1987 (Whittington *et al.*, 2000). In 1991, several thousand nests at Dyer Island in South Africa were abandoned. It is thought that this was a result of lack of food (Crawford *et al.*, 1995).

2.6 The role of fisheries management

2.6.1 Single species approach

Modern fisheries management, as practised for the last 70 years, tends to focus mainly on its target resource or resources and the fishing activities relating to that resource. Even though it is based on ecosystems theory, the target species is assumed to exist in isolation of the ecosystem (Garcia *et al.*, 2003).

The management of fishing resources in this context primarily uses an indicator in order to formulate strategies that optimize single stock yield. This indicator is the Maximum Sustainable Yield (MSY) of that stock (Degnbol & Jarre, 2004). MSY results in a strategy that aims to keep a stock at an intermediate level and to set the harvest rate equal to the annual growth rate (Zabel *et al.*, 2003) in order to harvest the maximum amount of stock while keeping the population growth rate as high as possible.

MSY does not however take into account the effect of fishing on size/age structure of the population or on the habitat of the stock nor the disruption of the usual predator-prey relationships.

The overall management objective in this approach is to maintain sustainable levels of the target resource. The objective does not extend to multiple species nor does it include consideration of environmental parameters (Hutchings *et al.*, 2009). This results in the assessment and management of South African marine resources as individual species, although there is an increasing trend to consider multiple stocks (Hutchings *et al.*, 2009). This single species approach leads to management strategies that focus on controlling fishing while merely observing proxies for the state of the ecosystem as direct intervention is limited.

As part of the management strategies, the use of fishery resources is optimized as a source of human livelihood, food and recreation. This is done without regard to the effects on the predator-prey relationships of the target resource, the effects on associated species or the effect of fishing on the marine environment. This narrow focus upon the human activity, and control thereof, ignores stakeholders such as fishery-dependent communities, whose livelihoods depend on the employment generated by fishing and its related activities, and measures such as protection of specified areas and habitats (Garcia *et al.*, 2003).

This approach to fisheries management is losing favour to an ecosystems approach, as described in the following section.

2.6.2 Ecosystems Approach to Fisheries Management

The ecosystems approach to fisheries management aims to extend conventional single species management to “recognize the interdependence between human-wellbeing and ecosystem health” (Garcia *et al.*, 2003; FAO, 2003).

Amongst the aims of an ecosystems approach are to

- maintain viable populations of all native species in an ecosystem
- maintain evolutionary and ecological processes
- manage activities over a sufficiently long period of time so as to maintain evolutionary potential of species and ecosystems
- to accommodate human use and occupancy within these constraints (Garcia *et al.*, 2003)

This approach to fisheries management recognizes that single species are rarely caught in isolation from other species and that both the targeted and incidental (in the form of bycatch) removal of species from the ecosystem impact not only that species but many others as well (Moloney *et al.*, 2004). Removal of the target species affects its predators, prey and competitors. Fishing also removes other species as bycatch as the result of only partially selective fishing gear. These removals and changes in fish populations can result in modified trophic interactions and food webs (FAO, 2009).

Fisheries need to understand the impact that their activities have on the ecosystem. The impact of exploiting the target resource can reduce the abundance and spawning potential of the resource as well as “modifying the age and size structure, sex ratio, genetics and species composition of the target species and associate and dependent species” (Garcia *et al.*, 2003).

Marine creatures are not the only ones affected. Habitat may be altered or damaged by fishing gear which would affect marine species (FAO, 2003). Land-bound predators such as penguins would be affected if the spatial distribution of their prey species were to change due to the effect of fishing.

An EAF recognises that humans are also an integral component of the ecosystem, and any management strategy would need to take this in to account (De Young *et al.*, 2008).

2.7 Previous models of African penguin populations

The following two models represent the recent major attempts to model the penguin populations of Dassen and Robben Island.

2.7.1 Shannon and Crawford model (1999)

Shannon & Crawford (1999) describes a model used to evaluate the effects of egg harvesting on Dassen Island in the early 20th century, and oiling in the latter half of the 20th century. The model used a quarterly time step with annual survival and mortality for adult penguins. The mean value of parameters used in this model were taken from measurements of Robben Island penguins, or from a population model of these penguins.

Records of eggs harvested were used along with a linear regression model in order to estimate the proportion of the annual harvest that occurred in each quarter and the rate of harvest. Both chronic and catastrophic oiling were considered in the model. They were modelled similarly but with different parameters.

Shannon & Crawford (1999) found that there was no harvest rate that did not cause a decrease in mean population size over 57 years but that the effect of harvesting could be minimised if the majority of harvesting took place in the third quarter.

Catastrophic oiling was found to reduce the mean population to 76% of what it would have been without oiling, 50 years after an oil spill. If penguins were rehabilitated the population was only reduced to 88% of the population without oiling.

The impact of chronic oiling varied with the assumed level of disturbance during searches for oiled birds from reducing the population to 89% of the non-oiling scenario when no rehabilitation was attempted, to only 5% of the non-oiling scenario when daily searches were conducted.

2.7.2 Vortex model (1999)

The Vortex model (Whittington *et al.*, 2000), run as part of the Penguin Population and Habitat Viability Assessment workshop, focussed on Robben Island as it was the best known island in terms of demography. The simulation model

was initialised with a population of 5 000 birds and a carrying capacity of 25 000. Models were developed for three levels of juvenile survival, two levels of adult survival, three levels of reproductive success and four scenarios with respect to catastrophes.

Vortex is an individual-based simulation model in that each penguin is individually tracked and demographic events such as breeding or mortality are recorded at each discrete time step. The model has mean probabilities of occurrence for each demographic event with a specified annual variation. In addition, catastrophes can occur that would reduce survival and reproduction. The frequency and severity of catastrophes can be specified by the user.

The model for Robben Island was run for 25 years with a starting population of 5 000 adults. The parameters used were taken from Shannon & Crawford (1999). Adult survival was taken as constant bar the occurrence of catastrophes (oiling and human disturbance).

The model showed that, using the best estimates of the demographic parameters of the Robben Island penguin population, due to low breeding success (chicks per nest per year) and survival rates, the population could not sustain itself without immigration. Higher adult survival combined with increased breeding success, or much higher breeding success alone, could result in a self-sustaining population. The occurrence of catastrophes meant that both breeding success and survival had to be much higher in order to produce positive long term growth.

Finally, higher immature survival combined with either higher adult survival and/or higher breeding success led to self-sustaining populations even with catastrophes. The model further showed that the increase in the population that occurred in the late 80s and 90s could not have occurred without immigration - at least 1 000 immigrants each year.

2.8 Systems dynamics and penguin population modelling

A comprehensive search revealed no currently available models of African penguins that have used a systems dynamics approach. Previous penguin population simulation models from, for example, Jackson *et al.* (1976) and Crawford *et al.* (1999), and the two models discussed in the section above, are mathematical models that do not follow the principles of systems dynamics modelling.

Semeniuk *et al.* (2010) provides a systems dynamics model of a stingray population with tourism as a population pressure. The model has two components: the stingray population and the tourist population. The tourist population influences the immigration rate of stingrays into the modelled population and the stingray mortality rate, and the stingray population influences the attractiveness of the area to tourists. Management actions influence both the tourist population and the stingray population, and drive the two components of the model.

The authors found that results of their model could not have been predicted if the two components had been examined in isolation. It was only through the combination of ecological and social components that viability of the wildlife attraction could be properly evaluated.

The relevance of this model to the penguin model described in this dissertation is limited. The penguin model has a more detailed population dynamics component than that of the stingray population, and the pressures upon the penguin population are, in general, acting upon the natural mortality of the penguins as opposed to the immigration of penguins into the population.

Faust *et al.* (2003) demonstrates how a stage-based systems dynamics model can be useful in the demographic management of captive populations. A systems dynamics model of the behaviour of captive populations can include the effects of both biology and management. This leads to a better understanding of the impact of management decisions on the population, and can highlight areas of concern.

The Faust model focusses on the population dynamics of three subspecies of bears in captivity. As there are no major external pressures on the population beyond space available, the model focusses on age structure and breeding, in terms of biological factors, and birth and space management, in terms of population management. Demographic data for the captive populations is readily available from stud books and the modellers make good use of this data both for parametrisation of the model, and to compare the results of the model with an age-based matrix model.

The Faust model demonstrates that population management and population dynamics can be combined effectively in a systems dynamics model. Furthermore, the model can be used as a valuable management tool due the flexibility of the model and the ease of alteration of model parameters.

The Semeniuk and Faust models demonstrate that systems dynamics can be used to effectively model an animal population, however the populations are

modelled at a different level of detail, and lack the addition of the types of population pressures required of the model in this dissertation. As literature is scarce on using systems dynamics to model a population such as a penguin colony, “Business Dynamics: Systems Thinking and Modeling for a Complex World” (Sterman, 2000) was used as a guide.

2.9 Conclusion

The models discussed in the sections above provide a useful starting point for the development of this penguin model. Using the information from the Shannon and Crawford model, as well as information regarding the life stages of a penguin and the demographic parameters of the population on Robben Island, the prototype model, as detailed in chapter 4, was built.

University of Cape Town

Chapter 3

Research Methodology

3.1 Introduction

This chapter outlines the process of research involved in constructing this model. The sections below will describe what approach was used to design the model, the process of gathering information through a series of meetings and presentations, the data gathered and how the results of the model were analysed.

3.2 Research design

Penguin population dynamics can be represented by a purely mathematical model as in, for example, Crawford *et al.* (1999) if all factors are quantifiable and if mathematical functions and relationships can be defined between variables. The inclusion of pressures, whose effects can not be quantitatively defined due to lack of data, necessitates a move to a paradigm that can incorporate expert opinion. This can then be used to qualitatively define the relationship between population pressures and survival rates that would normally be left out of a mathematical model.

According to Munro & Mingers (2002), the points below indicate a situation where the use of soft operations research is appropriate:

- a range of decision makers and stakeholders with conflicting objectives
- many important factors that cannot be quantified

- a subset of stakeholders that do not have the necessary skills to fully understand complex mathematical models thus,
- the methods used must be transparent and accessible to stakeholders

These factors are present when modelling penguin populations and so it is appropriate to use aspects of soft OR. In particular, it was decided to approach the problem using *Vensim*, a simulation programme suitable for constructing a systems dynamics based model. A systems dynamics approach is useful when, as in this case, there are significant feedback loops and the system may involve non-linearity and relationships best defined by a graph. This approach has the advantage of clearly representing the model components and interactions on-screen which aids stakeholders in understanding the model structure and the relationships between variables.

3.3 Methodology

Both qualitative and quantitative data were used to develop the model. This data was obtained through discussions in meetings and presentations as detailed below in 3.3.1, from published journal articles and from personal communication with various experts. The information gathered was used to develop the relationships between variables in the model as well as to ascertain the behaviour of certain pressures.

3.3.1 Client consultations and presentations

The Penguin Modelling Group is the client for the model and has provided information and advice through a series of meetings and emails. A summary of the meetings is set out below followed by the three presentations of the model.

Meeting one: The meeting held on 22 April 2010 set out the requirements for a penguin pressure model. The objective of this model was an assessment of the combined effects of multiple pressures on the African penguin population. It was to be used to explore which management actions or measures would be most beneficial for penguins (i.e. to increase breeding success and reduce mortality). It was decided that the basis for this model was the Shannon and Crawford model (Crawford *et al.*, 1999), but that model would be amended as described in chapter 4.

Meeting two: The next meeting, on 5 July 2010, was the first time the model was presented to the modelling group. The design of the model was discussed but food-related issues were excluded. The modelling group had various requests for improvements to the model. The conflict between realism and the need to keep the model as simple as possible arose in requests to have a smaller time step (weekly or fortnightly instead of monthly), and links between climatic factors and chick condition. The group accepted that the structure of the model did not allow for the individual tracking of penguins and focussed on the overall effects to each age class.

Meeting three: The meeting on 11 August 2010 concentrated on food availability and its effects in the model. The meeting was spent discussing the most appropriate way to model food availability. The penguin experts in the group reached consensus on which biomass data was to be used for the effects on breeding penguins, and which was to be used for non-breeding penguins. It was also decided to take a semi-qualitative approach and construct an index of food availability. These suggestions were incorporated into the model.

Meeting four: Feedback on model calibration was given at the meeting on 20 September 2010. Further discussions around the effect of climatic factors and oiling took place. It was also decided to run the model with good conditions in order to determine if the population would grow as expected. Finally, the model objectives were revisited and a discussion amongst participants clarified these further. A spreadsheet of parameters was sent to all group participants. Most parameters were accepted. Those that the group queried were referred to the relevant expert in that aspect for clarification and any necessary changes were implemented.

Presentation: Model launch The model was launched on 3 November 2010 at the University of Cape Town. Representatives from Cape Nature, BirdLife SA, the Department of Agriculture, Forestry and Fisheries, the Department of Environmental Affairs and the University of Cape Town were invited to the launch. Approximately 25 people attended. The structure of the model was explained and preliminary results were shown. A number of questions and concerns were raised and answered during the launch.

Presentation: EAF SWG The model was also presented to the Ecosystems Approach to Fisheries management scientific working group (EAF SWG) on 21 January 2011. The revised model was presented and a discussion resulted in a list of recommendations that are detailed in 5.7. The EAF SWG endorsed the model as a useful and complementary approach to the current models in order to investigate the decline of the African penguin population.

Presentation: Pelagic SWG On 17 May 2011, a short overview of the model was presented to the Pelagic scientific working group. As the full specifications of the model were not available to the group, the members of the group felt they could not properly evaluate the model and so comments were kept very general. The group did agree that the population model component was good but were uneasy with the use of expert opinion where data were not available.

3.3.2 Data

An important source of data was Crawford *et al.* (1999) as this provided the initial estimates of survival rates for each age class, breeding proportions and breeding success. The estimates for the Crawford model were adjusted to take into account the penguin pressure model structure. There was general agreement from the Penguin Modelling Group that the base survival rates were likely a couple of percent higher than those used in the Crawford model as those ones incorporated all pressures on survival.

3.3.2.1 Food availability

The data used for food availability are based on biomass surveys of sardines and anchovies from two specific areas (Strata C and D as defined by the surveys and illustrated in figure 5.1 in chapter 5) and from the November or May survey as appropriate. The catch data used is based on a record of catch recorded in specific fishing blocks around Robben Island. The area covered by the catch data is contained within the appropriate biomass data but the area covered by the catch data is approximately 17% of the area covered by the survey. The biomass amounts were reduced so that the effective area of the survey was equivalent to that of the catch data. There are different views on what data is appropriate to use as that indicating general availability. As there is only one stratum with a statistically significant relationship to the breeding success of the penguins on Robben Island, this stratum was chosen to represent the general availability of

food. This is discussed further in section 5.6.5.2. As the biomass data shows no significant autocorrelation (Section 7.3), a programme was written in Excel using Visual Basic for Applications. This samples (with replacement) from the data available to produce a time series for use in the model.

Monthly data on sardine and anchovy catches in the six pelagic fishing blocks within a 15 nautical mile radius of Robben Island was formatted so that the programme that selects the biomass data also selects the appropriate catch data.

3.3.2.2 Population parameters

A summary of data relating to African penguins, compiled on 14 July 2010, was used to confirm breeding success (hatching and fledging success as well as chicks per pair) estimates. It also provided a time series of the numbers of moulting birds that was used to check whether the model could produce realistic projections. Other sources of information were consulted to determine numbers of adults at Robben Island but often sources conflicted with each other due to uncertainty in estimates. Where there was doubt, the larger of the estimates was used as it is highly likely that a count of moulting penguins underestimates the number of adults in the colony (Crawford *et al.*, 1999).

3.3.2.3 Oiling parameters

Data from SANCOBB on penguins admitted from Robben Island was used to determine the frequency of chronic oiling, and the effect it has on adult and immature penguins. The data was presented as information on the date of admission, date of release or death and age of penguin (adult or immature). The data was collated to give an indication of the number of penguins oiled in each oil spill (an oil spill was determined to cover all admission dates less than a week apart) as well as the average number of days between oil spills. This information was then used in the model.

3.3.3 Analysis

The purpose of the model is to provide input into management and research decisions. Analysis of the results centres around whether or not they contribute to the decision making process. It is important that the model can identify trends, cycles and crashes, and that it can show the effect of various management scenarios.

The model can be used in two ways. The first way is to look at a single run for an idea of what impact the various pressures have on the population. The second, and more useful way, is to run the model multiple times for each scenario with a different random number stream for each run and then compare the end populations for each scenario. The model has a set of five thresholds (see appendix D for details) and will produce the probability that the population at the end of the time period is below each threshold. This can be used to evaluate the differences between management actions or the effect of different pressures.

3.4 Limitations

As *Vensim Professional* is not a free programme, clients who have not purchased the programme are restricted to using *Vensim Model Reader*. However, the majority of constants and some lookup relationships can be edited via the associated Excel file in *Model Reader*.

The limitations of *Model Reader* are that users are not able to edit any equations, nor can they perform sensitivity analysis and, as Vensim only allows eight runs to be loaded at a time, this limits the exploration of the effect of variability in the model. Furthermore, in order to make full use of the gaming feature, someone needs to be able to use *Vensim Professional* to set up the gaming controls.

However, as chapter 8 demonstrates, it is still possible to facilitate learning and communication with the free version of *Vensim* as long as the facilitator has access to the full version.

Chapter 4

Prototype Model

4.1 Introduction

Penguin populations have been in decline since the beginning of the 20th century and it is important to determine what factors or population pressures have the greatest effects on population growth.

Various models have been developed to describe the population dynamics of different penguin populations around the world. The model developed in this chapter is based on a model by Shannon & Crawford (1999) as described in section 2.7.1. The assumptions and structure of the prototype model are discussed first followed by a presentation and discussion of the results. Finally, a general description is given of the necessary additions to the model in order to enable it to be of use in the decision making process.

4.2 Model objectives

The aim of the prototype model is to produce a systems dynamics model that replicates the results of the Shannon and Crawford model (Shannon & Crawford, 1999). The prototype model will have a monthly, as opposed to quarterly, time step and will introduce random variation in the input parameters.

It is expected that the results from this model and the Shannon and Crawford model will differ due to the change in time step and the stochastic nature of the parameters, but the results should still follow the same trajectory and be close at the start of the run.

4.3 Model assumptions

- The penguin population is in demographic equilibrium at time zero
- The number of eggs, chicks and immature penguin aged less than 1 year is zero as the simulation begins at the start of a breeding year
- The survival rate for each adult age class is assumed to be equal to a common survival rate (s)
- The survival rate of immature penguins between 1 and 2 years of age is equal to the adult survival rate
- The survival rate for immature penguins aged less than 1 year is lower due to inexperience in hunting and survival
- The penguin population is not influenced by immigration or emigration
- The Shannon and Crawford model was developed to investigate the effect of egg harvesting on a penguin population. The effect of harvesting will be ignored in this prototype model with the intent to rather reproduce the population dynamics.

The penguin population is divided up into 8 age classes:

1. Eggs (E)
2. Chicks (C)
3. Immature penguins less than 1 years old (A_0)
4. Immature penguins between 1 and 2 years of age (A_1)
5. Adults between 2 and 3 years of age (A_2)
6. Adults between 3 and 4 years of age (A_3)
7. Adults between 4 and 5 years of age (A_4)
8. Adults 5 years of age and older (A_5)

4.4 Model dynamics

The main dynamics of this population model are monthly mortality and annual survival. The population structure is shown diagrammatically in figure 4.1. The adult penguins form breeding pairs that lay eggs. These eggs hatch after one month and the chicks fledge after another three months. The immature penguins leave the island to hunt, returning near the end of their second year to moult into adult plumage.

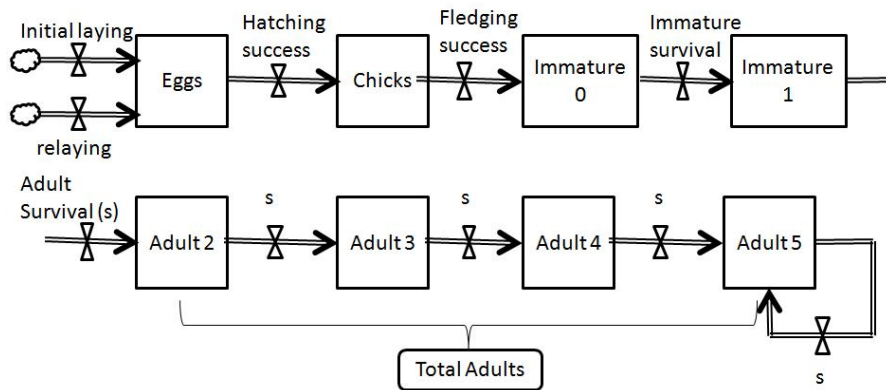


Figure 4.1: Diagram of population model

Adult penguins and those in the second immature class are subject to the same mortality throughout the year and the population in each of these age classes is decreased each month. At the end of each year, surviving penguins in these age classes move to a higher age class should one exist, otherwise they remain in that age class (i.e. in the case of penguins in age class A_5).

Eggs experience monthly mortality and progress to the Chicks age class after one month with a survival rate of s_e . Chicks behave similarly to Eggs except they progress to the first immature age class after 3 months with a survival rate of s_c .

Penguins in age class A_0 are treated somewhat differently from Penguins in the other age classes. Penguins in this age class are only removed at the end of the year when the surviving immature penguins move up to class A_1 . This was done in order to ensure that the correct proportion of penguins survived to the end of the year. As these penguins do not contribute to any other part of the model, except as input to the A_1 class, this does not effect the yearly model results.

The number of eggs laid each month is made up of two parts. The first part consists of the initial clutch laid by each breeding pair. This is determined by the proportion of breeding pairs that breed that month, the number of breeding pairs and the mean size of a clutch. The second part consists of clutches that are relaid after the initial clutch was lost, the brood was lost or the brood was successfully fledged. In each case only a portion of breeding pairs that experience these events relay. The first eggs are laid in January and the last batch of eggs (mainly relays) are laid in September.

The equations illustrating the model dynamics can be found in Appendix A.

4.5 Model structure

Initial numbers in each age class are set such that the adult population is initially in equilibrium in the absence of anything except natural mortality. For the population to be in equilibrium the following must hold true:

$$A_{i,t} = A_{i,t-1} \text{ for } i = 2, 3, 4, 5$$

Thus if

$$\text{Total Adults} = A_2 + A_3 + A_4 + A_5$$

At equilibrium

$$\text{Total Adults at } t = A_{2,t} + A_{2,t}s + A_{2,t}s^2 + A_{2,t}s^3 + A_{5,t}s$$

But

$$A_5 = A_5s + A_2s^3$$

Thus, dropping the t notation,

$$\text{Total Adults} = A_2 + A_2s + A_2s^2 + A_2s^3 + A_2\frac{s^4}{1-s} \quad (4.1)$$

$$= A_2\left(1 + s + s^2 + s^3 + \frac{s^4}{1-s}\right) \quad (4.2)$$

The equilibrium numbers are calculated for each adult age class as follows where s is the common adult survival probability:

$$A_2 = \frac{\text{Total Adults}}{1 + s + s^2 + s^3 + \frac{s^4}{1-s}} \quad (4.3)$$

$$A_5 = \frac{A_2 s^3}{1-s} \quad (4.4)$$

$$A_4 = A_2 s^2 \quad (4.5)$$

$$A_3 = A_2 s \quad (4.6)$$

$$A_1 = \frac{A_2}{s} \quad (4.7)$$

The number of eggs, chicks and immature penguins born that year are assumed to be zero as the simulation starts at the beginning of a breeding year (January-December).

Penguins in each adult age class and immature penguins in age class A_1 have a common survival probability, s . Immature penguins in age class A_0 have a mean survival probability, s_0 , that is lower than s . The probability of an egg hatching, s_e , and of a chick fledging, s_c , are set similarly to s and s_0 but are much lower due to risks specific to eggs and chicks. This is in accordance with the original model (Shannon & Crawford, 1999).

4.6 Data requirements

As in Shannon & Crawford (1999), it was assumed that each parameter lay either within 3 standard deviations of its mean or a specified range, and that it followed a (truncated) normal distribution. The means and standard deviations for each parameter were taken from the Shannon and Crawford model (Shannon & Crawford, 1999) and are shown in appendix D. The initial values of all parameters are set to the mean value for the first year. Thereafter, at the beginning of each year, a value is drawn from a truncated normal distribution with mean zero and the appropriate standard deviation, and added to the mean value. This new value is the input for that year.

The total number of adults at the beginning of the model is calculated from the number of adults observed moulting multiplied by a factor of 1.1. The adjustment factor is to include birds not counted as moulting due to time between counts (Crawford *et al.*, 1999).

These are the only external inputs to the model and all occur during setup.

Once the model starts running there are no further user inputs.

4.7 Results

The model was run using an initial population of 3 500 adult penguins. The parameters used resulted in a decrease in population over ten years as shown in figure 4.2. Two hundred iterations of the model with different random number streams produced results that are tightly grouped (Figure 4.3). The results from the prototype model are highly correlated with the results from the Crawford model (0.9926), and the figures for the first three years are within 10% of each other.

In order to maintain a stable population, without changing model parameters, annual immigration is required. Setting immigration into age class A_1 at 10% of the starting adult population results in a fairly stable population as seen in figure 4.4. Over 50 years the population at the beginning of each year remains close to the starting population.

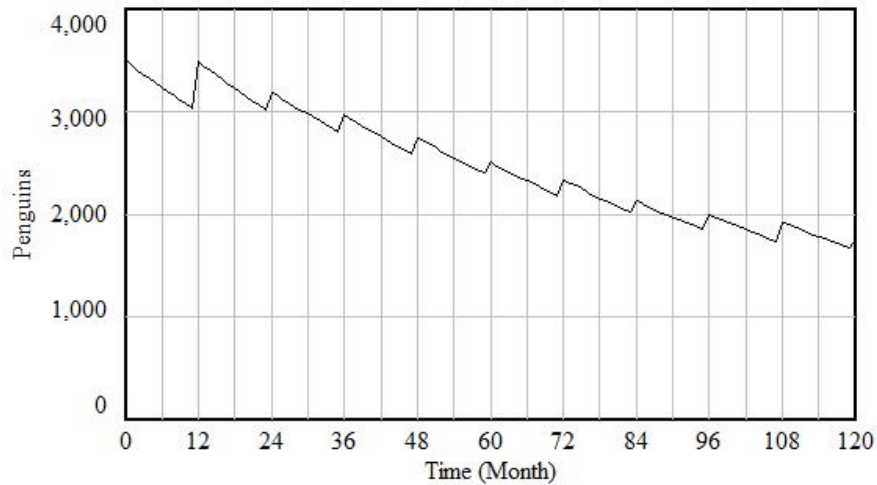


Figure 4.2: Initial run of prototype model

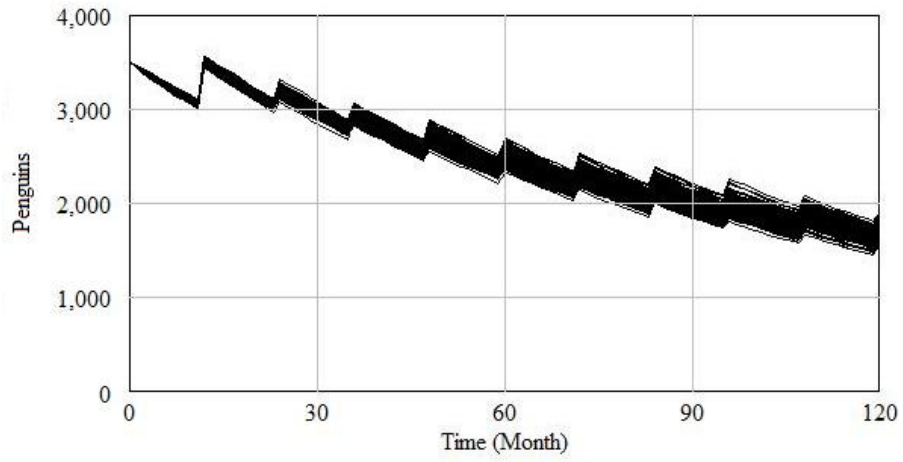


Figure 4.3: Multiple runs of prototype model

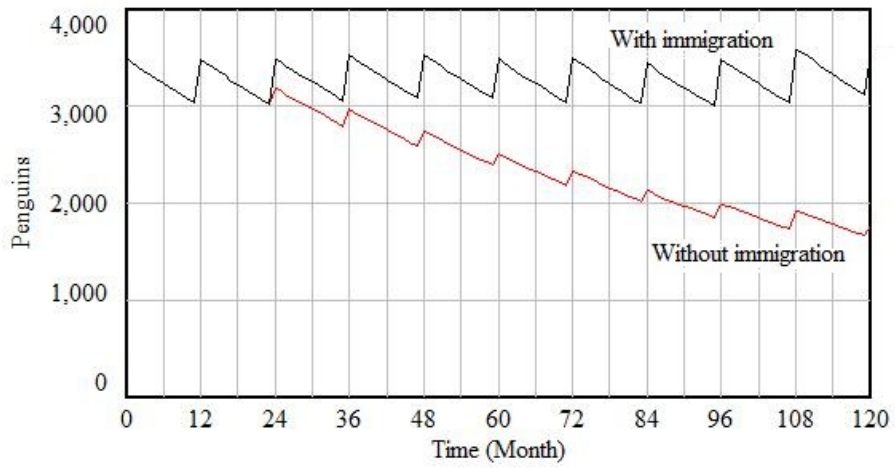


Figure 4.4: Prototype model with immigration

4.8 Discussion

The results from the prototype model show that using the parameters from the Shannon and Crawford model (Shannon & Crawford, 1999), the penguin population cannot sustain itself. This is the same result produced by running the original model although the numerical values obtained differ slightly due to the difference in time steps.

The number of chicks fledged per breeding attempt (Range: 0.2251 to 0.5943, mean of 0.3893) is close to the observed range of values on Robben Island but it is not enough to replace adult penguins lost each year. Immigration can be used to stabilise the population, however this influx of penguins needs to be constant which is not a realistic scenario as immigration should be related to food availability. Test runs show that in order to stabilise the population without immigration, the number of chicks fledged per breeding attempt should be just over 0.7 (as a result of increased egg and chick survival) combined with an adult survival rate of 0.88.

This suggests that the survival rates used in the full model as the base survival rates (before pressures are added) should be higher than the ones used in this model.

4.9 Additions to the prototype model

The model is required to incorporate pressures that act on the penguin population. These pressures include predation, food availability, climate, disease and disasters such as oiling. Figure 4.5 represents the effect of these pressures diagrammatically. In the diagram, E stands for Eggs, C for Chicks, I for Immature and A for Adults.

The effect of each individual pressure will either be added linearly through a logit function if it affects the survival rate or, in the case of disasters, the pressure will simply remove a portion of the age class(es) affected. The use of a logit function ensures that the resulting survival probability (the inverse of the logit function) will remain within reasonable bounds.

The following paragraphs explain how each of the pressures act on the modelled population of penguins. The specific implementation of each applicable pressure in the final model of Robben Island will be detailed in chapter 5.

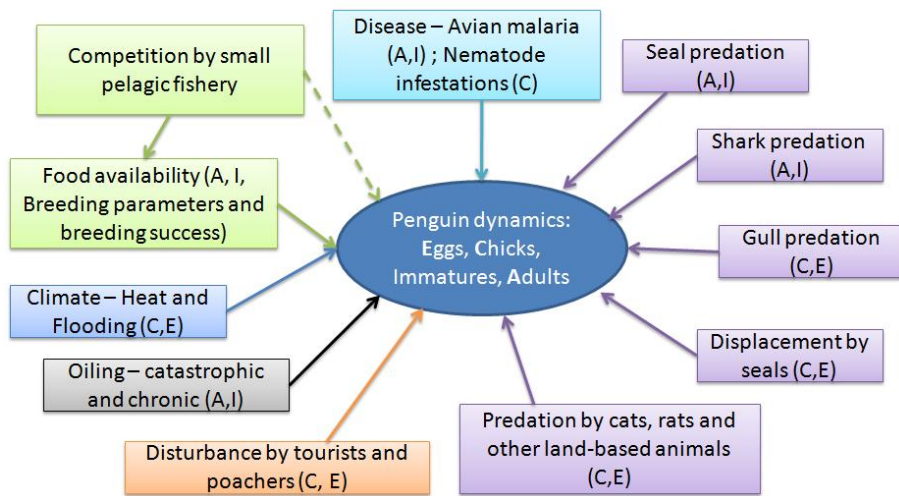


Figure 4.5: Population Pressures

Predators and disturbances: Penguins are preyed upon by sharks and seals as adults, and gulls, cats, rats and other land based predators as eggs and chicks. Eggs and chicks are also affected by seals as the seals displace their nests and by humans that disturb nests. The predators are assumed to have mean abundance in the year that the model starts and abundance that varies annually. Mean abundance will be set as zero in the model and the abundance can vary between -1 and 1. The higher the abundance, the lower the survival rates of the affected age class. Disturbances will either be modelled similarly to predators, or as a catastrophe such as oil spills.

Oil spills: Oiling is divided into chronic and catastrophic oiling according to the impact it has on the penguin population. Both chronic and catastrophic oiling are modelled in a similar fashion, only the parameters differ (frequency and size of effect).

A Poisson distribution will be used as it only takes on discrete values, is fully characterised by its mean value and that mean value is determined by how many events per time unit are expected. This is ideal for modelling the number of oil spills per month in this model. Each Poisson variable in the model is independent of any other random variable.

A value of 1 or more will indicate that an oil spill has occurred. A certain percentage of adult and immature penguins are directly affected by the oil spill

and a percentage of chicks and eggs are affected due to loss of parents. Those affected are removed from the population immediately, however the adult penguins are not removed permanently. After one month, 90% of oiled adults are returned to the population in the same age class but as part of the oiled cohort. These penguins have the same survival rates as non-oiled penguins, but they are much less likely to breed successfully and the chicks they produce have a lower probability of fledging (Barham *et al.*, 2007; Wolfaardt *et al.*, 2008)

Disease: Two diseases can affect the penguin population. The first one, Avian Malaria, affects the adult population while Nematode infestation affects the penguin chicks. The diseases strike the penguin population independently and at random whenever the Poisson variable returns a non-zero value. The diseases reduce the survival rate of the respective age classes by a set percentage in the absence of any effects from other parameters and the effect lasts for a pre-specified number of months.

Climate: The three climatic factors are cold, heat and flooding. Flooding occurs randomly according to a Poisson process and decreases the survival rates of both chicks and eggs. The expected number of flood events per month can be specified at the beginning of the model.

Excessive heat is mainly a risk factor in the summer months when it takes on a value of 1. During the rest of the year, heat is assigned a value of 0.5 or 0.25 depending on the month. A Poisson process determines when heat actually affects the survival rates of chicks and eggs.

Extreme cold is a risk factor during the winter months where it takes on value of 1. During the rest of the year it takes on a value of 0.5 or 0.25 depending on the month. A Poisson random variable determines when cold affects the survival rates of the chicks and eggs.

Food availability: Penguins search for food in two different zones during the year. Zone 1 is approximately 10 to 15 nautical miles around the penguin colony. This is the zone that penguins are restricted to while they are rearing their chicks. Zone 2 encompasses a much larger region around the colony and it is in this zone that penguins feed when they are not rearing chicks.

Penguins feed on sardine and anchovy, species that are also targeted by the small pelagic fishery. The model will read in data containing the biomass of each species in each zone. This information is then transformed through a function

that translates the data into an index of availability. This index varies between -1 and 1, with 1 indicating high prey abundance.

Catch data corresponding to the biomass data is also read into the model. This amount can be varied by adjusting the value of a 'fishing allowed' variable between 0 and 1 to investigate the effect of different levels of fishing on the penguin population. This option only applies to fishing in zone 1.

4.10 Conclusion

The initial prototype model is based on a model used to investigate the effect of harvesting penguin eggs on the penguin population of Dassen Island. As such, it is a good beginning for the penguin pressure model but needs many additions to be truly useful for the client in this instance. Additional information provided by the Penguin Modelling Group participants was used to produce the model in the following chapter. Only the pressures identified as being important to the Robben Island population were included in the full model.

Chapter 5

Robben Island Penguin Population Pressure Model

This chapter describes the final model that was developed for, and with the help of, the Penguin Modelling Group. The population dynamics are described first as they form the basis of the model. Each pressure is then briefly explained as the full model equations are given in appendix B.

5.1 Timing in the Model

The time unit used in the model is months. A model year runs from January to December. The model starts at month 0 so January of the first year would be month 0, and January of the second year would be month 12. In this document, t refers to the current month. Some quantities in the model update annually in January/December. This will be indicated by *Jan* or *Dec* instead of t in the text.

5.2 Definition of symbols

$A_{i,t}$	Number of adult penguins aged i at time t
$A_{i,t}^d$	Number of adults aged i that die in month t
A_i^s	Number of adults aged i that survive to the end of the year
$I_{i,t}$	Number of immature penguins aged i at time t

$I_{i,t}^d$	Number of immature penguins aged i that die in month t
I_i^s	Number of immature penguins aged i that survive to the end of the year
C_t	Number of chicks in month t
C_t^d	Number of chicks that die in month t
C_t^s	Number of chicks that successfully fledge at time t
E_t	Number of eggs in month t
E_t^d	Number of eggs that die in month t
E_t^s	Number of eggs that successfully hatch at time t
s_t^a	Annual survival rate at time t of adult penguins and immature penguins aged 1
s_t^i	Proportion of penguins born that year that survive to the end of the year
s_t^c	Fledging success of chicks at time t
s_t^e	Hatching success of eggs at time t

5.3 Initial set up

There are eight age classes:

- Eggs
- Chicks
- Two immature age classes: Immature penguins born this year and immature penguins born the previous year
- Four adult age classes: adults aged 2, 3, 4 and 5 or older

An immature or adult penguin is assigned to an age class based on its age next 'birthday' as at 1 January.

The number of adult penguins from age 2 upwards is set at an initial amount. This is assumed to be the total number of adult penguins at the beginning of the first year of simulation (January or time 0). The model then calculates how many penguins are in each adult age group by assuming the population is initially in equilibrium. The survival probability used in this calculation is the mean adult survival rate (Crawford *et al.*, 1999)

The number of immature penguins aged 1 at the beginning of the year is calculated by dividing the number of penguins aged 2 by the annual survival

probability. The number of eggs, chicks and immature penguins aged 0 that year are each set to zero, as the first eggs are laid in February.

5.4 Population Dynamics

5.4.1 Adult penguins

Adult penguins experience mortality in month t according to the equation:

$$A_{i,t}^d = A_{i,t} \left(1 - (s_t^a)^{\frac{1}{12}}\right) \text{ for } i = 2, \dots, 5 \quad (5.1)$$

At the end of each year, surviving adult penguins move up to the next age class according to the equations:

$$A_i^s = A_{i,Dec} - A_{i,Dec}^d \text{ for } i=2, \dots, 5 \quad (5.2)$$

$$A_{i,Jan} = A_{i-1,Dec}^s - A_{i,Dec}^s \text{ for } i=3, 4 \quad (5.3)$$

$$A_{2,Jan} = I_{1,Dec}^s - A_{2,Dec}^s \quad (5.4)$$

$$A_{5,Jan} = A_{5,Dec}^s + A_{4,Dec}^s \quad (5.5)$$

5.4.2 Immature penguins

Immature penguins aged 1 experience mortality in month t according to the equation:

$$I_{1,t}^d = I_{1,t} \left(1 - (s_t^a)^{\frac{1}{12}}\right) \quad (5.6)$$

At the end of each year, surviving immature penguins move up to the first adult age class according to the equation:

$$I_1^s = I_{1,Dec} - I_{1,Dec}^d \quad (5.7)$$

$$I_{1,Jan} = I_{0,Dec} - I_{1,Dec}^s \quad (5.8)$$

Immature penguins aged 0 (I_0) experience monthly mortality (in contrast to the prototype model). This mortality rate depends on the time between fledging and the end of the year. The model has 7 subclasses to represent the different periods (from one month to seven months) that the penguins will spend in this age class. The overall proportion of penguins that survive from fledging to the end of the year is equal to the immature survival rate. This method ensures that the effects of various pressures act appropriately on this age class. The

equation to determine monthly mortality in subclass j is:

$$I_{0,j,t}^d = I_{0,j,t} \left(1 - (s_t^j)^{\frac{1}{j}}\right) \text{ for } j = 1, \dots, 7 \quad (5.9)$$

5.4.3 Chicks

Chicks fledge after 3 months. This value was chosen as fledging takes between 60 days and 130 days (average of 95 days)(Crawford *et al.*, 2010). Each month chicks experience mortality in month t according to the equation:

$$C_t^d = C_t \left(1 - (s_t^c)^{\frac{1}{3}}\right) \quad (5.10)$$

After three months, remaining chicks are assumed to have fledged successfully and move into age class I_0 according to the following equations:

$$C_t^s = E_{t-3}^s s^c \quad (5.11)$$

$$C_t = C_{t-1} + E_t^s - C_t^d - C_t^s \quad (5.12)$$

s^c is the product of the monthly survival rates over the fledging period.

5.4.4 Eggs

The hatching period for eggs is assumed to be one month as it is usually an average of 40 days (Crawford *et al.*, 2010). Eggs experience monthly mortality according to the equation:

$$E_t^d = E_t(1 - s_t^e) \quad (5.13)$$

The eggs that do not die hatch after a month and become chicks as per equation 5.12. Eggs are increased by first clutches and by clutches that are relaid following clutch loss, brood loss or successful fledging of a brood by a breeding pair. This is discussed further under the section on breeding parameters.

5.5 Breeding parameters

This section details how the model calculates the number of eggs laid each month. The number of eggs laid in month t is the sum of the number of first clutches laid in month t and clutches laid following clutch or brood loss, or the successful fledging of a brood.

5.5.1 Calculation of breeding pairs

The number of potential breeding pairs (PBP) is calculated as:

$$PBP_t = \frac{\sum_i A_{i,t} b_i}{2} \quad (5.14)$$

b_i is the proportion of penguins aged i that are able to breed that year. The proportion of penguins able to breed in each age group is calculated from age at first breeding estimates. Each b_i is sampled from a truncated normal distribution with means and standard deviations taken from Crawford *et al.* (1999). It is assumed that all penguins able to breed can find a mate as once mated, penguins usually remain together for life and first time breeders can emigrate to other colonies to find a mate Crawford *et al.* (2010).

The actual number of breeding pairs (ABP) is:

$$ABP_t = PBP_t * B \quad (5.15)$$

B is the proportion of potential pairs that do breed that year. B is higher when food has been abundant in the previous two years, and lower when food has been lean.

5.5.2 Initial egg laying

The laying rate (L) is the percentage of breeding pairs that lay their first clutch in month t . The majority of pairs (23% each month) lay their first clutch between February and April each year. 27% lay between May and July (9% each month) with 4% laying their first clutch in August.

Clutch size (C) is determined as the weighted average of 1 egg per pair and 2 eggs per pair.

The number of eggs laid per month (initial clutches) is:

$$\text{Number of eggs laid in month } t = ABP_t * L_t * C_t \quad (5.16)$$

5.5.3 Relaying

Clutch loss, brood loss and successfully fledging at least one chick can result in breeding pairs laying a second clutch during the year. This clutch is laid two months after any of the three events mentioned above occur. Only a proportion of breeding pairs that experience any of those events relay. Second clutches

are only able to be laid until the month of August when the last of the initial clutches are laid to prevent clutches being laid at unrealistic times of the year.

5.5.4 Nest calculations

Let C be the clutch size (as set in the model) and let n_1 and n_2 be the number of one egg and two egg nests respectively.

By definition:

$$C = \frac{E_t}{n_1 + n_2} \quad (5.17)$$

But

$$E_t = n_1 + 2n_2 \quad (5.18)$$

Therefore

$$C = \frac{E_t}{E_t - n_2} \quad (5.19)$$

It therefore follows that the number of nests containing two eggs is calculated as

$$n_2 = \frac{E_t(C - 1)}{C} \quad (5.20)$$

The number of nests containing one egg is then:

$$n_1 = \frac{E_t}{C} - n_2 \quad (5.21)$$

The number of 1 chick nests and 2 chick nests is calculated from the number of 1 egg and 2 egg nests. As a 2 chick nest can only occur if both eggs of a 2 egg nest hatch:

$$\text{number of 2 chick nests} = n_2(s_t^e)^2 \quad (5.22)$$

1 chick nests occur when an egg from a 1 egg nest hatches or when only one egg from a 2 egg nest hatches. This is calculated as:

$$\text{number of 1 chick nests} = n_1 s_t^e + 2n_2(s_t^e)(1 - s_t^e) \quad (5.23)$$

The factor of 2 is due to the fact that either of the two eggs in the nest can survive. The number of whole clutches lost each month is:

$$\text{clutch loss at time } t = n_1(1 - s_t^e) + n_2(1 - s_t^e)^2 \quad (5.24)$$

The number of broods lost and the number of broods successfully fledged for 1

chick nests is simple as the chick either survives for the three months or dies before the end of three months.

The brood loss and brood success for 2 chick nests is slightly more complicated as the survival of the two chicks is not necessarily independent. The scenarios that can occur over the course of three months are shown in the table below:

Start of month 1	End of month 1	End of month 2	End of month 3	Result
2	2	2	2	Success
2	2	2	1	Success
2	2	2	0	Loss at month 3
2	2	1	1	Success
2	2	1	0	Loss at month 3
2	2	0	0	Loss at month 2
2	1	1	1	Success
2	1	1	0	Loss at month 3
2	1	0	0	Loss at month 2
2	0	0	0	Loss at month 1

Table 5.2: Brood loss/success table

Assuming independence, the number of broods lost and the number of broods successfully fledged is a matter of multiplying the number of 2 chick nests by the appropriate survival probabilities for each scenario. When this approach was applied to actual data from Robben Island, it resulted in an underestimation of brood loss and an overestimation of brood success. This suggests that the fates of the two chicks are not independent. An adjustment factor for brood loss, and for brood success, were computed as the mean adjustment factors required to closely reproduce the observed data. Currently an adjustment factor of 1.38 is applied to brood loss and 0.77 is applied to brood success as seen below where bs_1 and bs_2 are respectively the number of one chick and two chick broods fledged successfully and, similarly, bl_1 and bl_2 are the number of one and two chick broods that are lost.

$$\text{brood success} = bs_1 + bs_2 * 0.77 \quad (5.25)$$

$$\text{brood loss} = bl_1 + bl_2 * 1.38 \quad (5.26)$$

5.6 Pressures

5.6.1 Predators

The two predation pressures affecting penguins on Robben Island are sharks and land predators. Sharks are a direct danger to adult and immature penguins, and an indirect danger to chicks and eggs through the removal of parent penguins.

Land predators target chicks and eggs directly. These include predators such as feral cats and rats on the island. It was suggested that vehicles could also be considered land predators, however their effect would not be limited to chicks and eggs. It was decided not to include vehicles in this model.

The abundance of predators is represented on a scale of -1 to 1 with 1 being the highest abundance. A value of 0 represents an average abundance of predators that year. The abundance varies around a mean of 0 according to a truncated normal distribution with a standard deviation of 0.3.

5.6.2 Oiling

Oiling is split into catastrophic oiling and chronic oiling. The values given in the next paragraphs are base values for the model and can be altered.

Catastrophic oiling occurs on average every 50 years according to a Poisson process. The Poisson distribution was chosen as it is a discrete distribution over the positive integers and it is characterized by its mean value. The mean is the rate at which events occur per month. Catastrophic oiling directly affects approximately 24% of the adult and immature penguins (taken from the Vortex model of Whittington *et al.* (2000)) and indirectly affects a smaller proportion of chicks and eggs through the loss of parents. This smaller proportion is taken as 0.24 multiplied by the percentage of penguins currently parents of chicks and eggs respectively. It is assumed that the oil spill is cleaned up within the month.

Chronic oiling occurs on average every 3 months and affects less than 1% of adults and immatures with a smaller portion of chicks and eggs affected (as per catastrophic oiling). The frequency of spills as well as the proportion of adults and immature penguins affected were calculated from SANCOBB data.

Adult penguins that are oiled are assumed to be taken for cleaning and rehabilitation. Ninety percent of these penguins are rehabilitated to the colony one month after the oil spill. They are now marked as having been oiled and, as a result, have a much lower chance to breed. Their survival rates remain the

same as penguins that have never been oiled, but chicks born to oiled parents have a reduced fledging success.

5.6.3 Flooding

Flooding occurs in a similar way to oil spills. Floods occur randomly by sampling from a Poisson distribution with a mean of 1/60. This means floods occur on average every 5 years. Only chicks and eggs are affected by the flooding. A flood will kill approximately 40% of chicks and eggs that month. As no data are available on mortality rates due to flooding, these values are an estimate. Sensitivity analysis showed that the model is not sensitive to the estimates of time between floods or the effect of floods on chicks and eggs.

5.6.4 Climate

Penguin chicks and eggs are vulnerable to extremes of heat and cold. In the model, both heat and cold can affect the chicks and eggs throughout the year although the magnitude of the effect is dependent on the time of year. A hot spell has a much higher impact during the summer months, when the temperature is likely to be higher, than a hot spell during winter. A similar set up exists with cold spells.

A hot spell during summer reduces egg and chick survival rates to 50% of their base values while a cold spell during winter reduces egg and chick survival rates to 70% of their base values. Estimates of the time between hot and cold spells are used in the model as no data is currently available.

5.6.5 Food availability

Two zones exist around the island. The first zone, Zone 1, extends approximately 10 to 15 nautical miles around the island. Zone 2 is a larger, general region around the island indicating the availability of prey (small pelagic) to penguins when they are not rearing chicks.

5.6.5.1 Zone One

The recruit biomass of anchovy and sardine in Stratum D (figure 5.1) is used to indicate prey availability in Zone 1. This is the zone in which penguins with nests are restricted to foraging. It is assumed that the abundance of food in this zone will have an impact on chicks and eggs as low food abundance could

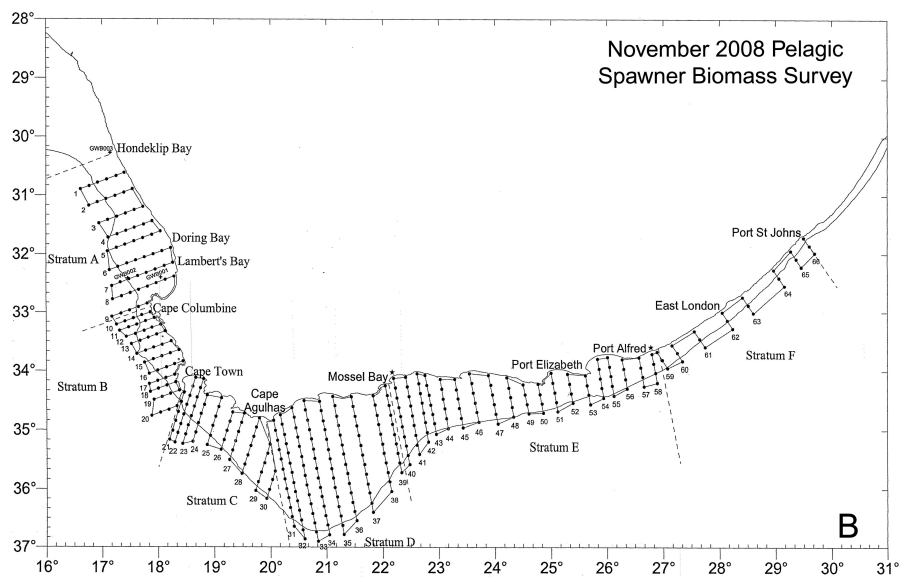
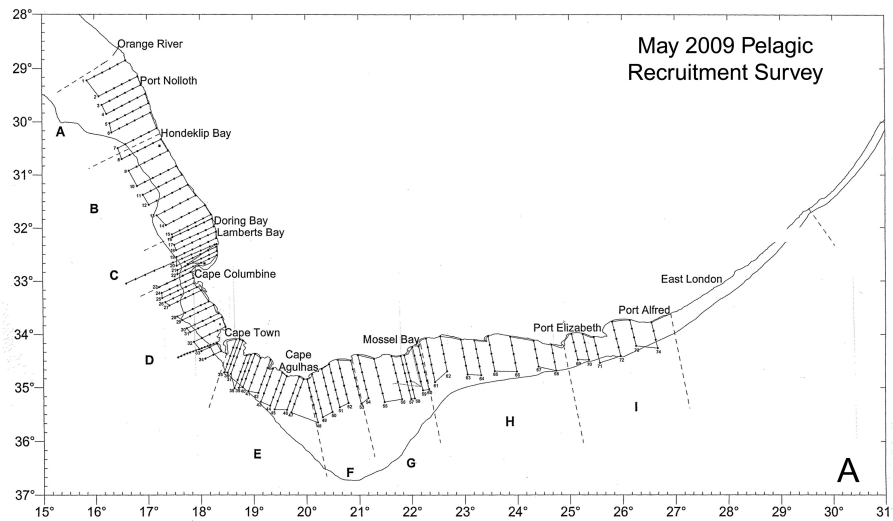


Figure 5.1: Map showing the strata used during the biomass surveys

lead to adult penguins abandoning nests to find food. High food abundance increases both hatching and fledging success.

The May recruit biomass data from Stratum D is read in from a spreadsheet. This becomes the mean monthly biomass available for the year. Each month a portion of the total biomass is assumed to be close enough to the island to be available to the penguins. The amount made available each month is normally distributed with a mean of the May recruit biomass, and a standard deviation equal to the standard deviation of all the years' recruit biomass amounts on the spreadsheet. The standard deviation remains constant throughout the simulation but the mean changes each year.

The biomass available around the island is decreased by fishing before becoming available to the penguins. Fishing was initially introduced into the model as a percentage of biomass caught each month. The percentage caught varied according to a truncated normal distribution with a certain mean and standard deviation. The amount of biomass removed through fishing was capped at 50%.

Further development of the model led to catch data being used to model the fishing in Zone 1 as this is a more realistic representation of fishing effort around the island. Monthly catch data, coupled with the biomass data for that year, is read into the model from a spreadsheet. This forms the basis for the amount of biomass removed by fishing around the island.

A complication arose when introducing the catch data. The catch data is calculated from the proportion of the area of a pelagic block position, a block 10 by approximately 8.5 nautical miles, that falls within a 15 nautical mile radius of Robben Island. This results in a area of approximately 456 square nautical miles. The area covered by Stratum D is 2 600 square nautical miles (Dagmar Merkle, pers. comm.). This is substantially larger than the catch data area and therefore, assuming that biomass in Stratum D is reduced only by catch in the 15 n.m radius around the island, leads to fishing having a negligible effect. A simple correction would be to assume that biomass is uniformly available in Stratum D and therefore to proportionally reduce the biomass available by the proportion of the catch area to the area of Stratum D. In the absence of more detailed information regarding the availability of schools in Stratum D, this correction will have to suffice.

The amount of prey available is then converted to a scale from -1 to 1 by comparing it to the overall minimum, maximum and median recruit biomass from the spreadsheet data. A value of 1 represents a high abundance of food. A non-linear function is constructed and the generic form is shown in table 5.3.

Zone 1 Biomass	0	m	m + σ	m + 2 * σ	m + 3 * σ
z1	-1	0	0.33	0.67	1

where m is the median of the Stratum D anchovy and sardine biomass and σ is the standard deviation of that biomass

Table 5.3: Zone 1 food availability function

5.6.5.2 Zone Two

Food availability was shown to have an important impact on breeding in Crawford *et al.* (1999). Work done by Lauren Waller and Les Underhill (personal email) indicates that, although Robben Island is situated in Stratum B (with respect to measurement of anchovy and sardine spawner biomass surveys), there is a relationship between the kilojoule (KJ) content of anchovies and sardine in Stratum C in the previous two years and the variation in breeders on Robben Island (adjusted R^2 of 61%). Stratum C data was therefore used to indicate general availability of prey in Zone 2 as this has an impact on breeding parameters. The exact relationship between breeders and calorific quantity is not used in the model, as it does not fit into the model structure. Instead, it was used as a basis to determine categories of Zone 2 food abundance that then determine the mean values of the breeding parameters. The food availability in Zone 2 is therefore the sum of the calorific content of anchovy and sardine spawners surveyed in November in Stratum C, lagged for the one and two years. This is then transformed into an index from -1 to 1 (with 1 indicating a high calorific content) via a non-linear function.

Zone 2 food availability also has an impact on adult and immature survival. Immature survival in Namibia has been shown to be highly sensitive to food availability in the general region around the island (Lynne Shannon, personal email). The adult survival effects depend on the current KJ content and the previous year's KJ content as this has an effect on the penguins during moulting, and the immature survival effect depends on only the current year's KJ content. The calorific values are transformed into an index from -1 to 1 via separate non-linear functions that are shown in table 5.4. Note that the first two functions take in the sum of the previous two years of Stratum C biomass whereas the last function (immature survival) only has one year of biomass as input. This is the reason why the first row is double that of the fourth row.

Zone 2 Biomass	0	$2*(m - 2 * \sigma)$	$2*m$	$2*(m + 2 * \sigma)$	$2*(m + 3 * \sigma)$
z2(adult survival)	-1	-0.25	0	0.25	1
z2(breeding prop)	-1	-0.25	0	0.25	1
Zone 2 Biomass	0	$m - 2 * \sigma$	m	$m + 2 * \sigma$	$m + 3 * \sigma$
z2(immature survival)	-1	-0.25	0	0.25	1

where m is the median of the combined anchovy and sardine Stratum C biomass (converted to kj) and σ is the standard deviation of the kj converted biomass

Table 5.4: Zone 2 food availability function

5.6.6 Density effects

There are three levels of population size that have an effect on the proportion of potential pairs that actually breed. Adult survival was not taken into account as immature penguins would settle in other colonies if the island was overpopulated. All three levels are set in the input spreadsheet. The highest population threshold would be the carrying capacity. This would typically be close to the theoretical maximum number of penguins the island could sustain. If the carrying capacity of the island is reached, the number of penguins able to breed is severely restricted in the model (the mean breeding proportion is reduced by 0.6).

Below carrying capacity are a low and a very low population thresholds. The low threshold represents a small population size where low competition for resources causes a small increase (0.2) in the mean breeding proportion.

The very low threshold represents a very small population size where an allee effect, that is a decrease in population growth at low density, is present (Courchamp *et al.*, 1999). For reasons such as gender imbalance, or decreased effectiveness in breeding, as the population drops below a certain level, these factors lead to a decrease in the number pairs able to be formed. This is represented as a decrease (-0.1) in the mean breeding proportion.

Tables B.17 and B.7 detail the equations that determine the effect of population size on the proportion of potential breeders that actually breed. In essence it is a series of IF statements that determine whether the population size is above or below each threshold and then apply the appropriate modifier to the mean of the random component of the breeding proportion.

Behavioural ecology suggests that it is also likely that a very small population will lead to decreases in survival rates. This will be considered for future inclusion into the model.

5.7 Comments on the model

The model attempts to represent reality in a manner that is simple enough to understand yet complex enough to reproduce the important behaviour of the system being modelled. At the model launch (3 November 2010, detailed in section 3.3.3.1), some questions were raised as to why certain aspects of penguin biology were not included in the model. From the comments received the following points may be viewed as justifiable simplifications in the current model:

- for the purpose of the model, the effect of foraging effort and the amount of sardine and anchovy eaten by other predators were considered unnecessary detail
- predators, such as gulls and seals, are not present in the model as they are not considered important predators on Robben Island
- similarly tourism and other human disturbances were classified as minor effects on Robben Island and were not included in the model

5.8 Conclusion

This chapter examined the structure of the model with reference to the population modelling and the specific pressures that were selected for Robben Island. The model can be adapted to other islands by varying the parameters used as well as the addition/subtraction of pressures applicable to each specific island.

The next chapter shows the results obtained from the model for realistic runs, ideal runs and possible management strategies.

Chapter 6

Model results

This chapter looks at four scenarios and the results produced by the model for each scenario. The first two use a random sample from the data and are intended to represent one possible outcome of the scenario. The last two scenarios use the original biomass and catch time series and the results shown are a summary of the outcomes of two hundred runs, varying the random number stream used each time. The pressures used in each scenario are covered in the detail descriptions. Results have been plotted in *Vensim*.

6.1 A stable population

The first scenario investigates the parameters needed to produce a stable penguin population in the absence of all pressures. This is interpreted in terms of the model as predators and food abundance staying at average levels for the entire time period, and no natural or man-made disasters occurring (i.e. no oiling, flooding or extreme weather events). There is still ‘natural’ annual variation in the breeding and relaying parameters.

As noted in chapter 4, section 4.8, the original survival estimates lead to a declining population unless immigration is introduced. This is shown by the **Total adults (original)** line in figure 6.1.

The prototype model showed that a stable population could be achieved with an adult survival rate of 0.88 and that the number of chicks fledged per breeding attempt (clutch size * egg survival * chick survival) should be just over 0.7. In the full model adult survival was then set to 0.88 and various values for

egg and chick survival were tried. It was found that if egg survival was set to 0.648 and chick survival was set to 0.59 (thus producing 0.703 chicks fledged per breeding attempt), the population remain relatively stable over 20 years. This is shown by the **Total adults (revised)** line in figure 6.1. These survival estimates were then used for the other scenarios in this chapter.

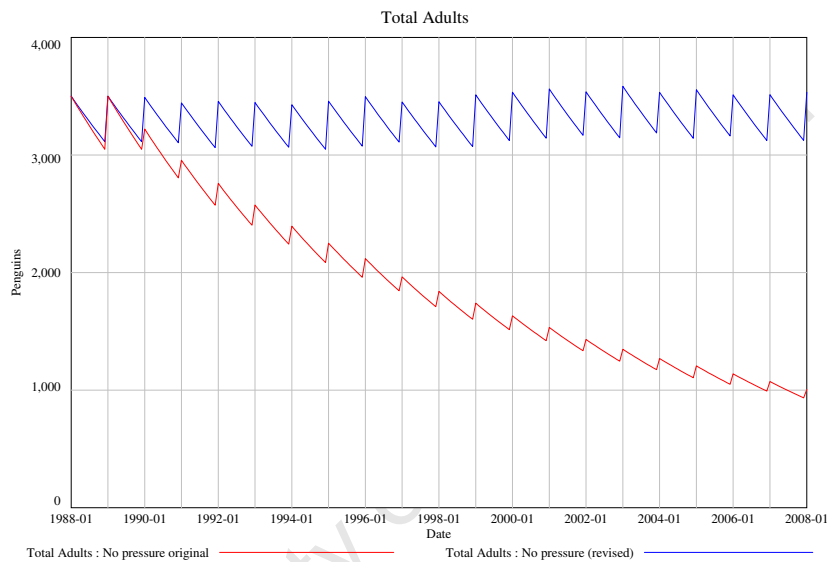


Figure 6.1: Population size under original parameters and revised parameters

6.2 Long term, ideal conditions

This scenario serves to illustrate how the penguin population increases rapidly when food is abundant and interference by man is removed.

This scenario used food levels twice what they currently are, and no fishing was allowed. Oiling, both chronic and catastrophic, was not allowed. Predators, flooding and extreme weather events remained in the model unchanged. The model was run for 500 years, and an artificial carrying capacity of three million was used. The penguin population is initially 3 500 adults.

As seen in figure 6.2, the penguin population increases dramatically over the first hundred years and then oscillates between two and five million adults. The

population doubles in the first seven years and, by year 50, has reached around 150 000 adults. At year 75 the rate of increase picks up strongly as the result of an ever increasing number of potential breeding pairs, until the population peaks at 5.5 million adults.

Although the carrying capacity is set at three million, it can be seen that the population oscillates around a value closer to 3.5 million. The pressure on a population above carrying capacity, namely a severe decrease in breeding proportion, is counteracted by the strong upward pressure from food abundance, and therefore does not act swiftly enough to keep the population around three million. In scenarios with realistic food levels, this is not a problem.

This run serves to illustrate the potential of the modelled population to increase dramatically, given abundant food and safety from the detrimental effects of oiling.

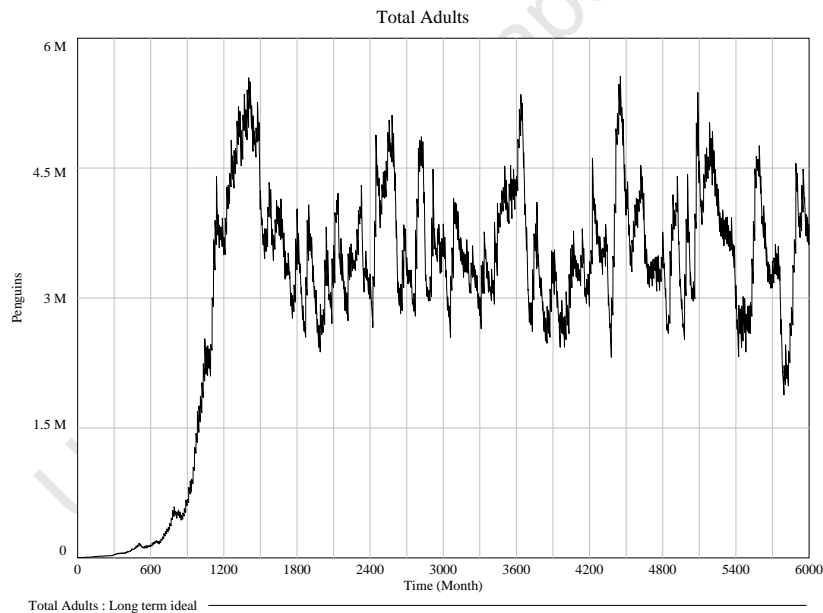


Figure 6.2: A long term population projection under extremely good conditions

6.3 Realistic scenarios

The biomass data used in the model runs from 1987 to 2009. During this time frame the actual penguin population on Robben Island increased from 3 468 moulting adults in the split year (July to June) 1988/1989 to a high of 16 975 in 2003/2004 before decreasing to only 3 745 in 2008/2009 (Figure 6.3).

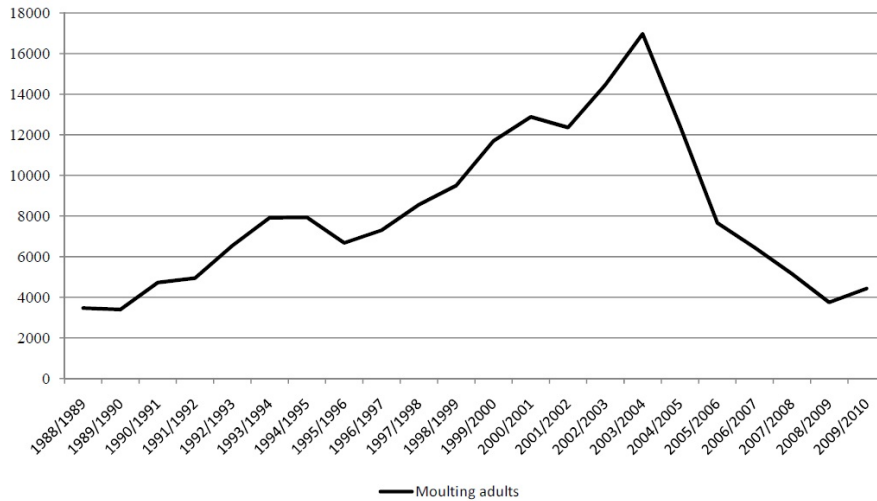


Figure 6.3: Number of moulting adults around the coastline of Robben Island

As mentioned in du Toit *et al.* (2004), the growth rate of 12.4% seen between 1992 and 2003 is greater than the breeding productivity of the penguins on Robben Island. The higher than expected increase is attributed to immigration of birds from Dyer Island.

The model was first run with all the pressures on, realistic biomass and catch data as well as accurate timing of the Cape Town Harbour spill (May 1998) and the Treasure oil spill (June 2000) (Wolfaardt *et al.*, 2009). The amount of oil spilt in the Cape Town Harbour spill was approximately a tenth of that spilt in the Treasure spill so the Cape Town Harbour spill in the model produces a value of 0.1 compared to a value of 1 for the Treasure spill.

The results of 200 runs with the random noise stream varied is shown in figure 6.4. Note that immigration is not modelled here. As can be seen from the graph, the population initially remains fairly stable in the majority of runs before declining. There is a slight recovery in the early 2000s but by the end of

the 21 years the population is, on average, around 2 000 adults (minimum: 1 757, maximum: 2 672).

The original parameter values based on data and expert opinion did not produce a model run that was a close fit to the data. This was largely due to the absence of immigration in the model, an important factor for the period between 1992 and 2003. The model provided the opportunity to fine tune the parameter values in order to understand the underlying factors that influenced the population growth over this time period.

The closest fit was achieved by turning off chronic oiling, flooding and extreme weather events. In addition, predator abundance was modified to have a mean of -0.5 (low mean abundance) until 2003 and thereafter a mean of 0.5 (high mean abundance). The immature survival rate for each run was then varied between 0.51 and 0.99 in order to replicate a situation with immigration in to the Immature 1 age class. This replicates a situation where not only do immature penguins born on Robben Island return to the island but that immature penguins from other colonies chose Robben Island as their breeding colony.

Two hundred runs of the model produced the results seen in figure 6.5. It can be seen that high immature survival, represented by the top grey band, combined with the low then high predator abundance results in a close fit to the actual data. If chronic oiling had been included, more immigration would be required to produce the same maximum population.

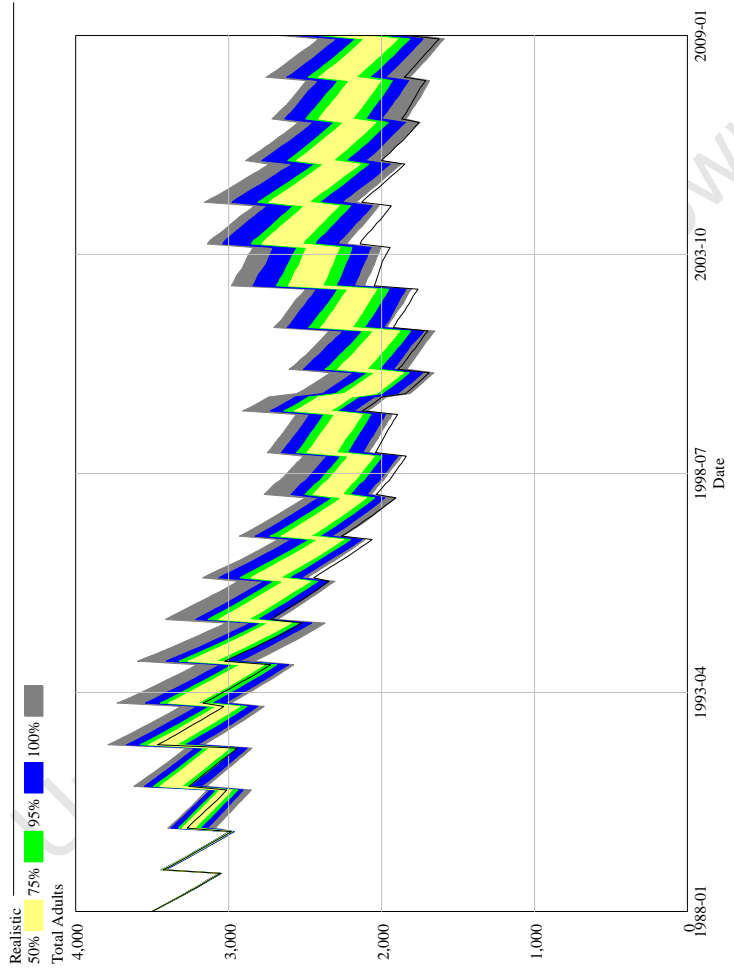


Figure 6.4: Model runs showing population without immigration

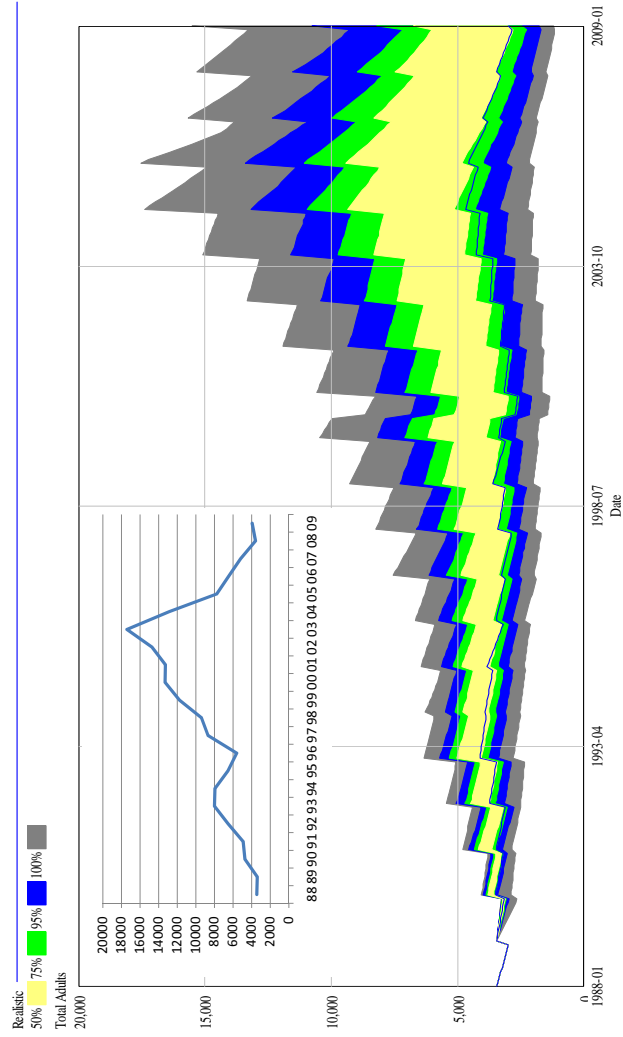


Figure 6.5: Model runs showing results with varying levels of immigration

6.4 The impact of fishing around the island

This section also uses realistic biomass and catch data as well as timing of oil spills (one in May 1998 and another in June 2000), however the first oil spill is not smaller than the second as in the section above.

The model was initially run with all pressures active and no island closure. The results from this run formed the baseline for successive runs. The model was then run with three year island closures (fishing not allowed in Zone 1), starting with the closure beginning in 1988 and then starting the island closure one year later for each successive run. The final run occurs when the island closure begins in 2006.

Important things to note when looking at the results is that the effect on the adult population due to the restriction on fishing only starts to appear two years after the restriction is put in place. This is because, in the model, the food abundance in Zone 1 only affects the survival rates of eggs and chicks (hatching and fledging success). It takes two years for an egg to enter the first adult age class (Age class I1 - Immature One). It then takes an additional year before that penguin is a potential breeder. It is for this reason that only the total number of adults is reported.

Table 6.1 shows the year in which the island is first closed, the maximum difference due to island closure in the total number of adults over the 21 years, the difference in the total number of adults at the end of 21 years, and any factors that may have an effect on those differences.

The results for the first five runs are affected by the initial population distribution that assumes that the population is in equilibrium. This effect diminishes in each successive run until all penguins initially present on the island have either died or have survived to the final age class.

The results for island closures that start in the years 1996 to 2000 are all affected by at least one oil spill occurring during the closed period. The smaller differences in these results are partially due to the loss of penguins in all age classes due to oiling, and to the lower breeding probabilities of the rehabilitated penguins.

Results that are unaffected by oiling or the initial population show that, given the set of pressures acting on the population, closing the area around the island to fishing results in a minimum difference of 9 and a maximum difference of 22 adult penguins at the end of 21 years. Furthermore the maximum difference in the total number of adults at any time during the 21 years was at least

that at the end, and often even greater.

There is evidence that restricting fishing around the island could be beneficial to the penguin population. These results are, however, dependent on the time series used for the pressures in this model for which there is no real world data and are subject to the limitations of the model.

Year	Total adults		Factors
	Max	End	
1988	91	41	Initial
1989	68	32	Initial
1990	48	25	Initial
1991	37	22	Initial
1992	30	18	Initial
1993	23	16	
1994	18	13	
1995	12	9	
1996	11	8	Oil
1997	9	8	Oil
1998	6	5	Oil x2
1999	4	3	Oil
2000	14	10	Oil
2001	24	19	
2002	25	22	
2003	15	13	
2004	11	10	
2005	13	13	
2006	11	11	

Initial: Population affected by initial distribution

Oil: Oil spill occurred during closed period

Table 6.1: The differences in adult population due to three year island closures

6.5 Conclusion

The first scenario simply shows that the base survival rates in this model need to be higher than the observed survival rates on Robben Island. This is obviously due to all pressures on the penguins being included in the observed survival rates. The value of this scenario is that the new base survival rates can be used for other scenarios.

The second scenario illustrates an ideal hypothetical world that would allow the penguin population to not only survive in the long term, but flourish. This

level of increase is not realistic as it would require a substantial increase in fish stocks, as well as a substantial reduction in oiling. It does however suggest that attempts to improve fish stocks, and to curb the impact of oiling on penguins, would be beneficial.

The third section in this chapter serves to illustrate the importance of immigration in future versions of this model. Once the model has been expanded to cover other islands, migration between colonies will become important. Research into how immigration is linked to food abundance or, indeed, if immigration is also linked to other factors, is needed to more fully understand its impact.

Finally, the results from closing the area around the island to fishing indicate that this is a management action that could positively affect the penguin population on Robben Island. The results from the model also indicate that events such as oiling can mask the benefits of closure. This will be important when the results from the real-world experiment are examined.

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Chapter 7

Sensitivity Analysis

7.1 Pressures in isolation

Each pressure was evaluated in isolation of the effects of the other parameters. Each parameter in turn was evaluated at 5 levels. The first and last levels were 'extreme' values - usually half and 1.5 times the usual parameter when possible. The middle level was the current parameter value. The second and fourth levels were small changes (10% above and below) from the current value. The table of values tested for each parameter is included in appendix E.

The model was run 200 times for each level of each parameter. Each run had a random noise seed taken from a uniform distribution. This meant that the noise generated by each random function would be different for each of the 200 runs. This vector of 200 randomly generated noise seeds remains the same for each successive test so that differences in the results are only based on changes to the parameters.

The evaluation of the effect of the changes in level on the penguin population was based on the change in the probability of the population at the end of 20 years being below a threshold percentage. Five thresholds were used. These were based on a percentage of the starting population: 100%, 75%, 50%, 25% and 5%. The result below show the percentage of total runs for which the population is below each threshold. Note that in the tables below, the last two columns sum to one. The first four columns provide a breakdown of the fifth column (the probability that the final population is below 100% of the starting population).The range of the population results was also examined to provide

information on which parameters produced the greatest range of results when altered.

The following sections summarise the results for each pressure:

7.1.1 Sharks

Note that, in the table below, a decrease in the base parameter translates to an increase in shark predation in the model as a larger proportion of penguins will be killed by sharks.

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0	0.935	0.065
Small decrease	0	0	0	0	1.000	0
Large decrease	0	0	0	0.685	1.000	0
Small increase	0	0	0	0	0.645	0.355
Large increase	0	0	0	0	0.470	0.530

Table 7.1: Changes to the effect of sharks

As the effect of the shark predation increases, the minimum and maximum values of the population after 20 years increase as well. The range of values for each of the five parameter estimates is fairly similar, but does increase as the effect of the predator decreases (from a range of 386 penguins at the end of the time period at the lowest estimate to 477 penguins at the highest).

Small changes in the effect of shark predation do not seem to have a large impact on the model results.

7.1.2 Land predators

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0	0.515	0.485
Small decrease	0	0	0	0	0.460	0.540
Large decrease	0	0	0	0.015	0.450	0.550
Small increase	0	0	0	0	0.540	0.460
Large increase	0	0	0	0	0.515	0.485

Table 7.2: Changes to the effect of land predators

The range of values for each test becomes successively smaller as one moves from the lowest to the highest parameter estimates. The minimum population

values increase as expected (an increase in the parameter estimate results in a decreased effect on the chicks and eggs) but, peculiarly, the maximum values decrease as the estimates increase. This is a result of the way the model is set up. A large negative effect on chick and egg survival, when the land predator number are high, corresponds with a large positive effect on chick and egg survival when land predators are scarce.

The effect on the penguin population is most noticeable for the lowest parameter estimates as this introduces the greatest variability in the chick and egg survival rates.

7.1.3 Catastrophic oiling

The analysis of this parameter was two fold. First, the average time between oil spills was varied while the effect was held constant, then the effect was varied while the time between spills remained constant.

7.1.3.1 Timing

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0.050	0.665	0.335
Small decrease	0	0	0	0.050	0.685	0.315
Large decrease	0	0	0	0.115	0.770	0.230
Small increase	0	0	0	0.035	0.645	0.355
Large increase	0	0	0	0.015	0.610	0.390

Table 7.3: Changes in frequency of oiling

The maximum population value of each scenario is the same - it is the number of adults that results from no catastrophic spill occurring during the twenty year period. The minimum number remains the same for the base, small increase and small decrease scenarios and, as expected, decreases for the large decrease and increases for the large increase. The range remains roughly the same for each scenario.

The shortest average time between catastrophic oiling (300 months) is longer than the time that the model is run for, and therefore changes to this parameter (in isolation at least) do not have a large effect on the outcome of the model.

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0.050	0.665	0.335
Small decrease	0	0	0	0.035	0.665	0.335
Large decrease	0	0	0	0	0.665	0.335
Small increase	0	0	0	0.055	0.665	0.355
Large increase	0	0	0.010	0.150	0.665	0.335

Table 7.4: Changes to the effect of oiling

7.1.3.2 Effect

The maximum value the population reaches is the same as in the previous subsection, and occurs when no oil spill occurs. The minimum value decreases, as expected, as the parameter values increase. The range therefore increases as the parameter values increase.

Changes to the effect a catastrophic oil spill has on the penguin population have a relatively small effect on the outcome as a catastrophic oil spill is so rare compared to the length of the model run.

7.1.4 Chronic oiling

As with the catastrophic oiling above, the analysis of this parameter was two fold. First, the average time between chronic oil spills was varied while the effect was held constant, then the effect was varied while the time between spills remained constant.

7.1.4.1 Timing

As chronic oiling is so frequent, the time between spills was varied between 1 and 5 months, with 3 months as the base value.

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0.300	1.000	0
Small decrease	0	0	0	0.960	1.000	0
Large decrease	0	0	0.010	1.000	1.000	0
Small increase	0	0	0	0.010	1.000	0
Large increase	0	0	0	0	1.000	0

Table 7.5: Changes in frequency of chronic oiling

A small change in the frequency of chronic oiling can have large impact on the end value of the population.

7.1.4.2 Effect

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0.300	1.000	0
Small decrease	0	0	0	0.080	1.000	0
Large decrease	0	0	0	0	1.000	0
Small increase	0	0	0	0.595	1.000	0
Large increase	0	0	0	0.985	1.000	0

Table 7.6: Changes to the effect of chronic oiling

Changes in the effect of chronic oiling do not have as large an impact as changes to the frequency of spills but, even so, small changes have a fairly large impact on the probability of the population ending up below or above 75% of its initial value.

7.1.5 Flooding

First, the effect of varying the average times between floods will be examined, followed by the effect of varying the impact a flood has on chicks and eggs.

7.1.5.1 Timing

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0	0.970	0.030
Small decrease	0	0	0	0	0.975	0.025
Large decrease	0	0	0	0	1.000	0
Small increase	0	0	0	0	0.965	0.035
Large increase	0	0	0	0	0.940	0.060

Table 7.7: Changes in the frequency of flooding

Changes in the average time between floods have a very small impact on the size of the population at the end of twenty years.

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0	0.970	0.030
Small decrease	0	0	0	0	0.965	0.035
Large decrease	0	0	0	0	0.890	0.110
Small increase	0	0	0	0	0.980	0.020
Large increase	0	0	0	0	0.985	0.015

Table 7.8: Changes to the effect of flooding

7.1.5.2 Effect

Overall, changes in parameters related to flooding appear to cause only small changes in the outcome of the model.

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7.1.6 Extreme cold

The extreme cold pressure is composed of two parts - time between cold events, and the effect of a cold event on chick and egg survival rates.

7.1.6.1 Timing

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0	0.900	0.100
Small decrease	0	0	0	0	0.900	0.100
Large decrease	0	0	0	0	0.970	0.030
Small increase	0	0	0	0	0.895	0.105
Large increase	0	0	0	0	0.880	0.120

Table 7.9: Changes in frequency of cold events

Changes in the timing of cold events do not cause large changes in the model results.

7.1.6.2 Effect

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0	0.900	0.100
Small decrease	0	0	0	0	0.905	0.095
Large decrease	0	0	0	0	0.955	0.045
Small increase	0	0	0	0	0.890	0.110
Large increase	0	0	0	0	0.810	0.190

Table 7.10: Changes in the effect of cold events

Changes in the effect of a cold event on chick and egg survival rates produce larger changes than changes in the time between events but, overall, the changes in model results are small.

7.1.7 Extreme heat

Extreme heat is modelled in the same way as extreme cold and therefore comprises of time between events, and the effect of an event on chick and egg survival rates.

7.1.7.1 Timing

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0	0.900	0.100
Small decrease	0	0	0	0	0.905	0.095
Large decrease	0	0	0	0	0.975	0.025
Small increase	0	0	0	0	0.885	0.115
Large increase	0	0	0	0	0.865	0.135

Table 7.11: Changes in frequency of heat events

Changes in the average time between heat events produce larger changes than changes in the average time between cold events as the effect of a heat event is greater than that of a cold event. The changes in probability themselves, though, are minor.

7.1.7.2 Effect

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0	0.900	0.100
Small decrease	0	0	0	0	0.910	0.090
Large decrease	0	0	0	0	0.960	0.040
Small increase	0	0	0	0	0.890	0.110
Large increase	0	0	0	0	0.825	0.175

Table 7.12: Changes to the effect of heat events

As with timing, changes in these parameters result in larger changes than changes in the cold event parameters but, overall, the changes to the model results are minor. This can also be seen in the minimum and maximum values for each test as they remain very similar, despite changes to the parameters.

7.1.8 Food availability

Both a small decrease and small increase in the effect of food availability have a small impact on the model results. A large increase in the effect has a dramatic effect on the model results, increasing the probability that the population exceeds its starting value by almost double. A large decrease results in a significant chance that the population will fall to below 75% of its initial value over

the twenty years. Changes in the effect of food availability do have an effect on model results.

Change to base parameters	Probability population at end of twenty years is:					
	<5%	<25%	<50%	<75%	<100%	>100%
No change	0	0	0	0	0.672	0.328
Small decrease	0	0	0	0	0.689	0.311
Large decrease	0	0	0	0.195	0.726	0.274
Small increase	0	0	0	0	0.631	0.369
Large increase	0	0	0	0	0.382	0.618

Table 7.13: Changes to the effect of food availability

7.1.8.1 Fishing allowed around island

This pressure is linked to food abundance. The user can choose to allow fishing around the island, in which case the catch data will be used to reduce the food available to the penguins in Zone 1, or to restrict or reduce fishing.

In order to examine the impact of this parameter on the model, two runs were made using the same food data with all other pressures turned off. The maximum difference in the number of breeding pairs between the two runs was recorded. As the sensitivity analysis feature could not be used to perform this analysis, this was done only ten times with a different noise seed each time (as determined by the `RANDBETWEEN()` function in Excel). Figure 7.1 shows the results from the ten repeats.

The largest difference overall was that of 141 breeding pairs, and the smallest was 52 breeding pairs, with a median difference of 84 pairs. This indicates that fishing around the island does have an impact, but it is quite dependent on the noise stream used for the run. A further complication is that the catch data is monthly while the monthly biomass estimates are based on annual data. This is discussed in the section on suggestions for further research (Section 9.4).

7.2 Changes to mean survival values

As the mean survival values are central to the population model, it is expected that changes to these values would result in significant changes to the final population size. As with the section above, the model was run 200 times with different noise streams used each time. The population size after twenty years

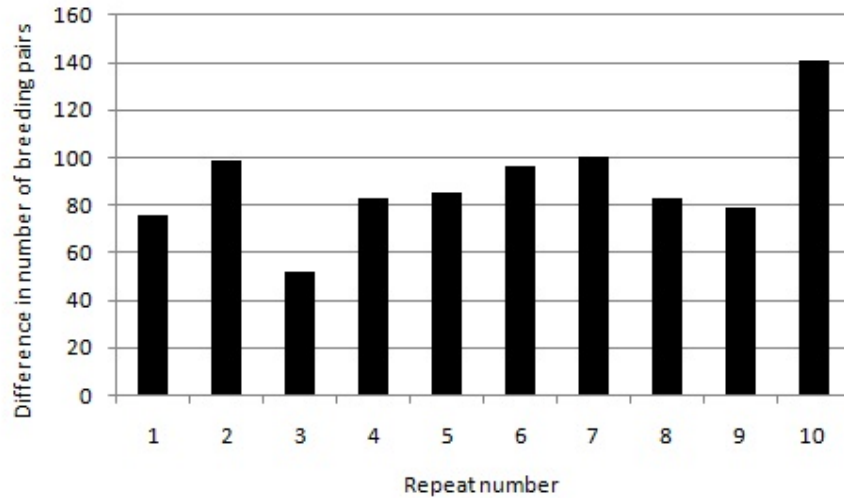


Figure 7.1: Maximum difference in breeding pairs for each repeat

was compared to the thresholds, and the probability of the population ending up below each threshold was recorded.

The base run resulted in a probability of 0.535 that the population would decline over the time period. Both a small and a large increase (a 10% and a 50% increase, capped at a maximum value of 0.99 for each survival rate) caused the population to increase over twenty years.

The small decrease lead to a certain decline to under 25% of the population's initial value. A large decrease caused the population to always decline to below 5% of the starting value.

As expected, changing these fundamental estimates produces significant changes in the model results. In addition, any large changes to these parameters would be unrealistic in terms of observed survival rates.

7.3 Biomass data

One of the important components of the model is the biomass data from Strata C and D. Biomass from Stratum D is used to model food in Zone 1 (the area directly around the island), and is linked in the model to egg and chick survival rates. Biomass from Stratum C is used to model food available further afield, and is linked to adult and immature survival as well as the proportion of adults

that choose to breed. Figure 7.2 shows the biomass in thousands of tonnes from both strata on the left axis and the number of breeding pairs on Robben Island on the right axis.

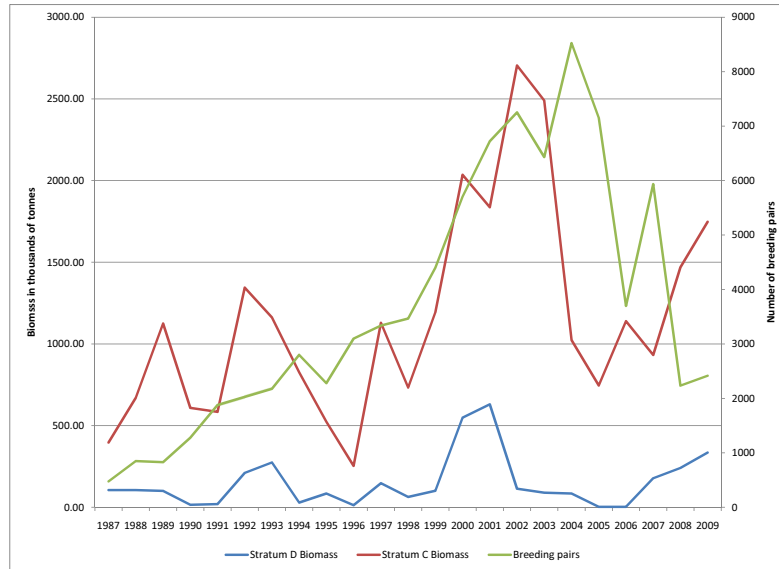


Figure 7.2: Time series of biomass and breeding pairs

It was suggested by the clients that there may be autocorrelation in the biomass time series. *R* (Team, 2009) was used to analyse six time series: Anchovy biomass from Strata C and D, Sardine biomass from Strata C and D and the summed biomass of Anchovy and Sardine from Strata C and D.

Runs tests resulted in *p* values of over 0.05 for all six time series, which supports the null hypothesis of randomness in the time series (Appendix E). The lengths of the time series available are not great enough to effectively model with an ARIMA (autoregressive integrated moving average) model, and both the runs test, and an examination of the autocorrelation and partial autocorrelation functions, suggest that autocorrelation is not present in any of the time series.

Instead, the model was run multiple times with a different random sample of the biomass and corresponding catch data in order to get a feel for the effect the data could have on the penguin population. The sensitivity analysis tool was

used to produce 200 runs of each food scenario. The maximum and minimum levels of the population for each scenario are displayed in table 7.14.

	Total Adults		Zone 1 biomass (tonnes)			Zone 2 biomass (tonnes)		
	Min	Max	Min	Max	Median	Min	Max	Median
1	2 946	4 097	406	96 054	15 198	253 396	2 704 366	975 557
2	3 506	4 801	406	96 054	19 136	253 396	2 704 366	1 128 911
3	3 456	4 584	482	110 232	18 392	396 735	2 704 366	1 126 920
4	4 085	5 832	3 408	96 054	18 392	396 735	2 704 366	1 128 911
5	4 316	5 838	406	96 054	12 908	584 292	2 704 366	1 081 060
6	3 314	4 589	2 606	110 232	18 392	523 347	2 489 522	1 126 920
7	3 365	4 633	406	96 054	16 186	523 347	2 035 251	1 092 307
8	3 588	5 317	406	110 232	18 392	523 347	2 704 366	932 352
9	2 951	4 286	406	58 652	10 382	253 396	2 704 366	879 269
10	2 670	3 823	406	110 232	17 596	253 396	1 836 670	977 601

Table 7.14: Results from ten different food scenarios

It is difficult to isolate the effect of the different biomass levels on the minimum and maximum number of adults, however a couple of observations can still be made.

Scenarios 1 and 2 have the same minimum and maximum biomass in Zone 1 and Zone 2, but scenario 2 has higher median biomass in each zone. The result is a higher minimum and maximum total adults in scenario 2.

Scenario 3 and 4 have identical minimum and maximum Zone 2 biomass, and median Zone 1 biomass. There is a difference of 1991 tonnes in Zone 2 median biomass. Scenario 4 has the higher minimum and maximum total adults, even though the Zone 1 maximum biomass is 14 000 tonnes lower. This is due to a large increase in minimum Zone 1 biomass, which is seven times higher than in scenario 3.

Scenarios 5 to 10 differ in three or more variables and it is therefore difficult to identify causes of increase or decrease in total adults without a model, however the number of data points is too few for a meaningful regression to be performed.

In order to examine the individual effects of Zone 1 and Zone 2 biomass data, the model was run five times keeping Zone 1 biomass (and catch) data constant but resampling Zone 2 biomass, and five times with Zone 2 biomass constant and resampling from Zone 1 biomass data. The results are shown in tables 7.15 and 7.16.

Scenarios 1 and 2 demonstrate that, for the same minimum value of biomass in Zone 2 but higher maximum and median biomass, the minimum and maxi-

	Total Adults		Zone 1 biomass (tonnes)			Zone 2 biomass (tonnes)		
	Min	Max	Min	Max	Median	Min	Max	Median
1	2 344	3 406	406	110 232	18 006	253 396	2 035 251	739 374
2	3 857	5 716	406	110 232	18 006	253 396	2 704 366	1 177 795
3	3 604	5 251	406	110 232	18 006	396 735	2 704 366	1 145 337
4	3 805	5 407	406	110 232	18 006	523 347	2 704 366	1 134 091
5	3 284	4 851	406	110 232	18 006	608 501	2 704 366	1 030 632

Table 7.15: Results from changing Zone 2 biomass

imum total adults are higher.

Scenarios 3, 4 and 5 demonstrate that, for the same maximum biomass but varying minimum and median biomass, the results are not as clear cut. Excluding scenario 4, it would seem as though a higher minimum but lower median biomass results in lower minimum and maximum total adults. Scenario 4 may produce a higher minimum and maximum total adults than scenario 3 as the median biomasses are fairly close while the minimum biomass has increased by over 100 000 tonnes.

	Total Adults		Zone 1 biomass (tonnes)			Zone 2 biomass (tonnes)		
	Min	Max	Min	Max	Median	Min	Max	Median
6	3 275	4 836	406	58 652	18 006	253 396	2 704 366	1 143 346
7	3 549	5 250	406	96 054	14 751	253 396	2 704 366	1 143 346
8	3 289	4 973	482	110 232	15 695	253 396	2 704 366	1 143 346
9	3 736	5 217	482	110 232	18 006	253 396	2 704 366	1 143 346
10	4 427	6 106	482	110 232	22 117	253 396	2 704 366	1 143 346

Table 7.16: Results from changing Zone 1 biomass

Scenarios 6 and 7 demonstrate that, for a constant minimum biomass, a large increase (approx 37 000 tonnes) in maximum biomass compared to a small decrease (approx 3 000 tonnes) in median biomass results in an increase in the minimum and maximum total adults.

Scenarios 8, 9 and 10 demonstrate that for constant minimum and maximum biomass, an increase in median biomass produces an increase in the minimum and maximum total adults.

As only five different scenarios have been investigated in each case, these results may not hold in general but do provide an indication as to the effect of varying biomass data in each zone.

Chapter 8

Workshop

A workshop on the model was held at the University of Cape Town on 17 August 2011. A wide range of participants were invited, and a total of ten delegates attended the workshop. The delegates ranged from penguin biologists to scientists involved in the scientific working groups for pelagic fishing, and for ecosystems approach to fisheries management. The participants used their own laptops and ran *Vensim Model Reader*. A brief summary of the workshop is provided followed by an evaluation of the model based on comments from the delegates.

8.1 Activities

The morning commenced with a brief introduction that emphasised the focus on communication and learning. Delegates were then given a tutorial on how to control the model from the Excel spreadsheet, what each view in the model covered, and how to interpret the graphs in each view. Participants then spent approximately an hour and a half changing parameters in the model and examining the effect these changes had on the total penguin population. The focus for most participants was what happened when certain pressures were turned off, and what the survival parameters needed to be in order to stabilise the population in the absence of modelled pressures. Delegates worked individually, or in pairs, but happily assisted each other and had numerous discussions regarding the interpretation of their results, especially when a result was not what they had expected.

After a break for tea, delegates finished experimenting with changing parameters and the workshop moved on to a tutorial on gaming in *Vensim*. The model was presented with three management strategies:

- Reduce chronic oiling
- Close the area around the island to fishing
- Control land predators on the island

Participants were then given the opportunity to run through the model, one year at a time, and to select what management strategies they would implement each year. Participants ran various scenarios from implementing one strategy per run to looking at combinations of strategies.

Some confusion arose over which values meant management strategies were implemented fully as opposed to not at all, as a value of one was defined as no management strategy and zero was defined as a fully implemented management strategy due to the way these parameters were implemented in the model. This was subsequently changed so that a value of one equates to full implementation of a management strategy. Once that had been rectified, delegates spent an industrious hour experimenting with the model. Once again, most participants happily helped each other and discussed what results they were achieving with others sitting near them. During the last half an hour of the workshop evaluation forms were given out and delegates filled these in while completing their experiments. These forms are included at the end of the appendices. The feedback from delegates forms the bulk of the next three sections.

8.2 Areas needing improvement

Participants felt that the large number of parameters could confuse issues, and that it would be especially important to present less choices to management. A further point with regard to using the model as a management tool is that managers may take the model results as ‘reality’, without taking into account the effect of variability in the pressures. As *Vensim Model Reader* does not support sensitivity analysis, this is a particularly important point to convey when explaining that the model is primarily a learning and communication tool, not a tool for accurate prediction.

Participants felt that the uncertainty around some parameters for which there is no hard data could lead to a lack of confidence in the model, but did

agree that this provided a useful indication as to where further research efforts should be directed. Participants also felt that it was difficult to keep track of the changes they had made so a facility for recording changes should be created, or users should be taught to use the Runs Compare tool in *Vensim*, although this may cause confusion as variables used purely for calculation purposes may be shown. Most delegates felt that some sort of scientific background was needed to understand the model. In order for it to be useful to a wider range of stakeholders, a more simplified appearance should be developed.

8.3 Strengths of the model

One of the primary strengths of the model is the number of pressures on the penguin population that have been modelled, and the flexibility to change the majority of parameters. Workshop delegates found the model easy to control from Excel as it is a familiar programme. This allowed them to feel comfortable experimenting with the model.

The graphical display of the relationships between the model variables aided in the understanding of the model structure. The graphic output also enabled a quick evaluation of changes to the model, and emphasised the impact that even small changes can have.

Some participants felt that the model helped them understand the scope and complexity of the problem facing the penguins. Most participants felt that the number of parameters that can be altered was a very useful facet of the model. Participants also felt that the gaming mode was a useful tool for involving managers, although it was suggested that a simplified model be presented for this purpose. The model was identified as being useful to stakeholders such as managers, government and conservation scientists, and fishing companies.

Delegates were asked to list what made this model different to current penguin models and other multispecies models. As a few pointed out, there really is no other penguin model to compare it to at the moment as the last model similar to this one was the Vortex model at the Penguin Population and Habitat Viability Assessment workshop in 1999 (Whittington *et al.*, 2000).

Features of the model that stood out for delegates were:

- The visual nature of the model - the structure is displayed graphically and the output is in the form of graphs

- The gaming mode - decision makers can experiment with different policy decisions and examine the possible outcomes
- The model attempts to follow a 'realistic' ecosystem - both predators and prey relationships are present in the model and all important pressures on the population are modelled.
- The number of pressures included in the model - the model includes most drivers for population growth
- The ability to turn pressures on or off completely - adds to the flexibility of the model and allows users to isolate individual pressures

8.4 Conclusion

Based on the feedback from participants at the workshop, the model would need some minor changes before it could be presented to managers in order to experiment with different strategies. The changes include a simplified appearance coupled with fewer choices that managers need to make, as well as a way to easily track changes to the model and the results.

The workshop ran well given the restricted time available for the participants to learn how to use the model. Participants quickly became comfortable changing parameter values and readily shared their opinions regarding their results with others around them. This gave everyone a chance to indicate which parts of the model and/or the data used in the model they agreed with, and which they thought should be researched more thoroughly.

Overall, the model was well received and definitely encouraged team work and discussion amongst users.

Chapter 9

Conclusion

9.1 The role of modelling

The modelling process has allowed the Penguin Modelling Group to engage with the data available, and has forced everyone to examine their assumptions of survival rates and the effects of the various pressures on the penguin population. This process has opened up discussion on the effect of individual pressures, on which pressures are important on Robben Island, and what level of detail needs to be modelled. This process has also allowed experts in areas other than penguins - statisticians, managers and fishery scientists - to discuss their views on the model, and to add their expertise.

As the model was developed over a series of meetings and presentations, everyone involved in the development of the model could see the effect of the suggestions from the previous meeting and then refine these suggestions, if necessary. It has also increased awareness of the lack of data on some aspects of the model.

This model is the start of a series of models intended to cover all the penguin colonies in Southern Africa. It should develop into a powerful tool for management to use in order to understand how policy decisions can affect the penguin populations and, also, which factors have the greatest effect on the mortality rates of the penguins.

9.2 Data needs

In an ideal situation, appropriate and plentiful data would be available for all aspects of the model. The development of the model has highlighted those parameters for which data is either not available at all, or not available in a suitable format. Although the model performs adequately using estimates from the penguin modelling group, data for the following areas would assist in refining those estimates.

Pressures such as shark predation and predation from cats, rats and other land predators are two pressures for which very little data is available. The abundance of these predators was assumed to be random, and to vary around some initial abundance. It would be helpful to have more information on:

- whether abundance of these predators is seasonal
- whether their abundance is linked to any other factors such as biomass of fish, or the density of the penguin population
- the effect that these predators have on the mortality rates of the applicable age classes

Data on weather patterns and the effect of flooding needs to be gathered, as well as research into whether flooding occurs solely with the cold events or if it does occur independently, as currently modelled. The effect of building artificial burrows for the penguins to protect from flooding and weather can then be added to the model.

Most importantly, the effect of food availability and the modelling of the food available to penguins needs to be improved. Information that would be useful in this regard:

- seasonality of biomass availability
- small boat surveys around the island that would allow an even greater degree of realism in the biomass modelling
- the relationship between biomass available and mortality rates for chicks and eggs

The effect of the number of chicks and eggs should then be introduced into the equation that determines the index of food availability. This would only be

worthwhile once the equations for determining the biomass available in Zone 1 each month have been refined.

Research is available on the link between adult mortality and food availability in Zone 2, but used parameters not in the model. It would be worth examining if the model could be restructured so that this data can be used.

9.3 Summary of findings

Iterations of the model with only natural mortality showed that the survival rates used in the Shannon and Crawford model were too low to produce a stable population in the absence of immigration. Once the survival rates were raised, within reasonable bounds, for adults, chick and eggs, the population stabilised. These new survival rates were approved by the Penguin Modelling Group and were then used for all other runs of the model.

Two scenarios - ideal and realistic - were examined in order to determine if any factors in the model would need to be adjusted to achieve them. An ideal environment was assumed to be one with high food levels and no fishing or oiling. This resulted in a population explosion with penguin numbers reaching over a million in less than one hundred years. No other parameters were adjusted to achieve this scenario.

The realistic scenario used the original time series of biomass availability as well as accurate timing of oil spills. Runs of the model with all population pressures included led to a declining population. In order to replicate the rapid population growth of the 1990s, immigration was added to the model in the form of an increased immature survival rate; chronic oiling, flooding and extreme weather events were removed and predator abundance was lowered. Predator abundance was raised after the year 2003 in order to replicate the decline in the population at that point, despite continuing immigration.

An experiment is currently under way to examine the effect of closing the area around a penguin colony to fishing for a period of three years. The impact of this policy decision was examined by running the model with no fishing allowed for three years in Zone 1. The three year period started one year later in each successive run. It was shown that, although restricting fishing around the island was always beneficial to the penguin population, an oil spill during the closed period resulted in a very small benefit from the closure. This would be important for managers to be aware of when interpreting the results of the

experiment, in the event of an oil spill during that time. It also suggests that other factors may reduce or exaggerate the effect of closing the island to fishing.

Sensitivity analysis shows that the model is sensitive to changes in the frequency and effect of chronic oiling, whether fishing is allowed around the island and the effect of food availability on survival rates. These results suggest areas for further research and possible management strategies.

Finally, the workshop showed that the model is a useful learning tool. The workshop participants felt that it could be used a tool to communicate the effects of management strategies to managers, and could also encourage managers to experiment with the model themselves.

9.4 Suggestions for further research

As mentioned above, the Robben Island model provides a base for modelling other penguin colonies. Robben Island was chosen as the first island to model as there is more data available and better understanding about the pressures on this penguin population than the other islands. As such, modelling of other colonies will require research to determine their population parameters and how each of the potential pressures affect them. Further research is required to determine the causes of migration between colonies as this is something that would need to be added to the model, once more than one colony is present. Other directions for research have already been mentioned in section 9.2.

9.5 Concluding remarks

This dissertation has provided a penguin population model that can be used as a base to model other islands. Collaborative modelling between experts in the Penguin Modelling Group, as well as input from other scientists, produced a model with buy-in from numerous non-governmental organisations concerned with conservation. The modelling process has created a sense of ownership of the model within the modelling group, and has produced a model that is understood by a range of users. It is the most up-to-date model that includes all the pressures that are important to the colony on Robben Island, and can potentially be used as a decision support tool to help both fisheries and conservation managers, as well as scientists involved in penguin research.

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Appendix A

Prototype Model Equations

Note that time in the model equations, t , is defined as time since start of model modulo 12 i.e. $t \in (0, 11)$ where 0 represents January and 11, December. The symbols used are defined as follows:

q_a as the mortality experienced by adult penguins per month

s as the one year survival rate for penguins aged 1 year and older

$$s = (1 - q_a)^{12}$$

q_c as the mortality experienced by chicks per month

s_c as the proportion of chicks that fledge

$$s_c = (1 - q_c)^3$$

q_e as the proportion of eggs lost per month

s_e as the proportion of eggs that hatch

$$s_e = (1 - q_e)^2$$

s_0 as the proportion of penguins fledged that survive to the end of the year

$A_{i,n}$ as the number of penguins alive in that age class at the beginning of year n

A_i^d as the number of penguins that die in that age class per month

A_i^l as the number of penguins that survive to the end of the year in that age class

C_n as the number of chicks alive at the beginning of year n

C^d as the number of chicks that die per month

C^l as the number of chicks that fledge successfully per month

E as the number of eggs alive at the beginning of year n

E^d as the number of eggs that are lost per month

E^l as the number of eggs that hatch successfully per month

A.1 Equations

For age class A_i ($i = 1$ to 5):

$$\begin{aligned}
 A_{i,n+1} &= A_{i,n} + (A_{i-1}^l - A_i^d - A_i^l)dt & 1 \leq i \leq 4 \\
 A_{i,n+1} &= A_{i,n} + (A_{i-1}^l - A_i^d)dt & i = 5 \\
 A_i^l &= A_i - A_i^d & t = 11 \\
 &= 0 & otherwise \\
 A_i^d &= A_i * q_a
 \end{aligned}$$

For age class A_0 :

$$\begin{aligned}
 A_{0,n+1} &= A_{0,n} + (C^l - A_0^d - A_0^l)dt \\
 A_0^l &= A_0 * s_0 & t = 11 \\
 &= 0 & otherwise \\
 A_0^d &= A_0 * (1 - s_0) & t = 11 \\
 &= 0 & otherwise
 \end{aligned}$$

For eggs and chicks:

$$\begin{aligned}
 C_{n+1} &= C_n + (E^l - C^d - C^l)dt \\
 C^d &= C * q_c \\
 C^l &= \text{DELAY CONVEYOR}(E^l, 3, q_c, \text{laying rate}, 0, 3)
 \end{aligned}$$

$$\begin{aligned}
 E_{n+1} &= E_n + (\text{initial laying} + \text{relaying} - E^d - E^l)dt \\
 E^d &= E * q_e \\
 E^l &= \text{DELAY FIXED}((\text{initial laying} + \text{relaying}) * s_e, 1, 0)
 \end{aligned}$$

Note: for a description of DELAY CONVEYOR and DELAY FIXED, see section B.2.

The equations for egg production are as follows:

$$\begin{aligned}
 IE_t \text{ (initial egg laying at time t)} &= \text{breed year} * \text{clutch size} * \text{laying rate}_t \\
 RE_t \text{ (relaying)} &= IE_{t-3} * CL * Rc && 3 \leq t \leq 5 \\
 &= IE_{t-3} * CL * Rc \\
 &\quad + IE_{t-6} * (BL * Rb) \\
 &\quad + IE_{t-6} * (1 - CL - BL) * Rs && 6 \leq t \leq 8
 \end{aligned}$$

A.2 Parameter values

Parameter	Mean value	Range/Std dev
Mean adult survival	0.860	0.82-0.90
Mean immature survival	0.510	0.110
Mean chick survival (Fledging success)	0.370	0.078
Mean egg survival (Hatching success)	0.548	0.073
Hatching time (months)	1	
Fledging time (months)	3	

Table A.1: Parameter values for penguin population

Parameter	Value
Initial number of adults (Adults)	3 500
Average proportion of sexually mature adults that choose to breed each year	0.834
Proportion of adults in age class 2 that are sexually mature (b2)	0.050
Range of b2 is 0 to 0.1	0.050
Proportion of adults in age class 3 that are sexually mature (b3)	0.330
Range of b3 is 0.03 to 0.63	0.030
Proportion of adults in age class 4 that are sexually mature (b4)	0.740
Range of b4 is 0.675 to 0.805	0.065
Proportion of adults in age class 5 that are sexually mature (b5)	1.000
Probability of relaying after clutch loss (Rc)	0.305
Annual variation in Rc	0.101
Probability of relaying after brood loss (Rb)	0.218
Annual variation in Rb	0.153
Probability of relaying after successful fledging of a brood (Rs)	0.218
Annual variation in Rs	0.114

Table A.2: Parameter values for breeding calculations

Time	Laying rate	Effective month
0 - 2	0.23	Feb - Apr
3 - 5	0.09	May - Jul
6	0.04	Aug
7-11	0.00	Sep - Jan

Table A.3: Laying rate

Appendix B

Full model equations

B.1 Subscripts used in equations

[Subscript]: subscript values

[i0m]: one, two, three, four, five, six, seven

[age]: I1, A2, A3, A4, A5

[oiled]: no, yes

[thresh]: 5%, 25%, 50%, 75%, 100%

[fish]: ab, sb, ac, sc (anchovy and sardine from Stratum D (ab, sb) and from Stratum C (ac,sc))

[z2sub]: as, bp, js (adult survival, breeding proportion and juvenile survival)

B.2 Format of common functions in Vensim

- DELAY CONVEYOR(input, ctime, leak, initprofile, inittot, initctime) - returns the value of **input** delayed by **ctime**. Fractional leakage per time unit is given by **leak**. Initial amount of material on the conveyor is given by **inittot** and is distributed according to the time profile, **initprofile**. The initial value returned by the function is determined by **initctime**.
- DELAY FIXED (input, delay time, initial value) - returns the value of the **input** delayed by **delay time**. The **initial value** is used at the start of

the simulation.

- IF THEN ELSE(*cond*, *tval*, *fval*) - traditional If-Then-Else statement. Returns **tval** if *cond* is true else returns **fval**.
- INTEG (*rate*, *initial value*) - Performs numerical integration.
- PULSE TRAIN (*start*, *width*, *tbetween*, *end*) - returns a value of 1 starting at time **start**, lasting for interval **width** and then repeats this every **tbetween** time until time **end**. It returns a value of 0 at all other times.
- RANDOM NORMAL(*m,x,h,r,s*) - returns a random number from a normal distribution with minimum value **m**, maximum value **x**, mean **h** and standard deviation **r**. **s** is the stream ID for the distribution to use.
- RANDOM POISSON (*m,x,M,h,r,s*) - **m**, **x** and **s** as in RANDOM NORMAL, **M** is the mean, **h** is a shift parameter (to the right) and **r** is a stretch parameter.
- SUM(*x[i!]*) - the sum of an array over the subscript range(*s*) with the exclamation mark(*s*).

B.3 Control equations

month	=	MODULO (Timer, 12)
Timer	=	INTEG (1, 0)
NOISE SEED	=	<i>constant from spreadsheet</i>
seed	=	0
v pulse	=	PULSE TRAIN (11, 1, 12, 999999)

B.4 Penguin population model equations

Eggs[oiled]	=	INTEG (initial egg laying[oiled] + relaying[oiled] - MAX (Eggs[oiled], eggs lost[oiled]) - hatching[oiled]), 0)
eggs lost[oiled]	=	MAX (0, Eggs[oiled]*(frac egg mortality + oilE + floodE - frac egg mortality*oilE - frac egg mortality*coilE - oilE*coilE - frac egg mortality*floodE - oilE*floodE - coilE*floodE + frac egg mortality*oilE*coilE + frac egg mortality*oilE*floodE + oilE*coilE*floodE - frac egg mortality*oilE*coilE*floodE))
hatching[oiled]	=	DELAY FIXED((initial egg laying[oiled] + relaying[oiled])*(1 - (frac egg mortality + oilE + coilE + floodE - frac egg mortality*oilE - frac egg mortality*coilE - oilE*coilE - frac egg mortality*floodE - oilE*floodE - coilE*floodE + frac egg mortality*oilE*coilE + frac egg mortality*oilE*floodE + oilE*coilE*floodE)), Hatching time, 0)
Hatching time	=	1
frac egg mortality	=	1 - (egg survival) ¹ /Hatching time
egg survival	=	1/(1 + EXP(- egg survival logit))
egg survival logit	=	e0 + catE*cat abundance + sharkE*shark abundance + heatE*climate Heat + coldE*climate Cold - food effect E*zi
e0	=	-ln(1/(mean egg survival) - 1)
mean egg survival	=	<i>constant from spreadsheet</i>

Table B.1: Egg age class equations

Chicks[oiled]	=	INTEG (hatching[oiled] - MAX (Chicks[oiled], chick deaths[oiled] - fledging[oiled]), 0)
chick deaths[oiled]	=	MAX (0, Chicks[oiled]*frac chick mortality[oiled])
frac chick mortality [oiled]	=	1 - chicks survival[oiled] ^{1/Fledging time} + oilC + coilC + floodC - (1 - chicks survival[oiled] ^{1/Fledging time})*oilC - oilC*coilC - (1 - chicks survival[oiled] ^{1/Fledging time})*floodC - oilC*floodC - coilC*floodC + (1 - chicks survival[oiled] ^{1/Fledging time})*oilC*coilC + (1 - chicks survival[oiled] ^{1/Fledging time})*oilC*floodC + oilC*coilC*floodC - (1 - chicks survival[oiled] ^{1/Fledging time})*oilC*coilC*floodC
chicks survival[no]	=	1/(1 + EXP (-chicks survival logit))
chicks survival[yes]	=	1/(1 + EXP (-chicks survival logit))*0.5
chicks survival logit	=	c0 + catC*cat abundance + sharkC*shark abundance + heatC*climate Heat + coldC*climate Cold - food effect C*z1
c0	=	-ln(1/(mean chick survival) - 1)
mean chick survival	=	<i>constant from spreadsheet</i>
fledging[oiled]	=	DELAY CONVEYOR (hatching[oiled], Fledging time, frac chick mortality[oiled], laying rate, 0, Fledging time)
Fledging time	=	3
chicks per pair	=	clutch size*egg survival*chicks survival[no]

Table B.2: Chick age class equations

Immature 0[i0m]	= INTEG (IF THEN ELSE (month = 11-x :AND: INTEGER (SUM (fledging[oiled!]))>0, SUM (fledging[oiled!]), 0) - immature 0 deaths[i0m] - immature 0 survival[i0m], 0) for x = 1, 2 ... 7
immature 0 survival[i0m]	= PULSE TRAIN (11, 1, 12, 99999)*(Immature 0[i0m] - immature 0 deaths[i0m])
immature 0 deaths[i0m]	= Immature 0[i0m]*((1 - immature survival[i0m]) + oil[i0m] + coil[i0m] - (1 - immature survival[i0m])*oil[i0m] - (1 - immature survival[i0m])*coil[i0m] + (1 - immature survival[i0m])*oil[i0m]*coil[i0m])
immature survival[i0m]	= 1/(1 + EXP (-immature survival logit[i0m])) ^{1/x} for x = 1, 2 ... 7
immature survival logit[i0m]	= i0 + sharkI*shark abundance - food effect I*z2[js]
i0	= -ln(1/(mean immature survival) - 1)
mean immature survival	= constant from spreadsheet

Table B.3: Immature age class equations

Adult Penguins[I1, no]	= INTEG (SUM (immature 0 survival[i0m!]) - Adult deaths[I1, no] - Adults survival[I1, no], equiAdults/initial survival prop)
Adult Penguins[A2, no]	= INTEG (Adults survival[I1, no] - Adult deaths[A2, no] - Adults survival[A2, no], equiAdults)
Adult Penguins[A3, no]	= INTEG (Adults survival[A2, no] - Adult deaths[A3, no] - Adults survival[A3, no], equiAdults*initial survival prop)
Adult Penguins[A4, no]	= INTEG (Adults survival[A3, no] - Adult deaths[A4, no] - Adults survival[A4, no], equiAdults*initial survival prop ²)
Adult Penguins[A5, no]	= INTEG(Adults survival[A4, no] - Adult deaths[A5, no], (equiAdults*initial survival prop ³)/(1 - initial survival prop))
equiAdults	= Adults/(1 + initial survival prop + initial survival prop ² + initial survival prop ³ + (initial survival prop ⁴)/(1 - initial survival prop))
initial survival prop	= mean adult survival
Adults	= <i>constant from spreadsheet</i>
Adult deaths[age, oiled]	= MAX (0, Adult Penguins[age, oiled]*(frac adult mortality + oilA - frac adult mortality*oilA + coilA - frac adult mortality*coilA - oilA*coilA + frac adult mortality*oilA*coilA))
frac adult mortality	= 1 - adult survival ^{1/12}
adult survival	= 1/(1 + EXP (-adult survival logit))
adult survival logit	= a0 + sharkA*shark abundance - food effect A*z2[as]
a0	= -ln(1/(mean adult survival) - 1)
mean adult survival	= <i>constant from spreadsheet</i>
Adults survival[age, oiled]	= PULSE TRAIN (I1, 1, 12, 99999)*(Adult Penguins[age, oiled] - Adult deaths[age, oiled])

Table B.4: Adult age class equations

Adult Penguins[I1, yes] = INTEG (rehabilitated penguins[I1] - Adult deaths[I1, yes] - Adults survival[I1, yes], 0)
 Adult Penguins[A2, yes] = INTEG (Adults survival[I1, yes] - Adult deaths[A2, yes] - Adults survival[A2, yes] + rehabilitated penguins[A2], 0)
 Adult Penguins[A3, yes] = INTEG (rehabilitated penguins[A3] + Adults survival[A2, yes] - Adult deaths[A3, yes] - Adults survival[A3, yes], 0)
 Adult Penguins[A4, yes] = INTEG (rehabilitated penguins[A4] + Adults survival[A3, yes] - Adult deaths[A4, yes] - Adults survival[A4, yes], 0)
 Adult Penguins[A5, yes] = INTEG (rehabilitated penguins[A5] + Adults survival[A4, yes] - Adult deaths[A5, yes], 0)
 rehabilitated penguins[age] = MAX (0, IF THEN ELSE (catastrophic oiling*oil on + chronic oiling*coil on > 0, (Adult deaths[age, no] - Adult Penguins[age, no]*(1 - 1/(1 + EXP(- adult survival logit + oilA*catastrophic oiling + coilA*chronic oiling)))^{1/12})*0.9, 0))

Table B.5: Oiled adult age class equations

Total Adults = SUM (Adult Penguins[age!, oiled!]) - SUM (Adult Penguins[I1, oiled!])
 ITotAdults[thresh] = IF THEN ELSE (Total Adults < ITAThreshold[thresh], 1, 0)
 ITAThreshold[5%] = 0.05*Adults
 ITAThreshold[25%] = 0.25*Adults
 ITAThreshold[50%] = 0.5*Adults
 ITAThreshold[75%] = 0.75*Adults
 ITAThreshold[100%] = Adults

Table B.6: Total adults and threshold equations

actual breeding pairs [oiled]	=	potential breeding pairs[oiled]*breeding proportion[oiled]
potential breeding pairs [oiled]	=	(b2*Adult Penguins[A2, oiled] + b3*Adult Penguins[A3, oiled] + b4*Adult Penguins[A4, oiled] + b5*Adult Penguins[A5, oiled])/2
b2	=	INTEG (r b2 - out b2, 0.05)
r b2	=	RANDOM NORMAL (-0.05, 0.05, 0, 0.05, seed)*v pulse
out b2	=	DELAY FIXED (rb2, 12, 0)
b3	=	INTEG (r b3 - out b3, 0.33)
r b3	=	RANDOM NORMAL (-0.3, 0.3, 0, 0.03, seed)*v pulse
out b3	=	DELAY FIXED (rb3, 12, 0)
b4	=	INTEG (r b4 - out b4, 0.74)
outbp	=	DELAY FIXED (r bp, 12, 0)
r b4	=	RANDOM NORMAL (-0.065, 0.065, 0, 0.065, seed)*v pulse
out b4	=	DELAY FIXED (rb4, 12, 0)
b5	=	1
breeding proportion [oiled]	=	$\begin{cases} \text{INTEG}(r \text{ bp} - \text{out bp}, \text{mean bp}) & \text{if oiled} = \text{no} \\ 0.2 & \text{if oiled} = \text{yes} \end{cases}$
mean bp	=	<i>constant from spreadsheet</i>
r bp	=	RANDOM NORMAL (-0.15, 0.166, febp + adjustment factor, 0.05, seed)*v pulse + v pulse*IF THEN ELSE (Total Adults>carrying capacity, -0.6, 0)
total breeding pairs	=	SUM (actual breeding pairs[oiled!])

Table B.7: Model equations for breeding pairs calculations

initial egg laying[oiled]	=	actual breeding pairs[oiled]*clutch size*laying rate
clutch size	=	2*%2 + 1*%1
%1	=	1 - %2
%2	=	RANDOM UNIFORM (0.81, 0.92, 0)
laying rate	=	eggs per month(month)
eggs per month()	=	<i>see table D.8</i>
relaying[oiled]	=	DELAY FIXED (IF THEN ELSE (month > 5, 0, (clutches lost[oiled]*Rc + broods lost [oiled]*Rb + brood success[oiled]*Rs)*clutch size), 1, 0)

Table B.8: Initial egg laying and relaying equations

clutches lost [oiled]	=	number of 1 egg nests[oiled]*frac egg mortality + number of 2 egg nests[oiled]*(frac egg mortality) ²
number of 1 egg nests[oiled]	=	Eggs[oiled]/(clutch size) - number of 2 egg nests[oiled]
number of 2 egg nests[oiled]	=	(Eggs[oiled]/(clutch size))*(clutch size - 1)
broods lost [oiled]	=	broods lost 1[oiled] + broods lost 2[oiled] + broods lost 3[oiled]
broods lost 1[oiled]	=	number of 1 chick nests[oiled]*(frac chick mortality[oiled]) + number of 2 chick nests[oiled]*(frac chick mortality[oiled]) ² *bladj
number of 1 chick nests[oiled]	=	DELAY FIXED (number of 2 egg nests[oiled]*2*((1 - frac egg mortality)*frac egg mortality) + number of 1 egg nests[oiled]*(1 - frac egg mortality), 1, 0)
number of 2 chick nests[oiled]	=	DELAY FIXED (number of 2 egg nests[oiled]*((1 - frac egg mortality) ² , 1, 0)
broods lost 2[oiled]	=	d 1 chick[oiled]*((1 - delayed chick mortality[oiled])*frac chick mortality[oiled]) + d 2 chick[oiled]*((1 - delayed chick mortality[oiled])*frac chick mortality[oiled]) ² + 2*d 2 chick mortality[oiled]*(1 - delayed chick mortality[oiled])*(delayed chick mortality[oiled])*frac chick mortality[oiled]*bladj
d 1 chick[oiled]	=	DELAY FIXED (number of 1 chick nests[oiled], 1, 0)
d 2 chick[oiled]	=	DELAY FIXED (number of 2 chick nests[oiled], 1, 0)
delayed chick mortality[oiled]	=	DELAY FIXED (frac chick mortality[oiled], 1, 0)
broods lost 3[oiled]	=	d2 1 chick[oiled]*(1 - delayed 2 chick mortality[oiled])*(1 - delayed chick mortality[oiled])*frac chick mortality[oiled] + d2 2 chick[oiled]*((1 - delayed chick mortality[oiled]) ² *(1 - delayed chick mortality[oiled]) ² *frac chick mortality[oiled]) ² + 2*(1 - delayed 2 chick mortality[oiled])*frac chick mortality[oiled]*frac chick mortality[oiled]*bladj
d2 1 chick[oiled]	=	DELAY FIXED (d 1 chick[oiled], 1, 0)
d2 2 chick[oiled]	=	DELAY FIXED (d 2 chick[oiled], 1, 0)
delayed 2 chick mortality[oiled]	=	DELAY FIXED (delayed chick mortality[oiled], 1, 0)
bladj	=	1.38
brood success[oiled]	=	(d2 1 chick[oiled]*(1 - delayed 2 chick mortality[oiled])*(1 - delayed chick mortality[oiled])*(1 - frac chick mortality[oiled]) + d2 2 chick[oiled]*2*(1 - delayed 2 chick mortality[oiled])*(1 - delayed chick mortality[oiled])*(1 - frac chick mortality[oiled]) - ((1 - delayed 2 chick mortality[oiled])*(1 - delayed chick mortality[oiled])*(1 - delayed chick mortality[oiled]) ²))*bsadj
bsadj	=	0.77

Table B.9: Model equations for egg laying, relaying and nest size calculations

Rb	=	INTEG (r rb - out rb, 0.218)
r rb	=	RANDOM NORMAL (-0.218, 3*0.153, 0, 0.153, seed)*v pulse
out rb	=	DELAY FIXED (r rb, 12, 0)
Rc	=	INTEG (r rc - out rc, 0.305)
r rc	=	RANDOM NORMAL(-3*0.101, 3*0.101, 0, 0.101, seed)*v pulse
out rc	=	DELAY FIXED (r rc, 12, 0)
Rs	=	INTEG (r rs - out rs, 0.218)
r rs	=	RANDOM NORMAL (-0.218, 3*0.114, 0, 0.114, seed)*v pulse
out rs	=	DELAY FIXED (r rs, 12, 0)

Table B.10: Model equations for relaying calculations

B.5 Pressures on the penguin population

oil on	=	<i>constant from spreadsheet</i>
catastrophic oiling	=	INTEG (oil event - cleaning, 0)
oil event	=	IF THEN ELSE (oilstart >= 1, 1, 0)
oilstart	=	RANDOM POISSON (0, 1e+007, 1/months between oiling, 0, 1, 0)
months between oiling	=	<i>constant from spreadsheet</i>
cleaning	=	IF THEN ELSE (catastrophic oiling > 0, 1, 0)
oilA	=	%oilA*catastrophic oiling*oil on
%oilA	=	<i>constant from spreadsheet</i>
oilI[i0m]	=	%oilI*catastrophic oiling*oil on
%oilI	=	<i>constant from spreadsheet</i>
oilC	=	%oilC*catastrophic oiling*oil on
%oilC	=	%oilA*%parentsC
%parentsC	=	SUM (number of 1 chick nests[oiled!] + number of 2 chick nests[oiled!])*2/Total Adults
oilE	=	%oilE*catastrophic oiling*oil on
%oilE	=	%oilA*%parentsE
%parentsE	=	SUM (number of 1 egg nests[oiled!] + number of 2 egg nests[oiled!])*2/Total Adults

Table B.11: Catastrophic oiling equations

coil on	=	<i>constant from spreadsheet</i>
chronic oiling	=	INTEG (oil event2 - cleaning2, 0)
oil event 2	=	oilstart2
oilstart2	=	RANDOM POISSON (0, 1, 1/(months between chronic oiling), 0, 1, 0)
months between chronic oiling	=	<i>constant from spreadsheet</i>
cleaning2	=	IF THEN ELSE (chronic oiling > 0, 1, 0)
coilA	=	%coilA*chronic oiling*coil on
%coilA	=	<i>constant from spreadsheet</i>
coilI[i0m]	=	%coilI*chronic oiling*coil on
%coilI	=	<i>constant from spreadsheet</i>
coilC	=	%coilC*chronic oiling*coil on
%coilC	=	%coilA*%parentsC
coilE	=	%coilE*chronic oiling*coil on
%coilE	=	%coilA*%parentsE

Table B.12: Chronic oiling equations

climateOn	=	<i>constant from spreadsheet</i>
climate Cold	=	cold*cold spells
cold	=	$\begin{cases} 0.25 & \text{if month} = 0, 1, 2, 10, 11 \\ 0.50 & \text{if month} = 3, 4, 8, 9 \\ 1.00 & \text{otherwise} \end{cases}$
cold spells	=	RANDOM POISSON (0, 2, 1/months between cold spells, 0, 1, 0)
months between cold spells	=	<i>constant from spreadsheet</i>
coldC	=	$(-c0 - \ln((1 + \text{EXP}(-c0)))/\%coldC - 1))*climateOn$
%coldC	=	<i>constant from spreadsheet</i>
coldE	=	$(-e0 - \ln((1 + \text{EXP}(-e0)))/\%coldE - 1))*climateOn$
%coldE	=	<i>constant from spreadsheet</i>
climate Heat	=	hot spells*heat
heat	=	$\begin{cases} 0.25 & \text{if month} = 5, 6, 7 \\ 0.50 & \text{if month} = 2, 3, 4, 8, 9, 10 \\ 1.00 & \text{otherwise} \end{cases}$
hot spells	=	RANDOM POISSON (0, 2, 1/months between hot spells, 0, 1, 0)
months between hot spells	=	<i>constant from spreadsheet</i>
heatC	=	$(-c0 - \ln((1 + \text{EXP}(-c0)))/\%heatC - 1))*climateOn$
%heatC	=	<i>constant from spreadsheet</i>
heatE	=	$(-e0 - \ln((1 + \text{EXP}(-e0)))/\%heatE - 1))*climateOn$
%heatE	=	<i>constant from spreadsheet</i>

Table B.13: Climate equations

floodOn	=	<i>constant from spreadsheet</i>
flooding	=	INTEG (flooding event - flooding end, 0)
flooding event	=	RANDOM POISSON (0, 99999, 1/months between floods, 0, 1, 0)
months between floods	=	<i>constant from spreadsheet</i>
flooding end	=	DELAY FIXED (flooding event, 1, 0)
floodC	=	%floodC*floodOn*flooding
%floodC	=	<i>constant from spreadsheet</i>
floodE	=	%floodE*floodOn*flooding
%floodE	=	<i>constant from spreadsheet</i>

Table B.14: Flooding equations

catOn	=	<i>constant from spreadsheet</i>
cat abundance	=	INTEG (r cat - out cat, 0)
r cat	=	RANDOM NORMAL (-1, 1, 0, 0.3, 0)*v pulse
out cat	=	DELAY FIXED (r cat, 12, 0)
catC	=	$(-c0 - \ln((1 + \text{EXP}(-c0))/\%catC - 1)) * catOn$
%catC	=	<i>constant from spreadsheet</i>
catE	=	$(-e0 - \ln((1 + \text{EXP}(-e0))/\%catE - 1)) * catOn$
%catE	=	<i>constant from spreadsheet</i>

Table B.15: Land predator (cats, rats, etc) equations

sharkOn	=	<i>constant from spreadsheet</i>
shark abundance	=	INTEG (r shark - out shark, 0)
r shark	=	RANDOM NORMAL (-1, 1, 0, 0.3, 25)*v pulse
out shark	=	DELAY FIXED (r shark, 12, 0)
sharkA	=	$(-a0 - \ln((1 + \text{EXP}(-a0))/\%sharkA - 1)) * sharkOn$
%sharkA	=	<i>constant from spreadsheet</i>
sharkI	=	$(-i0 - \ln((1 + \text{EXP}(-i0))/\%sharkI - 1)) * sharkOn$
%sharkI	=	<i>constant from spreadsheet</i>
sharkC	=	$(-c0 - \ln((1 + \text{EXP}(-c0))/\%sharkC - 1)) * sharkOn$
%sharkC	=	<i>constant from spreadsheet</i>
sharkE	=	$(-e0 - \ln((1 + \text{EXP}(-e0))/\%sharkE - 1)) * sharkOn$
%sharkE	=	<i>constant from spreadsheet</i>

Table B.16: Shark predation equations

adjustment factor	=	IF THEN ELSE (Total Adults < low threshold :AND: Total Adults ≥ very low threshold, 0.2, 0) + IF THEN ELSE (Total Adults < very low threshold, -0.1, 0)
low threshold	=	<i>constant from spreadsheet</i>
very low threshold	=	<i>constant from spreadsheet</i>
carrying capacity	=	<i>constant from spreadsheet</i>
Extinction	=	IF THEN ELSE (actual breeding pairs[no] < 10, 1, 0)

Table B.17: Density equations

data pulse	=	PULSE TRAIN(-1, 1, 12, FINAL TIME) + pulse(0, 1)
foodOn	=	<i>constant from spreadsheet</i>
biomass data[ab]:	=	<i>constant from spreadsheet</i>
biomass data[sb]:	=	<i>constant from spreadsheet</i>
recruit biomass	=	data pulse*(biomass data[ab] + biomass data[sb])
mean	=	INTEG (recruit biomass - PULSE TRAIN (11, 1, 12, 1e + 008)*mean, 0)
monthly biomass	=	RANDOM NORMAL (MAX (0, mean - 3*stdev), mean + 3*stdev, mean, stdev, 0)
stdev	=	<i>constant from spreadsheet</i>
catch data[ab]:	=	<i>constant from spreadsheet</i>
catch data[sb]:	=	<i>constant from spreadsheet</i>
mean fisheries catch	=	catch data[ab] + catch data[sb]
fisheries catch	=	mean fisheries catch*fishing allowed
fishing allowed	=	<i>constant from spreadsheet</i>
catch	=	MIN(monthly biomass, fisheries catch)

Table B.18: Zone 1 biomass and catch input equations

Zone 1 Biomass	=	INTEG (monthly biomass - catch - fish mortality - (mean1 + mean2)*pulse(0, 1), mean1 + mean2 - (catch1 + catch2))
fish mortality	=	DELAY FIXED (MAX (0, (monthly biomass - catch)), 1, 0)
mean1	=	<i>constant from spreadsheet</i>
mean2	=	<i>constant from spreadsheet</i>
catch1	=	<i>constant from spreadsheet</i>
catch2	=	<i>constant from spreadsheet</i>
z1	=	Zone 1 prey abundance(Zone 1 Biomass)
Zone 1 prey abundance()	=	<i>see table D.9</i>

Table B.19: Zone 1 abundance equations

biomass data[ac]:	=	<i>constant from spreadsheet</i>
biomass data[sc]:	=	<i>constant from spreadsheet</i>
spawner biomass[ac]	=	data pulse*(biomass data[ac])
spawner biomass[sc]	=	data pulse*(biomass data[sc])
kj	=	INTEG ((spawner biomass[ac]*kj value[ac] + spawner biomass[sc]*kj value[sc] - PULSE TRAIN(11, 1, 12, 1e + 008)*kj - pulse(0, 1)*kj), lag 1 fish[ac]*kj value[ac] + lag 1 fish[sc]*kj value[sc])
kj value[fish]	=	6.74, 8.59, 6.74, 8.59
Zone 2 level[bp]	=	INTEG ((PULSE TRAIN (12, 1, 12, 1e + 007)*(kj lag 1 + kj lag 2) - PULSE TRAIN (12, 1, 12, 1e + 007)*Zone 2 level[bp]), kj lag 1 + kj lag 2)
Zone 2 level[as]	=	INTEG ((PULSE TRAIN(12, 1, 12, 1e + 007)*(kj lag 1 + kj) - PULSE TRAIN (12, 1, 12, 1e + 007)*Zone 2 level[as]), kj + kj lag 1)
kj lag 1	=	DELAY FIXED (kj, 12, lag 1 fish[ac]*kj value[ac] + lag 1 fish[sc]*kj value[sc])
kj lag2	=	DELAY FIXED (kj lag 1, 12, lag 2 fish[ac]*kj value[ac] + lag 2 fish[sc]*kj value[sc])
lag 1 fish[ac]	=	<i>constant from spreadsheet</i>
lag 1 fish[sc]	=	<i>constant from spreadsheet</i>
lag 2 fish[ac]	=	<i>constant from spreadsheet</i>
lag 2 fish[sc]	=	<i>constant from spreadsheet</i>
Zone 2 Biomass[js]	=	kj
Zone 2 Biomass[as]	=	Zone 2 level[as]
Zone 2 Biomass[bp]	=	Zone 2 level[bp]
z2[z2sub]	=	Zone 2 prey abundance[z2sub](Zone2Biomass[z2sub])
Zone 2 prey abundance[z2sub]()	=	<i>see table D.10</i>

Table B.20: Zone 2 equations

febp	=	$Lbp(z2[bp]*foodOn)$
Lbp()		<i>see table D.11</i>
food effect A	=	$(-a0 - \ln((1 + EXP(-a0))/\%feA - 1))*foodOn$
%feA	=	<i>constant from spreadsheet</i>
food effect I	=	$(-i0 - \ln((1 + EXP(-i0))/\%feI - 1))*foodOn$
%feI	=	<i>constant from spreadsheet</i>
food effect C	=	$(-c0 - \ln((1 + EXP(-c0))/\%feC - 1))*foodOn$
%feC	=	<i>constant from spreadsheet</i>
food effect E	=	$(-e0 - \ln((1 + EXP(-e0))/\%feE - 1))*foodOn$
%feE	=	<i>constant from spreadsheet</i>

Table B.21: Food effect equations

Appendix C

VBA code

Declares important variables

```
Dim data() As Single
Dim fish() As Single
Dim catchD() As Single
Dim catch() As Single
Public n, nrow
```

Clears all data from the Fish and Catch worksheets

```
Private Sub clearData_Click()
Worksheets("Fish").Range("F2", Worksheets("Fish").Range("F2")
    .End(xlDown).End(xlToLeft)).Clear
Worksheets("Catch").Range("C2", Worksheets("Catch").Range("C2")
    .End(xlDown).End(xlToLeft)).Clear
End Sub
```

*Reads data and stores it before
calling the sample and print functions*

```
Public Sub GenerateData_Click()
Call clearData_Click
Names the range from A3 to end of data in column A as AnchovyB
Set AnchovyB = Worksheets("Data").Range("A3", Worksheets("Data")
    .Range("A3").End(xlDown))
Reads the number of years of data  
to produce from the Fish worksheet
```

```

n = Worksheets("Fish").Range("I1").Value
Counts the number of rows in AnchovyB
(how many years of data)
nrow = AnchovyB.Rows.Count
Prepares the data matrix
ReDim data(nrow, 5)
i = 0
Reads the biomass data and stores it in the data array
For Each c In AnchovyB
    data(i, 0) = c.Value
    data(i, 1) = c.Offset(0, 1).Value
    data(i, 2) = c.Offset(0, 2).Value
    data(i, 3) = c.Offset(0, 3).Value
    data(i, 4) = c.Offset(0, 7).Value
    i = i + 1
Next c
Names the range from A2 to the end of column A
in the Data2 worksheet as catchData
Set catchData = Worksheets("Data2").Range("A2", Worksheets("Data2")
    .Range("A2").End(xlDown))
Runs the sample and print functions before
making the Fish worksheet active
Call sample(n, nrow, catchData)
Call printData(n)
Worksheets("Fish").Activate
End Sub

Samples from the data with replacement
Public Sub sample(n, nrow, catchData)
If data(0, 0) = 0 Then
    MsgBox ("Generate Data first!")
Else
Resizes the fish and catch arrays
    ReDim fish(n + 2, 6)
    ReDim catch((n + 2) * 12 + 12, 2)
Sets the seed for the random number generator to the current time
    Randomize

```

*Samples randomly from the data array
and stores it in the fish array*

```
For j = 0 To n + 1
    x = Int(nrow * Rnd)
    fish(j, 0) = data(x, 0)
    fish(j, 1) = data(x, 1)
    fish(j, 2) = data(x, 2)
    fish(j, 3) = data(x, 3)
    fish(j, 4) = data(x, 4)
```

*Gets the current year being sampled and finds the
appropriate catch data for that year*

```
    currentYear = fish(j, 4)
    For i = 0 To 11
        catch(j * 12 + i, 0) = catchData.Find
            (currentYear, Range("A2")).Offset(i, 2).Value
        catch(j * 12 + i, 1) = catchData.Find
            (currentYear, Range("A2")).Offset(i, 3).Value
    Next
Next
End If
End Sub
```

Outputs the data to the Fish and Catch worksheets

```
Public Sub printData(n)
```

*This first works out the time in months for each row
and outputs the biomass values*

```
For k = 0 To n + 1
    timeEntry = WorksheetFunction.Max(0, 12 * (k - 1) - 1)
    If k = 0 Then timeEntry = ""
    Worksheets("Fish").Range("A2").Offset(k, 0).Value = timeEntry
    Worksheets("Fish").Range("B2").Offset(k, 0).Value = fish(k, 0)
    Worksheets("Fish").Range("C2").Offset(k, 0).Value = fish(k, 1)
    Worksheets("Fish").Range("D2").Offset(k, 0).Value = fish(k, 2)
    Worksheets("Fish").Range("E2").Offset(k, 0).Value = fish(k, 3)
    Worksheets("Fish").Range("F2").Offset(k, 0).Value = fish(k, 4)
Next
```

*Fills in the final time value and zeros for each column
- needed to avoid errors in model*

```
Worksheets("Fish").Range("A2").Offset(n + 2, 0).Value = 12 * (k - 2)
Worksheets("Fish").Range("B2").Offset(n + 2, 0).Value = 0
Worksheets("Fish").Range("C2").Offset(n + 2, 0).Value = 0
Worksheets("Fish").Range("D2").Offset(n + 2, 0).Value = 0
Worksheets("Fish").Range("E2").Offset(n + 2, 0).Value = 0
Worksheets("Fish").Range("F2").Offset(n + 2, 0).Value = 0
```

Outputs first line for catch data

```
Worksheets("Catch").Range("A2").Offset(0, 0).Value = ""
Worksheets("Catch").Range("B2").Offset(0, 0).Value = catch(4, 0)
Worksheets("Catch").Range("C2").Offset(0, 0).Value = catch(4, 1)
```

Outputs catch data for the rest of the years

```
For k = 1 To n * 12 + 1
    Worksheets("Catch").Range("A2").Offset(k, 0).Value = k - 1
    Worksheets("Catch").Range("B2").Offset(k, 0).Value = catch(k, 0)
    Worksheets("Catch").Range("C2").Offset(k, 0).Value = catch(k, 1)
Next
End Sub
```

Resamples from the data without reading the original data again

```
Public Sub refreshData_Click()
n = Worksheets("Fish").Range("I1").Value 'counts number of rows
Call clearData_Click
Call sample(n, nrow, catchData) ' resamples data
Call printData(n) 'outputs it to spreadsheet
End Sub
```


Appendix D

Parameter values

The parameter values for constants in the model are given first (Tables D.1 to D.7) then the Lookup relationships are given by means of tables.

Parameter	Value
Mean adult survival	0.880
Mean immature survival	0.510
Mean chick survival (Fledging success)	0.590
Mean egg survival (Hatching success)	0.648
Hatching time (months)	1
Fledging time (months)	3

Table D.1: Parameter values for penguin population

Parameter	Value
Initial number of adults (Adults)	3 500
Average proportion of sexually mature adults that choose to breed each year	0.834
Proportion of adults in age class 2 that are sexually mature (b2)	0.050
Range of b2 is 0 to 0.1	0.050
Proportion of adults in age class 3 that are sexually mature (b3)	0.330
Range of b3 is 0.03 to 0.63	0.030
Proportion of adults in age class 4 that are sexually mature (b4)	0.740
Range of b4 is 0.675 to 0.805	0.065
Proportion of adults in age class 5 that are sexually mature (b5)	1.000
Adjustment to number of broods lost (bladj)	1.380
Adjustment to number of broods successful (bsadj)	0.770
Probability of relaying after clutch loss (Rc)	0.305
Annual variation in Rc	0.101
Probability of relaying after brood loss (Rb)	0.218
Annual variation in Rb	0.153
Probability of relaying after successful fledging of a brood (Rs)	0.218
Annual variation in Rs	0.114

Table D.2: Parameter values for breeding calculations

Parameter	Value
If shark abundance is at its maximum (1):	
Value by which adult survival is multiplied	0.800
Value by which immature survival is multiplied	0.800
Value by which chick survival is multiplied	0.900
Value by which egg survival is multiplied	0.900
If land predator abundance is at its maximum (1):	
Value by which chick survival is multiplied	0.850
Value by which egg survival is multiplied	0.850

Table D.3: Parameter values for predator abundance

Parameter	Value
Average time in months between catastrophic oil spills	600
Proportion of adult penguins oiled in a catastrophic spill	0.240
Proportion of immature penguins oiled in a catastrophic spill	0.100
Average time in months between chronic oil spills	3
Proportion of adult penguins oiled in a chronic spill	0.008
Proportion of immature penguins oiled in a chronic spill	0.0006

Table D.4: Parameter values for oiling

Parameter	Value
Average time in months between floods	60
Proportion of chicks lost to flooding	0.400
Proportion of eggs lost to flooding	0.400
Average time in months between cold events	40
If a cold event is at its worst:	
Value by which chick survival is multiplied	0.700
Value by which egg survival is multiplied	0.700
Average time in months between heat events	36
If a heat event is at its worst:	
Value by which chick survival is multiplied	0.500
Value by which egg survival is multiplied	0.500

Table D.5: Parameter values for weather and climate

Parameter	Value
If food availability is at its worst:	
Value by which adult survival is multiplied	0.800
Value by which immature survival is multiplied	0.700
Value by which chick survival is multiplied	0.500
Value by which egg survival is multiplied	0.500
kj value [sardine]	8.59
kj value [anchovy]	6.74

Table D.6: Parameter values for food calculations

Parameter	Value
Number of adults below which breeding proportion reduces	200
Number of adults below which breeding proportion increases	1500
Number of adults the island can comfortably support	3 000 000

Table D.7: Parameter values for density calculations

Time	Laying rate	Effective month
0 - 2	0.23	Feb - Apr
3 - 5	0.09	May - Jul
6	0.04	Aug
7-11	0.00	Sep - Jan

Table D.8: Eggs per month lookup

Zone 1 Biomass	0	m	$m + \sigma$	$m + 2 * \sigma$	$m + 3 * \sigma$
z1	-1	0	0.33	0.67	1

where m is the median of the Stratum D anchovy and sardine biomass and σ is the standard deviation of that biomass

Table D.9: Zone 1 prey abundance lookup

Zone 2 Biomass	0	$2*(m - 2 * \sigma)$	$2*m$	$2*(m + 2 * \sigma)$	$2*(m + 3 * \sigma)$
z2(adult survival)	-1	-0.25	0	0.25	1
z2(breeding prop)	-1	-0.25	0	0.25	1
Zone 2 Biomass	0	$m - 2 * \sigma$	m	$m + 2 * \sigma$	$m + 3 * \sigma$
z2(immature survival)	-1	-0.25	0	0.25	1

where m is the median of the combined anchovy and sardine Stratum C biomass (converted to kj) and σ is the standard deviation of the kj converted biomass

Table D.10: Zone 2 prey abundance lookup

z2(breeding prop)	-1.00	0.00	1.00
febp	-0.10	0.00	0.10

Table D.11: Adjustment to breeding proportion lookup

Appendix E

Sensitivity analysis

E.1 Pressures in isolation

Table E.5 shows the minimum, maximum and the range of population sizes for each scenario and each pressure. This was used to identify unusual trends as well as to examine variability in the results.

Tables E.2, E.3 and E.4 show the probability that the population at the end of the time period will be below a certain percentage of the initial population. The columns do not add up to 1 as the first four rows provide a break down of the last row. Note that a dash in the table indicates a probability of zero.

Parameter	Base	Large decr.	Small decr.	Small incr.	Large incr.
Adult survival	0.880	0.440	0.792	0.968	0.990
Immature survival	0.516	0.258	0.466	0.568	0.774
Chick survival	0.590	0.259	0.530	0.649	0.885
Egg survival	0.648	0.324	0.583	0.713	0.972
<i>Effect of shark abundance on:</i>					
Adult survival	0.80	0.40	0.72	0.88	0.99
Immature survival	0.80	0.40	0.72	0.88	0.99
Chick survival	0.90	0.45	0.81	0.99	0.99
Egg survival	0.90	0.45	0.81	0.99	0.99
<i>Effect of land predator abundance on:</i>					
Chick survival	0.850	0.425	0.765	0.935	0.990
Egg survival	0.850	0.425	0.765	0.935	0.990
Months between catastrophic oiling	600	300	540	660	900
<i>Effect of catastrophic oil spills on:</i>					
Adult survival	0.240	0.120	0.216	0.264	0.360
Immature survival	0.100	0.050	0.090	0.110	0.150
Months between chronic oiling	3	1	2	4	5
<i>Effect of chronic oil spills on:</i>					
Adult survival	0.008	0.004	0.0072	0.0088	0.012
Immature survival	0.0006	0.0003	0.00054	0.00066	0.0009
Months between floods	60	30	54	66	90
<i>Effect of floods on:</i>					
Chick survival	0.400	0.200	0.360	0.440	0.600
Egg survival	0.400	0.200	0.360	0.440	0.600
Months between cold events	40	20	36	44	60
<i>Effect of cold events on:</i>					
Chick survival	0.700	0.350	0.630	0.770	0.990
Egg survival	0.700	0.350	0.630	0.770	0.990
Months between heat events	36	18	32	40	54
<i>Effect of heat events on:</i>					
Chick survival	0.500	0.250	0.450	0.550	0.750
Egg survival	0.500	0.250	0.450	0.550	0.750
<i>Effect of food availability on:</i>					
Adult survival	0.800	0.400	0.720	0.880	0.990
Immature survival	0.700	0.350	0.630	0.770	0.990
Chick survival	0.500	0.250	0.450	0.550	0.750
Egg survival	0.500	0.250	0.450	0.550	0.750

Table E.1: Parameter values tested during sensitivity analysis

Mean survival values					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	1.000	-	-	-
25%	-	1.000	1.000	-	-
50%	-	1.000	1.000	-	-
75%	-	1.000	1.000	-	-
100%	0.535	1.000	1.000	0.000	0.000

Effect of shark abundance					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	-	0.685	-	-	-
100%	0.935	1.000	1.000	0.645	0.470

Effect of land predator abundance					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	-	0.015	-	-	-
100%	0.515	0.450	0.460	0.540	0.515

Average time between catastrophic oil spills					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	0.050	0.115	0.050	0.035	0.015
100%	0.665	0.770	0.685	0.645	0.610

Effect of catastrophic oil spills					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	0.010
75%	0.050	-	0.035	0.055	0.150
100%	0.665	0.665	0.665	0.665	0.665

Table E.2: Results of analysis: Probability population will be below threshold

Average time between chronic oil spills					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	0.010	-	-	-
75%	0.300	1.000	0.960	0.010	-
100%	1.000	1.000	1.000	1.000	1.000

Effect of chronic oil spills					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	0.300	-	0.080	0.595	0.985
100%	1.000	1.000	1.000	1.000	1.000

Average time between floods					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	-	-	-	-	-
100%	0.970	1.000	0.975	0.965	0.940

Effect of floods					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	-	-	-	-	-
100%	0.970	0.890	0.965	0.980	0.985

Table E.3: Results of analysis (*cont.*)

Average time between cold events					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	-	-	-	-	-
100%	0.900	0.970	0.900	0.895	0.880

Effect of cold events					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	-	-	-	-	-
100%	0.900	0.955	0.905	0.890	0.810

Average time between heat events					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	-	-	-	-	-
100%	0.900	0.975	0.905	0.885	0.865

Effect of heat events					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	-	-	-	-	-
100%	0.900	0.960	0.910	0.890	0.825

Effect of food availability					
Threshold	Base	x 0.5	x 0.9	x 1.1	x 1.5
5%	-	-	-	-	-
25%	-	-	-	-	-
50%	-	-	-	-	-
75%	-	0.195	-	-	-
100%	0.672	0.7261	0.689	0.631	0.382

Table E.4: Results of analysis (*cont.*)

Pressure:	Large decrease			Small decrease			Base		
	Min	Max	Range	Min	Max	Range	Min	Max	Range
Mean survival	0	0	0	297	337	40	3 261	3 737	476
Shark	2 408	2 794	386	3 025	3 475	450	3 142	3 604	462
Land predators	2 576	4 957	2 381	3 048	4 051	1 003	3 171	3 854	683
Catastrophic oiling timing	1 953	3 733	1 780	2 026	3 733	1 707	2 026	3 733	1 707
Catastrophic oiling effect	2 630	3 733	1 103	2 141	3 733	1 592	2 026	3 733	1 707
Chronic oiling timing	1 711	2 308	5 97	2 154	2 732	578	2 423	2 984	561
Chronic oiling effect	2 871	3 500	629	2 511	3 055	544	2 423	2 984	561
Flood timing	2 796	3 477	681	2 970	3 590	620	2 962	3 590	628
Flooding effect	3 134	3 653	519	3 000	3 603	603	2 962	3 590	628
Cold event timing	3 110	3 589	479	2 977	3 668	691	2 977	3 668	691
Cold event effect	2 904	3 668	764	2 964	3 668	704	2 977	3 668	691
Heat event timing	2 989	3 679	690	2 977	3 668	691	2 977	3 668	691
Heat event effect	2 836	3 632	796	2 952	3 662	710	2 977	3 668	691
Food availability	2 901	5 246	2 345	2 294	5 488	3 194	2 778	5 332	2 554
				Large increase					
	Small increase			Min	Max	Range			
Mean survival	30 019	34 820	4 801	361 934	449 409	87 475			
Shark	3 236	3 710	474	3 270	3 747	477			
Land predators	3 234	3 742	508	3 261	3 753	492			
Catastrophic oiling timing	2 026	3 733	1 707	2 217	3 733	1 516			
Catastrophic oiling effect	1 914	3 733	1 819	1 497	3 733	2 236			
Chronic oiling timing	2 586	3 263	677	2 629	3 280	651			
Chronic oiling effect	2 339	2 914	575	2 021	2 654	633			
Flood timing	3 000	3 590	590	3 053	3 590	537			
Flooding effect	2 924	3 578	654	2 775	3 529	754			
Cold event timing	2 977	3 668	691	3 113	3 668	555			
Cold event effect	2 990	3 668	678	3 027	3 668	641			
Heat event timing	2 942	3 517	575	3 099	3 690	591			
Heat event effect	3 001	3 673	672	3 094	3 693	599			
Food availability	2 985	5 098	2 113	3 108	4 681	1 573			

Table E.5: Range of final population size

Biomass (Stratum) time series	Test result	P value
Anchovy (D)	-1.4876	0.1369
Sardine (D)	-1.0599	0.2892
Sum (D)	-1.4876	0.1369
Anchovy (C)	-1.9153	0.0555
Sardine (C)	-1.4876	0.1369
Sum (C)	-1.0599	0.2892

Table E.6: Table of results for the runs tests

University of Cape Town

Appendix F

Evaluation forms

These are the evaluation forms that the participants filled out at the end of the workshop.

University of Cape Town

Robben Island Penguin Population Model – Evaluation

Name: *Christina Mosley*

How easily were you able to work with the model?

Very easy Easy Okay Difficult Very difficult

Comments:

How easy was it to understand the relationships between variables in the model?

Very easy Easy Okay Difficult Very difficult

Comments:

What makes or would make this model a useful tool for communicating issues to stakeholders?

The flexibility of being able to change parameters & management options

What aspects make or would make this model a useful learning tool?

It is useful to be able to change the parameters & see what happens.

Do you think this model could be used to convey information to stakeholders?

Yes. The best way may be to present various scenarios with different demographic parameters & food availability etc and then let the stakeholders play with the model.

Which groups of stakeholders do you think would most benefit from this?

Managers & (government) scientists

Which groups of stakeholders would the model be unsuitable for and why?

People without a basic scientific background might struggle to understand the model

In your opinion, what makes this model different from other penguin models and from multi-species models?

I don't have much experience with other models so it's hard to tell, sorry!

Any other comments:

I found it difficult to keep track of all the different runs I did & what parameters I had used. If there isn't a way to do this in version, then perhaps warn people to keep track of things before they start.

Robben Island Penguin Population Model – Evaluation

Name: *Res Altwegg*

How easily were you able to work with the model?

Very easy Easy Okay Difficult Very difficult

Comments: *Took me a moment to understand what all the symbols and things in graphs mean.*

How easy was it to understand the relationships between variables in the model?

Very easy Easy Okay Difficult Very difficult

Comments: *Not easy to see from the graph (only qualitative)*

What makes or would make this model a useful tool for communicating issues to stakeholders?

Once people trust the model, it is a great tool for communication. Graphical options + gaming very useful. Perhaps we should make a simpler version for communication.

What aspects make or would make this model a useful learning tool?

Gaming, and the fact that so many drivers are in the model. Perhaps include more controls in the gaming option.

Do you think this model could be used to convey information to stakeholders?

Yes

Which groups of stakeholders do you think would most benefit from this?

Managers, Scientists.

Which groups of stakeholders would the model be unsuitable for and why?

In your opinion, what makes this model different from other penguin models and from multi-species models?

Other penguin models: includes more drivers, but more difficult to estimate effects of uncertainty.

Any other comments:

Robben Island Penguin Population Model – Evaluation

Name: *Jane Coetzer*

How easily were you able to work with the model?

Very easy Easy Okay Difficult Very difficult

Comments:

How easy was it to understand the relationships between variables in the model?

Very easy Easy Okay Difficult Very difficult

Comments:

What makes or would make this model a useful tool for communicating issues to stakeholders?

The graphic output enables quick evaluation of effect and stresses impact of even very small changes in pressures.

What aspects make or would make this model a useful learning tool?

Documentation is required, as are the need for ability to change fixed parameters. Data Sources need specification & assumptions need to be listed so sensitivities can be tested.

Do you think this model could be used to convey information to stakeholders?

Potentially yes, although caution is needed when presenting such to managers without informing them of underlying model & assumptions.

Which groups of stakeholders do you think would most benefit from this?

Conservation managers

Which groups of stakeholders would the model be unsuitable for and why?

refers back to above, some managers could take a particular outcome as "reality" and not understand variability / sensitivities to input / assumptions

In your opinion, what makes this model different from other penguin models and from multi-species models?

No other penguin models to compare with yet!

Any other comments:

Robben Island Penguin Population Model – Evaluation

Name: *FG Ryan*

How easily were you able to work with the model?

Very easy Easy Okay Difficult Very difficult

Comments:

How easy was it to understand the relationships between variables in the model?

Very easy Easy Okay Difficult Very difficult

Comments: *complex interactions + probably too many options to facilitate understanding in a short workshop*

What makes or would make this model a useful tool for communicating issues to stakeholders?

OK for "penguin people" but probably too many variables that can be tweaked for fishery users

What aspects make or would make this model a useful learning tool?

I would select ideal set of penguin data & then make them fixed

Do you think this model could be used to convey information to stakeholders?

Yes, but probably in a simplified format?

Which groups of stakeholders do you think would most benefit from this?

Probably "penguin group" by forcing them to better understand interactions

Which groups of stakeholders would the model be unsuitable for and why?

Not convinced it will improve relations with pro-fishing lobby

In your opinion, what makes this model different from other penguin models and from multi-species models?

Extra realism (although lots of rather poorly supported parameters)

Any other comments: *I'd remove density dependence & boost numbers at which Allee effect kicks in*

Robben Island Penguin Population Model – Evaluation

Name: Larry D

How easily were you able to work with the model?

Very easy Easy Okay **Difficult** Very difficult

Comments: Took a while to understand -

How easy was it to understand the relationships between variables in the model?

Very easy Easy **Okay** Difficult Very difficult

Comments:

What makes or would make this model a useful tool for communicating issues to stakeholders?

Some practical examples of how to examine changes in any one param.

What aspects make or would make this model a useful learning tool?

It seems anything is possible in this model - some sense of realism for issues managers doubts would be useful.

Do you think this model could be used to convey information to stakeholders?

yes

Which groups of stakeholders do you think would most benefit from this?

- 1) Fishing + biodiversity governance managers
- 2) Fishing company managers + share holders

Which groups of stakeholders would the model be unsuitable for and why?

Fishermen - not used to graphs and multiple variables

In your opinion, what makes this model different from other penguin models and from multi-species models?

It covers the range of complexity impacting bird pop.

Any other comments:

It certainly helped me understand the scope & complexity in the model, reduced in the gaming mode to 3 practical actions: controlling fishing, oil pollution and land protection. One needs specific desirable outcomes.

Robben Island Penguin Population Model – Evaluation

Name: *Lauren Waller*

How easily were you able to work with the model?

Very easy Easy **Okay** Difficult Very difficult

Comments:

How easy was it to understand the relationships between variables in the model?

Very easy Easy **Okay** Difficult Very difficult

Comments: *It's not always easy to go back and find what parameters are behind the trends observed.*

What makes or would make this model a useful tool for communicating issues to stakeholders?

The model shows stakeholders that there are a range of threats/parameters to be considered that could have an effect on penguins. It shows that the system is complex.

What aspects make or would make this model a useful learning tool?

*The diagrams on each page that show how the model components have been constructed are excellent in showing the thought process followed.
Also a useful teaching tool to students*

Do you think this model could be used to convey information to stakeholders?

Yes. Shows how changing parameters through interventions can affect overall population.

Which groups of stakeholders do you think would most benefit from this?

Stakeholders that are familiar with penguin biology and management issues.

Which groups of stakeholders would the model be unsuitable for and why?

In your opinion, what makes this model different from other penguin models and from multi-species models?

It's clear that has adopted to realistically include an 'ecosystem' approach.

Any other comments:

Robben Island Penguin Population Model – Evaluation

Name: C. VAN DER LUGEN

How easily were you able to work with the model?

Very easy Easy Okay Difficult Very difficult

Comments:

How easy was it to understand the relationships between variables in the model?

Very easy Easy Okay Difficult Very difficult

Comments:

Consider including a 'glossary' or such in model for easy identification of terms

What makes or would make this model a useful tool for communicating issues to stakeholders?

Easy to see the effects of changing parameters on outputs (eg %fec)

What aspects make or would make this model a useful learning tool?

It is already, but some way of providing 'average' results from repeated runs (without changing param values) but changing

Do you think this model could be used to convey information to stakeholders?

Yes, but caution must be exercised - the model is not reality; particularly w.r.t. food variability. e.g. food, would be useful.

Which groups of stakeholders do you think would most benefit from this?

Broad variety, from fishing companies, conservation bodies, fishery managers, etc

Which groups of stakeholders would the model be unsuitable for and why?

Can't think of any.

In your opinion, what makes this model different from other penguin models and from multi-species models?

Model considers a variety of pressures, can vary pressures, parameters etc individually.

Any other comments:

Engageable among; instructive; useful.

Robben Island Penguin Population Model – Evaluation

Name: LYNNE SHANNON

How easily were you able to work with the model?

Very easy Easy Okay Difficult Very difficult

Comments: very user friendly.

How easy was it to understand the relationships between variables in the model?

Very easy Easy Okay Difficult Very difficult

Comments: Version graphically display those relationships nicely, and with combinations of excel sheets, v. nice.

What makes or would make this model a useful tool for communicating issues to stakeholders?

Setting managers (for e.g.) clear on a carefully planned set of scenarios (evening setting that public notes of what it is for effort reduction, etc) to guide them through. This only let them play (once they have been clear of what they need to look for / impact).

What aspects make or would make this model a useful learning tool?

Flexibility in changing parameters + effects + (graphically) being able to compare scenarios – that is really nice!

Do you think this model could be used to convey information to stakeholders?

YES

Which groups of stakeholders do you think would most benefit from this?

Fisheries managers, conservation authorities (a combination).

Which groups of stakeholders would the model be unsuitable for and why?

Stock assessors as they can't see the wood for the trees + would miss the point of the model!

In your opinion, what makes this model different from other penguin models and from multi-species models?

User-friendly framework; that stakeholders (experts in any one) were involved in the model planning + discussion right from the start.

Any other comments:

WELL DONE LEE-ANNE!