THE ASSESSMENT OF AND MANAGEMENT PROCEDURE DEVELOPMENT FOR THE NAMIBIAN MONKFISH RESOURCE

by

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Submitted for the degree of Master of Science
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March 2006

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Acknowledgement

Firstly, I would like to thank God for giving me strength and courage throughout the years. The Sam Nuuyoma Endowment Fund, the Namibian Hake Association and BENEFIT can never be thanked enough for funding my study. Leesa, Petro and Neville of BENEFIT, thanks for being patient and putting up with my nagging. Carola Kirchner and Peter Schneider of NatMIRC, thanks for providing the data. The guidance and constructive comments of my supervisor, Doug Butterworth, are greatly appreciated. Special thanks to Susan Johnston and Eva Plagányi-Lloyd for always being positive and patient with me, even when I appeared lost, and for constructive comments on earlier drafts of this thesis. The rest of the MARAM group is thanked for various tips and tricks on coding in admb and for proofreading this thesis. To my parents, Tate na Meme Iiyambo, akuti anuwa "...uudhigu wondunda wu pula eengudhi dhayo". Only heaven knows what you went through, raising a man so well like you did. You are the best. Komeine, thanks for being such a good friend. Lastly but definitely not least, Emma, thanks for believing in me. 143…

Abstract

The Namibian monkfish fishery has increased in importance over the last two decades, now being one of the largest and most valuable of its kind in the world. Although two monkfish species (*Lophius vomerinus* and *L. vaillanti*) are caught off the Namibian coast, the less abundant of the two (*L. vaillanti*, contributing only 1% to total landings) is not explicitly dealt with in this thesis, and the resource is treated as one species. The purpose of this thesis is to undertake a Bayesian assessment of the resource, and to use this as the basis to develop an Operational Management Procedure (OMP) for the resource.

First, the biology, history of the fishery, and the history of monkfish stock assessment and management are reviewed briefly. Then the reasons for using an Age-Structured Production Model (ASPM) for assessment are discussed.

The ASPM applied estimates the Namibian monkfish resource in 2004 to be at about 30% (CV=0.17) of its pristine level in terms of its spawning biomass. This itself is not a major cause for concern, as it suggests that the resource is slightly above its maximum sustainable yield level. However, the maximum sustainable yield of just over 9000 tons (CV=0.12) per annum is less than recent catches, and there is a downward trend in both the catch rates and the fishery independent abundance index from surveys over recent years, all of which call for some caution in management.

The Namibian monkfish resource was managed through effort control until the year 2000. The TAC approach was then introduced and has been applied since the 2001 fishing season. The key problem in formulating TAC recommendations with longer-terms objectives in mind is uncertainties about likely future trends, particularly in recruitment. An OMP is therefore developed for the Namibian monkfish resource, to try and address this problem.

The candidate OMPs are based on an $f_{0.n}$ harvesting strategy coupled to a Schaefer surplus production model, together with limitations on the extent of TAC changes from year to year. Their anticipated performances, in terms of catch and risk of resource depletion, are evaluated. Candidate OMPs are also tested for robustness across a range of alternative operating models. The baseline OMP chosen does not seem to be very robust to low values of the recruitment "steepness" parameter, large levels of recruitment variability, and bias in CPUE as an index of abundance. All the associated robustness tests result in an appreciable increase in the resource depletion risk. A change in the maximum allowed TAC decrease in any year from 15% to 25% solves this problem, although it also results in lower catches and higher inter-annual catch variation. All the OMP options considered suggest that a decrease in the TAC in the short term is likely to be required.

A few points to consider for future work on assessment and management of the Namibian monkfish resource are detailed. Efforts should be made to investigate the consequence of age-dependence in natural mortality on the performance of the candidate OMPs. Since the resource is exploited by two different "fleets" (the monkfish and sole directed "fleet" and the hake directed "fleet"), the differences between the fishing selectivities of these two "fleets" should be considered. Furthermore, the fits of population models to the data should include consideration of commercial and survey catch-at-age data. Age data might also be incorporated into the OMP, for example, by using an age-disaggregated model instead of an age-aggregated model as the model within the OMP.

Introduction and Overview of Thesis

Monkfish has become a valuable resource to Namibia over the last two decades, developing into a fishery of its own in 1994 after years of being exploited only as a hake-directed fishery by-catch (Maartens, 1999). Informed management of this valuable resource is therefore needed to conserve it and to make the best use of it.

Some extensive efforts to assess this resource have been made, especially by Maartens (1999). One of the four recommendations she made (pp: vi) was "...to develop a management procedure for Namibian monkfish with the main objective being the sustainable exploitation of the resource". She suggested a Bayesian statistical approach as being an option for future stock assessment work on monkfish, thereby getting one step closer to accounting for and conveying the full range of uncertainty related to both models and parameter values. In this way the Bayesian approach deals naturally with issues that the frequentist approach has difficulties in handling.

In this thesis, a Bayesian statistical approach, based on an Age-Structured Production Model (ASPM), is applied to assess the Namibian monkfish resource. This assessment then provides the operating model used in the development and testing of possible Operational Management Procedures for the monkfish resource.

Overview

Chapter 1 discusses the biological and historical background of the Namibian monkfish fishery, as detailed in the literature. The history of monkfish stock assessment and management is also discussed in this Chapter.

Chapter 2 describes the data available to assess the Namibian monkfish resource and provides some details as to how these data are collected, analyzed and used.

Chapter 3 details the Age-Structured Production Model (ASPM) developed and outlines reasons why it was chosen to describe the monkfish dynamics, and hence also used in the management procedure testing process of this resource.

Chapter 4 presents the Bayesian-based assessment of the Namibian monkfish resource.

Chapter 5 gives the general introduction and background information of the Operational Management Procedure (OMP) approach, and details the development and testing of an OMP for the Namibian monkfish resource.

Chapter 6 provides the overall conclusion and suggests some areas of future research.

1 Biological and Historical Background

1.1 Review of the Biology of Monkfish

1.1.1 Species and Stock Structure

Two species of monkfish inhabit the waters of Namibia: *Lophius vomerinus* and *Lophius vaillanti* (MFMR, 2005). *L. vomerinus* is a demersal species that inhabits from the tidal zone to depths of more than 600m (Maartens, 1999), with the major part of the stock being distributed at depths of 100 to 500m (MFMR, 2005). *L. vaillanti,* also a demersal species, is commonly found in the northern parts of Namibia at depths greater than 400m (MFMR, 2005 and Maartens and Booth, 2001b). In this thesis I concentrate on *L. vomerinus,* as its landed mass makes up about 99% of the landed monkfish (Maartens, 1999), and is by far the more important of the two species in terms of both abundance and value to the Namibian commercial trawl fishery (Maartens and Booth, 2001a). Both of the Namibian monkfish species do not seem to be limited to certain bottom types, and both are found on soft and rough grounds. However, the majority of the stock is found over soft bottom habitat because most of the Namibian continental shelf consists of a soft bottom (Maartens, 1999).

Historically, there has been some confusion regarding the taxonomic status of the southern African *Lophius*. As a result of this confusion, *L. vomerinus* has also been referred to as *L. upsicephasus* in the literature (Walmsley *et al.,* 2005). *Upsicephalus* means "upturned head" while the specific name *vomerinus* means "having vomerine teeth" (Maartens, 1999). The name *L. vomerinus* is used throughout this thesis.

L. vomerinus is distributed from northern Namibia (21°S) to Durban on the east coast of South Africa (30°S, 31°E; Leslie and Grant, 1990). *L. vaillanti* is distributed north of Walvis Bay (23°S) (Maartens, 1999).

1.1.2 Spawning and Maturity

There is a paucity of knowledge on the general life history of *L. vomerinus* in southern African waters. The International Commission of the Southeast Atlantic Fisheries (ICSEAF) member countries and in particular Spanish researchers have identified two separate recruitment areas in Namibia (these are areas with high abundance of 0-aged monkfish) (Maartens and Booth, 2005). The first is off Walvis Bay (23°S to 25°S) at depths between 150m and 300m, and the second near the Orange River (28°35'S) at depths between 100m and 300m (ICSEAF, 1984, 1985). Historical data on the reproductive biology of this species in Namibia are restricted to these areas (Maartens and Booth, 2005).

A study on the monthly gonado-somatic index (GSI) by Maartens (1999) suggested that *L. vomerinus* have a protracted spawning season, with males having reproductive peaks in April, October and February, whilst females have peaks from August to October.

There is an indication that *L. vomerinus* spawn throughout the year with a slight increase in spawning intensity over the winter period (MFMR, 2005). *L. vomerinus* spawn flat gelatinous egg masses, called veils, into the water, which float near the water surface (MFMR, 2005). Monkfish spawning is thought to occur at or near the seabed (Matsuura and Yoneda, 1986), as cited by Maartens (1999).

Length and age at sexual maturity have been estimated by Maartens (1999) for *L. vomerinus* off Namibia. Female *L. vomerinus* achieve 50% sexual maturity at around 32.1cm, which corresponds to an approximate age of 3 years. Male *L. vomerinus* achieve 50% sexual maturity at around 23.7cm, which corresponds to an approximate age of 2 years. Further studies by Maartens and Booth (2001a) have showed different values for 50% maturity, as per Table 3.1.

1.1.3 Growth

L. vomerinus is a relatively slow-growing and long-lived species, with a life span in excess of 10 years (Maartens *et al.*, 1999). The maximum known length recorded in Namibian waters is 117cm total length (TL) (ICSEAF, 1980). The growth patterns for male and female *L. vomerinus* differ appreciably, with females generally growing faster than males (Maartens *et al.*, 1999).

Growth parameters for *L. vomerinus* off Namibia, derived from the von Bertalanffy equation, have been published by Maartens *et al.* (1999) and are used by Maartens and Booth (2001a).

The von Bertalanffy equation is written as follows:

$$L_t = L_\infty(1 - e^{-\kappa(t-t_0)}) \qquad 1.1$$

where L_t is the mean total length of a fish aged *t* years, L_∞ is the asymptotic or maximum body length, κ, called the Brody growth coefficient, is a growth rate parameter and t_0 is the (theoretical) age at which length would be zero.

The following power model provides the length-weight relationship:

$$w_t = \alpha(L_t)^\beta \qquad 1.2$$

where w_t is the mean weight at age *t* years and L_t is the length at age *t* (eqn. 1.1).

Table 1.1 lists the estimates for the length-at-age and mass-at-age parameters for combined sex data fitted to a von Bertalanffy model for *L. vomerinus* off Namibia (Maartens and Booth, 2001a). Figures 1.1 and 1.2 show the growth curves plotted using the estimates shown in Table 1.1. The historic catch data that are available are sex-aggregated, hence the estimates in Table 1.1 are the ones used in these analyses.

1.1.4 Feeding

Lophiiformes (to which *L. vomerinus* belongs) are generally described in the literature as one of the most typical groups of sit-and-wait predators among fishes as well as being a characteristic example of fish that lure their prey by moving the illicium[1] (MFMR, 1999). They are also described as being opportunistic predators, with diet depending upon the behaviour of prey as well as the size of an individual's mouth (MFMR, 1999).

From a study conducted on the biology of the monkfish off the central Namibian shelf, the food items that could be identified from the stomach contents included shark, squid (*Todarodes sagittatus*), Cape horse mackerel (*Trachurus capensis*), banded whiptail (*Caelorinchus fasciatus*), orange roughy (*Hoplostethus atlanticus*), and blackbelly rosefish (*Helicolenus dactylopterus*) (Maartens, 1994). Very few cases of cannibalism (monk feeding on monk) have been reported (Maartens, 1994), which compares well with what was observed on *L. vomerinus* off the South African coasts (Walmsley *et al.*, 2005). Other species such as southern cuttlefish (*Sepia australis*), pelagic goby (*Sufflogobius bibarbatus*) and hake (*Merluccius capensis*) have also been reported to be prey for *L. vomerinus* off the Namibian coast (Bianchi *et al.*, 1993; Froese *et al.*, 2006).

Walmsley *et al.* (2005) describe the feeding behaviour of *L. vomerinus* as highly piscivorous, with the species feeding primarily on demersal fish. The diet of *L. vomerinus* off the South African coast show a shift from small prey to large prey with increasing predator size (Walmsley *et al.*2005).

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[1] The 'fishing pole' and 'lure' in the mouth of lophiiform (pediculate) fishes, used to attract prey close to the mouth.

A high proportion of *L. vomerinus* stomachs have been found to be empty off Namibia (Maartens, 1994) and off South Africa (Walmsley *et al.* 2005). Walmsley *et al.* (2005) interpret this, based on studies by Kosaka (1966), Benincasa (1983), Crozier (1985) and Macpherson (1985), as an indication that *L. vomerinus* moves to capture prey only when guaranteed a return and that they do not eat again until the prey is almost completely digested. This strategy is reported to be common within the genus *Lophius* to ensure maximum return for energy expended in capturing prey.

1.1.5 Predators

Relatively few fish have been reported to prey upon *L. vomerinus* off the Namibian coast (only the Slime skate (*Raja pullopunctata*)) and off the South African west coast (Lesser gurnard (*Chelidonichthys queketti*)) (Bianchi *et al.*, 1993; Froese *et al.*, 2006). However, as they reach a length of only 35cm TL and a mass of only 200g, *Chelidonichthys queketti* would be feeding on only small monkfish and hardly on big ones.

1.2 History of Monkfish Fishery

1.2.1 Development of the Fishery

The fishery for monkfish *L. vomerinus* and *L. vaillanti* is an important component of the demersal fishery off Namibia (Maartens and Booth, 2001b). The demersal trawl fishery off southern Africa developed before the turn of the 19th century (Boyer and Hampton, 2001), but the statistics on the exploitation of the Namibian monkfish date back only to 1974 (ICSEAF, 1980).

Monkfish used to be taken only as a bycatch in the trawl fishery directed at hake (*Merluccius* spp.) but due to increasing market demands that caused the escalation of its value, a fishery directed at monkfish and also sole (*Austroglossus microlepis*) (Maartens and Booth, 2001a) developed. Catches of more than 14 000 tons were recorded by the International Commission for the Southeast Atlantic Fisheries (ICSEAF) during 1981 and 1982, after which they decreased over the years to approximately 6 000 tons by the end of 1989 (Figure 1.3) (MFMR, 1996). In 1982, ICSEAF recommended that in view of the escalating commercial importance of monkfish, efforts should be made to collect data for stock assessment purposes (ICSEAF, 1980).

Monkfish catch data were collected by the ICSEAF between 1974 and 1989. These takes occurred as by-catches in the hake (*Merluccius* spp.) directed fishery in Divisions 1.4 (20°S to 25°S) and 1.5 (25°S to 30°S) (ICSEAF, 1982). Spain, however, indicated occasional monkfish directed fishing by some of its vessels within Divisions 1.4 and 1.5 and by 1984, the Spanish surveys revealed the presence of two species: *L. vomerinus* in coastal waters between 100m and 500m, and *L. vaillanti* in waters deeper than 400m (ICSEAF, 1980).

After Namibia's independence in 1990 and with the departure of foreign vessels from Namibian waters, annual monkfish catches initially decreased to approximately 1 500 tons in 1990, but then increased to more than 12 000 tons in 1994 (Maartens and Booth, 2001b). Subsequently, monkfish landings decreased to approximately 10 000 tons during the period 1995 to 1997, followed by the highest catch ever of almost 17 000 tons recorded during 1998 (MFMR, 1999). From 1994 until around the 2000 fishing season, the monkfish fishery was an effort limited fishery based on the number of vessels that have monk and sole exploitation rights (MFMR, 1996). The time series of monkfish catches is shown in Table 1.2 and Figure 1.3.

1.2.2 The Current Fishery

The Namibian monkfish fishery forms part of a two-species fishery with two separate but overlapping fishery interest groups (Maartens, 1999). The first of these groups is the monkfish and sole fishery that targets monkfish with a bycatch of sole and hake. The second group is the hake-directed fishery that catches on average 30% of the total annual monkfish landings as a bycatch. MFMR (2005) reports a decrease of the hake-directed bycatch to around 15% for the last two years (Table 1.2).

Annual catches in this fishery are controlled by total allowable catches (TACs), which have been set since the 2001 fishing season[2], with monkfish-dedicated surveys conducted since the end of the year 2000 (MFMR, 2004 and 2005). These surveys are discussed in more detail in section 2.3 following. The bulk of the monkfish landed in Namibia is caught by means of bottom trawling. Different types of nets are used by the monkfish industry. The two common denominators for these nets, however, are that all of them are fitted with "tickler chains" in front of the footrope in order to scare the fish off the bottom, and that in most cases trawls have a fairly low vertical opening of less than 2m. The minimum legal mesh size for monkfish is 75mm in the cod-end; the majority of the fleet however use a mesh size of either 110mm or 120mm (Maartens, 1999).

Monkfish vessels fish mainly between the 300m and 500m depth contours. They do however catch along the entire Namibian coast with the majority of catches taking place between Walvis Bay and Lüderitz, with only a few monkfish caught in the far south of the Namibian territorial waters due to untrawlable fishing grounds (MFMR, 2004 and 2005). With experimental gillnet licenses having been awarded recently, fishing now occurs in this far southern part of the Namibian territorial waters, an area that served as a reserve in the past (MFMR, 2004 and 2005).

Monkfish is typically landed as processed tails in different size classes ranging from XXS to XL (Table 1.3). The XXS and XS size classes are often combined as one US size class (Maartens and Booth, 2001a). The prices of monkfish, amongst other factors, depend on

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[2] Fishing season for Namibian monkfish is the same as that for Namibian hake: April to March.

the size class, with smaller size classes fetching lower prices than the larger size classes (http://www.namibianmonk.com/ind_info.htm, 01-09-2005).

1.3 History of Stock Assessment and Management

The first attempt at managing the Namibian monkfish resource was made in 1994 with the implementation of fishing rights to catch monkfish and sole with a hake by-catch quota (Maartens 1999). The monkfish fishery was managed through effort control, with limited access and a restriction of 800 horsepower on vessel capacity until the year 2000 (Maartens 1999).

A research project on the Namibian monkfish started in 1993, with the stock assessment component concentrating on length-based models to assess the status of the resource and to estimate relative biomass indices from hake directed research surveys between 1994 and 1996 (Maartens 1999).

Several approaches have been used to assess the state of the monkfish resource, such as Length Cohort Analysis (LCA) (which requires a length composition, representative of the catch under steady-state conditions (Jones 1984), as cited by Maartens (1999)), the Thompson and Bell predictive model (Maartens *et al.*, 1997) and a deterministic Age-Structured Production Modeling (ASPM) approach (this model was tuned using trends in catch-per-unit-effort data as well as relative abundance indices) (Maartens, 1999 and MFMR, 2004 and 2005).

Large proportions of sexually immature monkfish were reported to have been harvested during the fishing seasons from the mid-90s to the late-90s (Maartens *et al.*, 1997). In reaction to this, three grid-selection experiments were carried out to size-select and release juvenile (grid-selection) monkfish in Namibia, in a joint project between the Namibian Ministry of Fisheries and Marine Resources, the Namibian Monk and Sole Association and the Nansen Programme in Namibia (MFMR, 2004). Budget constraints and technical difficulties made it impossible for the experiments to test the survival of monkfish that had passed through the grid to be carried out.

The decision making process in Namibia, as outlined by Maartens (1999), entails the following: scientists from the Stock Assessment Group of the Ministry of Fisheries and Marine Resources (MFMR) provide recommendations on the status of the resource to the Director of the MFMR. On consideration and approval by the Director, the recommendations are presented to the Sea Fisheries Advisory Council. This Council provides a set of independent recommendations to the Minister of Fisheries and Marine Resources, by whom the final management decision is made.

The broad management objective is to facilitate the utilization of the monkfish stock to its full potential through scientifically based management strategies, while ensuring its long-term sustainability. In this thesis, the stochastic ASPM is used to assess and as a basis for the development of the OMP for the Namibian monkfish resource.

Table 1.1: Estimates of the parameter values of the von Bertalanffy growth equation and weight-at-length equation for *L. vomerinus* off Namibia (from: Maartens and Booth, 2001a).

Parameter	Estimate
$L_\infty (cm)$	95.00
$\kappa (yr^{-1})$	0.10
$t_0 (yr)$	-0.31
$\alpha (gm / cm^\beta)$	0.011
β	3.06

Table 1.2: Annual landings (tons) of the Namibian monkfish for the period 1974 to 2004, taken by various fisheries (2004 statistics are incomplete[3]) (from MFMR, 2005).

Year	Monkfish fleet	Hake fleet	Others[4]	Total (x1000 tonnes)	% Monkfish caught by Hake fleet
1974				0.3	
1975				1.1	
1976				0.9	
1977				5.7	
1978				7.4	
1979				3.5	
1980				3.2	
1981				15.6	
1982				16.3	
1983				12.9	
1984				8.5	
1985				8.5	
1986				13	
1987				11.7	
1988				5	
1989				6.6	
1990				1.5	
1991				4.6	
1992				8.1	
1993				9.2	
1994	8809	3349		12.2	27
1995	6476	3654		10.1	36
1996	6158	3590		9.8	37
1997	7237	3022	169	10.4	29
1998	13479	2950	141	16.6	18
1999	10351	3031	755	14.1	21
2000	10551	3807	38	14.4	26
2001	9018	3233	168	12.4	26
2002	9544	5389	329	15.3	35
2003	10943	2080		13.0	16
2004	7300	1331		8.6	15

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[3] The catch for the year 2004 is therefore set to the TAC value for that year.

[4] "Others" represent the amount caught as bycatch by some other fisheries.

Table 1.3: Total length and tail weight range of monkfish in six different size categories. (from Maartens and Booth, 2001a).

Category	Tail weight range (g)	Total length range (cm)
XXS	0-50	10-16
XS	50-100	17-25
S	100-250	26-36
M	250-500	37-48
L	500-1000	49-59
XL	1000+	60+

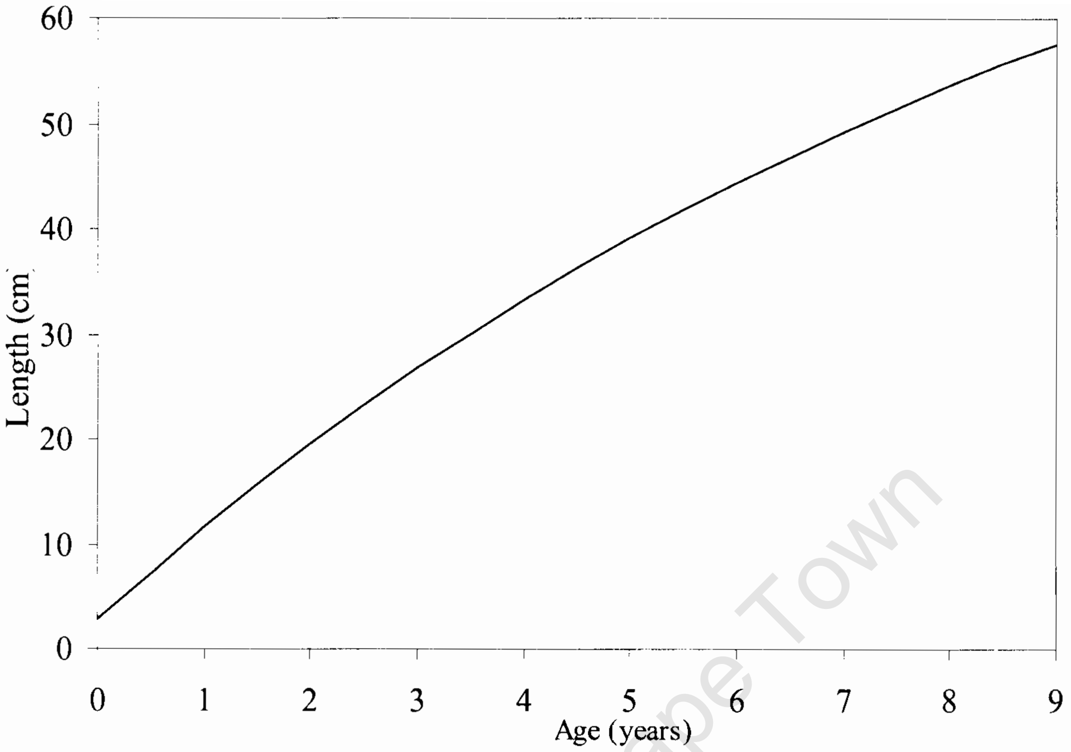

Figure 1.1: Estimated mean length-at-age from the Von Bertalanffy growth equation for *L. vomerinus* off Namibia for both sexes combined.

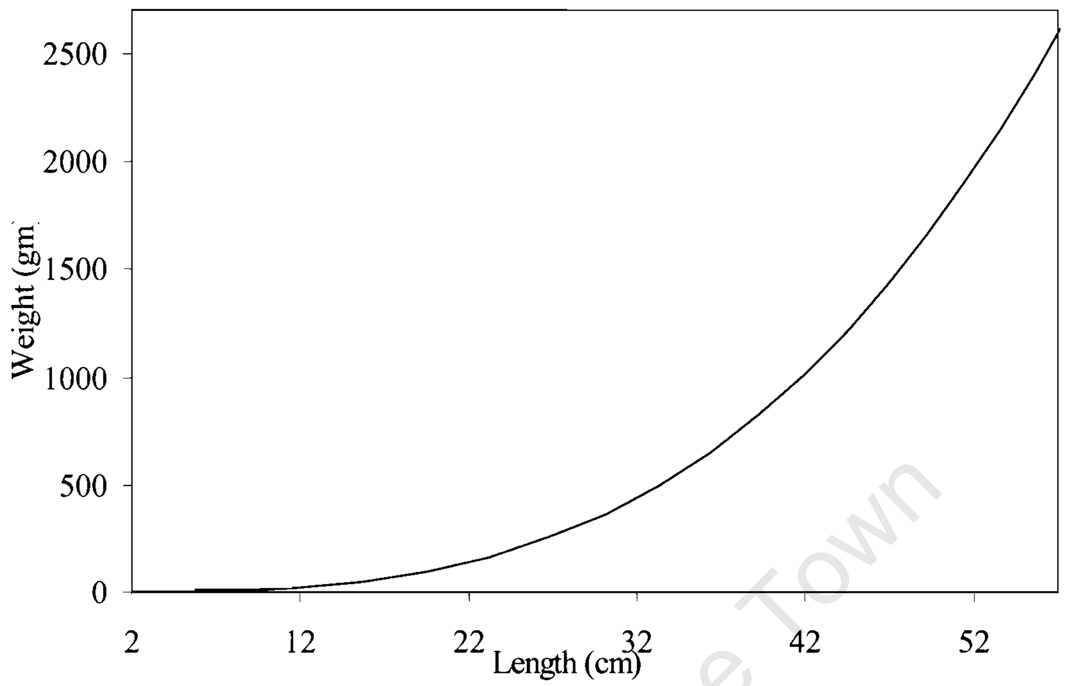

Figure 1.2: Estimated mean weight-at-length from the power curve for *L. vomerinus* off Namibia for both sexes combined.

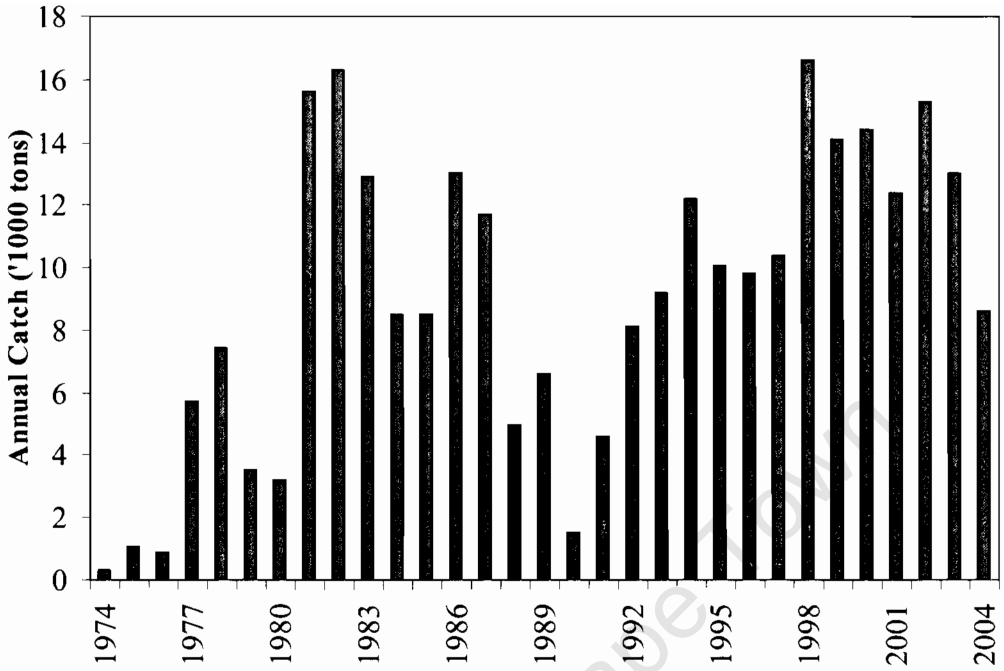

Figure 1.3 Catch time series for Namibian monkfish (see main text for data sources).

2 Data Available for Stock Assessment

The data available for use in the assessment of the Namibian monkfish can be divided into three main types: the annual catches (by mass), commercial catch rates and survey biomass estimates.[5] Biological data such as weight-at-age (see Chapter 1, section 1.1.3), the maturity-at-age as well as the fishing selectivity are also used to model this resource.

2.1 Catches

Prior to 1993, commercial catches (by mass) for the Namibian monkfish that were available from the beginning of the fishery (1974) were recorded as bycatches by the hake targeting vessels. From 1994 to the present, the commercial catches from the monkfish and sole directed "fleet" are recorded separately from the ones from the hake directed "fleet". The catches from these two "fleets" are, however, combined in this study due to the fact that both these fleets are considered for the analyses in this thesis to have the same fishing selectivity. This assumption was made in the absence of catch-at-length data for the two fisheries that might have allowed a distinction. Therefore the time-series of the total annual catches used for this analysis runs from 1974 to 2004 (Table 1.2). The catch for 2004 is set to the TAC value for that year, as catch estimates for that year were not finalized at the time of this analysis.

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[5] Though catch-at-age data have been used in earlier analyses, this work had to be based on data provided by MFMR, Namibia, which was restricted to those listed here.

2.2 Catch Rates

Catch and effort data are available for the monk and sole fishery, and provide a catch per unit effort (CPUE) index, which is conventionally assumed to be proportional to abundance. Nonetheless, one must bear in mind that such proportionality may not always apply: for example, catch rate can stay steady during stock declines due to contractions in the range over which the fish are distributed (Hilborn and Walters, 1992).

To take into account some of the factors that could cause bias in the use of catch rates (CPUE) as an index of abundance, these data have been standardized using General Linear Modelling (GLM). The GLM model applied to standardize CPUE series used in these analyses includes factors such as 'year', 'month' and 'vessel' (Kirchner and Schneider, 2004). Depth and latitude were however not included in this model as was the case in the study by Maartens and Booth (2001a), because there were no grounds on which to include them since the depth and latitude could change from trawl to trawl within a day, and information was not available at the time of those analyses whether the depth and latitude information applied to the first or last trawl of the day, or whether it was averaged over the day (Kirchner and Schneider, 2004). GLM standardization was carried out to adjust for the effect that these factors have on the estimates of CPUE. The GLM standardized CPUE series for the Namibian monkfish are available for the period from 1991 to 2003 (Table 2.1), with the catch rate figure for 1997 missing due to problems that were experienced in the deck sampling that year, rendering the 1997 estimates questionable (MFMR, 1999). Hence they were considered by NatMIRC to be too unreliable to be included in the series.

2.3 Survey Biomass Estimates

Research surveys are particularly useful because the vessel characteristics are constant over time, and the region and time of the survey can be controlled. They are therefore less likely to be biased in providing estimates of trend than are indices obtained from the commercial fishery (Hilborn and Walters, 1992). Survey biomass estimates might however be expected to show more variability than the CPUE indices because research surveys typically take place only once or twice a year, while commercial CPUE series are obtained from data averaged over a whole year (Rademeyer, 2003).

From 1994 to 1999, monkfish survey data were collected during hake biomass surveys on board the *RV Dr. Fridtjof Nansen* for the first nine of these surveys, and on commercial hake fishing vessels for the last two surveys. Commercial vessels had to be used after the *Nansen* was no longer available. These data have been considered not to represent reliable indices of abundance due to the following: (i) these surveys were directed at catching hake and the gear-type used as well as the trawl speed differed considerably from that typical for the monkfish and sole-directed fleet; and (ii) the catching efficiency for monkfish was therefore reduced using the research gear and the calculated biomass estimates are considered to be underestimates of the stock size (Maartens *et al.,* 1997 and MFMR, 2004). Although these reasons do not exclude the use of these survey results as relative indices of abundance, they were nevertheless later abandoned by NatMIRC in favour of the use of results from monkfish dedicated surveys.

A series of monkfish dedicated surveys was thus initiated at the end of 2000. They have been conducted during summer. All surveys are conducted in the same way by use of what is known as an optimized geo-statistical stratified random design, i.e. the survey area is subdivided into blocks and a position is randomly chosen in each block at which monkfish is sampled. The catch rates of each of these positions are then used to determine the fish densities for the sampled block and these densities are then used to estimate the overall biomass. More details of these surveys are given in MFMR (2005). The survey biomass estimate series available for analyses in this thesis are from 2000 to 2004 (Table 2.2).

Table 2.1: GLM-standardized CPUE series for the Namibian monkfish for the period from 1991 to 2003 (Kirchner and Schneider, 2004).

Year	CPUE (kg/h)
1991	160.69
1992	211.52
1993	218.93
1994	256.61
1995	218.52
1996	178.44
1997	
1998	285.98
1999	217.61
2000	184.10
2001	163.90
2002	150.60
2003	164.22

Table 2.2: Biomass of monkfish in tons, estimated by the swept-area method for the period from 2000 to 2004. Sampling CVs are shown in parenthesis.

Year	Survey estimates	
2000	49000	(0.20)
2001	56000	(0.20)
2002	39000	(0.22)
2003	21000	(0.20)
2004	36000	(0.17)

3 The Age-Structured Production Model and Associated Estimation Methods

The Age-Structured Production Model (ASPM) used in this thesis for the assessment of the Namibian monkfish is similar to the one developed in Rademeyer (2003) for the assessment of the southern African hake stocks.

The ASPM was favoured over other models for the assessment of the Namibian monkfish resource mainly because of the data that are available. Although the catch-at-age or catch-at-length data desirable for input to this model (Hilborn and Walters, 1992) were not directly available, vulnerability-at-age and weight-at-age data, which had previously been estimated from the catch-at-length data by Maartens *et al.* (1999), were available. The ASPM is a flexible approach, and can be applied even though catch-at-age data are not available for some or even all years (Rademeyer, 2003).

The ASPM approach has gained increasing popularity in fishery modeling over recent years. It has been used to model many fisheries worldwide (Hilborn, 1990; McAllister and Ianelli, 1997; Punt and Hilborn, 1997; Restrepo and Legault, 1998; Cubillos et al., 2002; Payne et al., 2005) and particularly southern African fisheries (Geromont and Butterworth, 1999; Rademeyer, 2003; Plagányi-Lloyd, 2004; Johnston and Butterworth, 2005).

The ASPM approach models the population dynamics of the stock, and the outputs of the model are fitted to the GLM-standardized CPUE series and the survey biomass estimates by minimizing the negative log-likelihood function (and hence maximizing the likelihood function). The underlying population dynamics equations and the general specifications of the model are described below, and then the details of the contributions to the log-likelihood function follow. Quasi-Newton minimization is used to minimize the total negative log-likelihood function (and was implemented by using AD Model Builder^{TM}, Otter Research, Ltd.). The material that follows detailing the ASPM approach is based in large part on that in Rademeyer (2003).

3.1 Population Dynamics

3.1.1 Numbers-at-age

The Namibian monkfish dynamics are modeled using the following equations:

$$N_{y+1,0} = R_{y+1} \qquad 3.1$$

$$N_{y+1,a+1} = \left(N_{y,a}e^{-M/2} - C_{y,a}\right)e^{-M/2} \quad \text{for } 0 \le a < m-2 \qquad 3.2$$

$$N_{y+1,m} = \left(N_{y,m-1}e^{-M/2} - C_{y,m-1}\right)e^{-M/2} + \left(N_{y,m}e^{-M/2} - C_{y,m}\right)e^{-M/2} \qquad 3.3$$

where, $N_{y,a}$ is the number of fish of age a at the start of year y,

R_y is the recruitment (number of 0-year-old fish) at the start of year y,

M denotes a constant natural mortality rate on fish of all ages,

$C_{y,a}$ is the number of fish of age a caught in year y, and

m is the maximum age considered (taken to be a plus-group), and is set equal to 9 in this study.

This means that the only sources of loss for a closed population (where there is no immigration and emigration) are natural mortality and fishing mortality. The population model used here assumes that catches are taken as a pulse in the middle of the year, rather than incorporated in the form of a continuous fishing mortality. Therefore, these equations reflect Pope's approximation rather than the more customary Baranov catch equations (Pope, 1984). As long as the mortality rates are not too high, the differences between the Baranov and Pope formulations will be minimal (Pope, 1984). Use of this approximation considerably simplifies and speeds calculations.

3.1.2 Recruitment

The number of recruits at the start of year y is related to the spawner stock size by a stock-recruitment relationship. A Beverton-Holt form (Beverton and Holt, 1957) is assumed, i.e.:

$$R_y = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{(\varsigma_y - \sigma_R^2/2)} \qquad 3.4$$

where

α and β are spawning biomass-recruitment relationship parameters, α being the maximum number of recruits produced (on average), and β the spawning stock needed to produce an average recruitment equal to $\alpha/2$;

ς_y reflects fluctuations about the expected recruitment for the year y, and is assumed to be normally distributed with standard deviation σ_R (whose value is input in the applications considered here). These residuals are treated as estimable parameters in the model fitting process. The $-\sigma_R^2/2$ term is to correct for bias given the skewness of the log-normal distribution; it ensures that, on average, recruitment will be as indicated by the deterministic component of the stock-recruitment relationship;

B_y^{sp} is the spawning biomass at the start of year y, given by:

$$B_y^{sp} = \sum_{a=0}^{m} p_a w_a N_{y,a} \qquad 3.5$$

where w_a is the begin-year mass of fish of age a and p_a is the proportion of fish of age a that are mature.

In order to work with estimable parameters that are more biologically meaningful, the stock-recruitment relationship is re-parameterized in terms of the pre-exploitation equilibrium spawning biomass, K^{sp}, and the "steepness", h, of the stock-recruitment relationship, where "steepness" is a fraction of pristine recruitment that results when spawning biomass drops to 20% of its pristine level, i.e.:

$$hR_0 = \frac{\alpha 0.2K^{sp}}{\beta + 0.2K^{sp}} \tag{3.6}$$

where also:

$$R_0 = \frac{\alpha K^{sp}}{\beta + K^{sp}} \tag{3.7}$$

Solving these simultaneous equations gives:

$$\alpha = \frac{4hR_0}{5h-1} \tag{3.8}$$

and

$$\beta = \frac{K^{sp}(1-h)}{5h-1} \tag{3.9}$$

3.1.3 Starting values for Biomass Trajectories

Given a value for the pre-exploitation spawning biomass K^{sp} of Namibian monkfish, together with the assumption of an initial equilibrium age structure, it follows from the equations above that:

$$R_0 = \frac{K^{sp}}{\left(\sum_{a=0}^{m-1} p_a w_a e^{-Ma}\right) + p_m w_m e^{-Mm} / \left(1 - e^{-M}\right)} \qquad 3.10$$

The initial numbers-at-age for the projections, corresponding to an assumed deterministic equilibrium, are:

$$N_{0,a} = R_0 e^{-Ma} \qquad 0 \le a < m-1 \qquad 3.11$$

$$N_{0,m} = \frac{R_0 e^{-Mm}}{\left(1 - e^{-M}\right)} \qquad a = m \qquad 3.12$$

3.1.4 Total Catch and Catches-at-age

The number of monkfish of age *a* caught in year *y* is given by:

$$C_{y,a} = N_{y,a} e^{-M/2} S_a F_y \qquad 3.13$$

where

S_a is the age-specific commercial selectivity, assumed to be year-invariant,

F_y is the fully selected fishing proportion in year *y*, given by:

$$F_y = \frac{Y_y}{\sum_{a=0}^{m} w_{a+1/2} N_{y,a} e^{-M/2} S_a} \qquad 3.14$$

where

Y_y is the total catch (yield) by mass made in year y, and

$w_{a+1/2}$ is the mid-year mass of a fish of age $a+1/2$.

The model estimate of the mid-year exploitable ("available") component of biomass is calculated by converting the numbers-at-age into mid-year masses-at-age (using the mid-year individual weights) and applying natural mortality and fishing mortality for half the year:

$$B_y^{\exp} = \sum_{a=0}^{m} \left(w_{a+1/2} N_{y,a} S_a e^{-M/2}\right)\left(1 - S_a F_y / 2\right) \qquad 3.15$$

whereas the survey estimate of biomass at the start of the year (the austral summer) is given by:

$$B_y^{surv} = \sum_{a=0}^{m} w_a N_{y,a} S_a \qquad 3.16$$

Note that, given the limited data available, these analyses have assumed that the fishing and survey selectivity are the same.

3.2 The Likelihood Function

The model is fitted to the CPUE and survey biomass data to estimate model parameters. Contributions by each of these to the negative of the log-likelihood ($-\ln L$) are as follows.

3.2.1 CPUE Abundance Index Data

The likelihood is calculated assuming that the observed abundance index is log-normally distributed about its expected value:

$$I_y^i = \hat{I}_y^i e^{\varepsilon_y^i} \quad \text{or} \quad \varepsilon_y^i = \ln\left(I_y^i\right) - \ln\left(\hat{I}_y^i\right) \qquad 3.17$$

where

I_y^i is the abundance index for year y and series i,

$\hat{I}_y^i = \hat{q}^i \hat{B}_y^{\exp}$ is the corresponding model estimate, where $\hat{B}_y^{\exp}$ is the model estimate of exploitable biomass, given by equation 3.15,

$\hat{q}^i$ is the constant of proportionality (catchability coefficient) for abundance series i, and

ε_y^i from $N\left(0, \left(\sigma_y^i\right)^2\right)$.

The contribution of the abundance data to the negative log-likelihood function (after removal of constants) is given by:

$$-\ln L = \sum_i \left[\sum_y (\ln \sigma_y^i + \left(\varepsilon_y^i\right)^2 / 2\left(\sigma_y^i\right)^2) \right] \qquad 3.18$$

Homoscedasticity of residuals is assumed, so that $\sigma_y^i = \sigma^i$, the standard deviation of the residuals for the logarithms of abundance index *i,* which is estimated in the fitting procedure by its maximum likelihood value:

$$\hat{\sigma}^i = \sqrt{\frac{1}{n^i} \sum_y \left(\ln I_y^i - \ln q^i \hat{B}_y^{\exp}\right)^2} \qquad 3.19$$

where n^i is the number of data points for abundance series *i.*

The catchability coefficient q^i for abundance index *i* is estimated by its maximum likelihood value:

$$\ln \hat{q}^i = \frac{1}{n^i} \sum_y \left(\ln I_y^i - \ln \hat{B}_y^{\exp}\right) \qquad 3.20$$

3.2.2 Survey Abundance Data

For the surveys, an estimate of the sampling variance is available for each survey. The surveys are treated as relative abundance indices in a similar manner to the CPUE above.

The associated σ^i is estimated using equation 3.19 above. The estimated sampling variances were not used due to convergence problems experienced.

3.2.3 Stock-Recruitment Function Residuals

The stock-recruitment function residuals are assumed to be log-normally distributed. Thus the contribution of the recruitment residuals to the negative log-likelihood function (from Brandão and Butterworth (2005)) is given by:

$$-\ln L_{rec} = \sum_{y} \left[\ln \sigma_R + \varsigma_y^2 / \left(2\sigma_R^2 \right) \right] \qquad 3.21$$

which is added to the negative log-likelihood of equation 3.18 as a penalty (the frequentist equivalent of a Bayesian prior for these parameters). In this application, it is assumed that the resource was not at equilibrium at the start of the fishery, but that the resource was at deterministic equilibrium in 1964 with zero catches taken until the start of the fishery in 1974 (by which time it is hoped that virtually all "memory" of the original equilibrium has been lost because of subsequent recruitment variability). The reason for this is to allow the assessment to take account of such variability.

3.3 Estimation of Model Parameters and Precision

3.3.1 Estimating Posterior Distributions

The Bayesian estimation method was used to provide posterior distribution for parameter in the assessment of the Namibian Monkfish resource. Two of the estimable parameters, K^{sp} and M, were each given uniform prior distributions of $U[2000,300000]$ and $U[0.1,0.5]$ respectively, both intended to bound a feasible range. Given prior distribution functions $g(\theta)$ for these parameters θ, the posterior distribution functions $h(\theta)$ for these parameters are related to the priors and the likelihood functions $L(\theta)$ as follows: if one represents the data by y:

$$h(\theta|y) \propto L(y|\theta)g(\theta) \qquad 3.22$$

i.e $L(y|\theta)g(\theta)$ is proportional to the posterior probability density of θ given y. The marginal distribution of y is not exhibited because it is a proportionality factor and it can be written as:

$$m(y) = \int L(y|\theta)g(\theta)d\theta \qquad 3.23$$

From equations 3.22 and 3.23 it follows that:

$$h(\theta|y) = \frac{L(y|\theta)g(\theta)}{\int L(y|\theta)g(\theta)d\theta} \qquad 3.24$$

A prior was also specified for q^{survey}, in the form of a uniform distribution with smoothed edges, with the log of the distribution function for this prior then given by:

$$\left(\frac{q^{survey}-0.9}{0.4}\right)^{10} \qquad 3.25$$

i.e. q^{survey} was effectively given a uniform prior over $U[0.5,1.3]$, with the edges smoothed to avoid numerical difficulties of maximum likelihood estimates falling on boundaries. The values of q^{CPUE}, σ^{CPUE} and σ^{survey} were fixed to their maximum likelihood estimates; this correspond to assigning certain forms for the priors for these quantities (Ludwig and Walters, 1989). The penalty term (equation 3.21) in the likelihood for the stock-recruitment residuals amounts to integration over normal priors for parameters with the associated level of variability (σ_R), taken to be known exactly.

Where quoted in the results that follow, the 95% probability intervals have been evaluated from the marginal posterior distribution computed by application of the MCMC algorithm through AD Model Builder.

3.3.2 Fixed Input Parameters

Fishing selectivity-at-age:

Commercial and survey fishing selectivity-at-age, which were assumed to be the same, were taken to be as estimated by Maartens and Booth (2001a) by fitting a logistic form to the ascending limb of the percentage commercial and research survey catch-at-age data (Table 3.1). Although this method is subject to some bias because it fails to allow for decreasing numbers-at-age in the stock in fitting the logistic, this seems unlikely to impact the results that follow to any great extent.

Age-at-maturity:

The proportion of age a that are mature, p_a, was taken as estimated by Maartens and Booth (2001a) using a logistic ogive of the form $p_a = \left[1+\exp\left(-\left(a-a_{50}\right)/\delta\right)\right]^{-1}$, with a_{50} the point of inflection and δ the width of the ogive (see Table 3.1).

Weight-at-age:

The weight-at-age (begin and mid-year) was calculated using the von Bertalanffy growth equation (equation 1.1), and then the mass-at-length function (equation 1.2) given in section 1.1.3.

Table 3.1: Commercial and survey selectivity- and maturity-at-age values used in these analyses.

Age	Selectivity Commercial	 Survey	Maturity
0	0	0	0.02
1	0.5	0.5	0.05
2	1	1	0.12
3	1	1	0.27
4	1	1	0.50
5	1	1	0.73
6	1	1	0.88
7	1	1	0.95
8	1	1	0.98
9	1	1	0.99

4 Assessment of the Namibian Monkfish Resource

The Base-case assessment (with the specifications that follow) is the one used as the Base-case operating model for the Namibian monkfish resource. The sensitivity tests conducted for the Base-case assessment also serve as operating models for the robustness tests for the management procedures investigated. Such management procedures and their evaluation will be discussed in the next chapter.

4.1 Base-case Assessment Specifications

For the Base-case assessment of the Namibian monkfish resource, the following assumptions are made:

i) $\underline{B_{1964}^{sp} = K^{sp}}$: The model assumes that the resource is not at equilibrium at the start of the fishery (1974), but rather was at deterministic equilibrium in 1964 with zero catches taken until the start of the fishery (by which time virtually all "memory" of the original equilibrium has been lost because of subsequent recruitment variability). The purpose of this assumption is to allow for the possibility that the resource was not at deterministic equilibrium when exploitation commenced because of such variability.

ii) "Steepness" of the stock-recruitment relationship: Attempts were made to estimate "steepness", but there was inadequate information in the data to estimate this in addition to the other model parameters. The "steepness", h, was therefore fixed at 0.7. This value corresponds roughly to the median $(h = 0.74)$ of a distribution of h values for stock-recruitment functions fitted to the fisheries stock recruitment database developed by Myers *et al.* (1999).

iii) Natural mortality: M_a is taken to be age-independent (M), as there is not enough information in the data to estimate an age-dependent natural mortality rate.

iv) Selectivity-at-age: The selectivity-at-age, S_a, used for the Base-case assessment is as estimated by Maartens and Booth (2001a), and is as follows: $S_a = 0$ for $a = 0$, 0.5 for $a = 1$, and 1 for all other ages (see Table 3.1).

v) Stock-recruitment residuals: Estimation became unstable for high values of σ_R (which measures the extent of residual variability); hence this was fixed at 0.15 for the years from 1965 to 1994, but then raised to 0.4 for the years from 1995 to 2005 so that a more realistic level of variability in the recruitment was allowed for the years immediately preceding projections into the future. The residuals are estimated from year 1965 to 2005.

Maartens (1999) and MFMR (2004 and 2005) have also attempted to assess the Namibian monkfish resource using the ASPM approach. Maartens (1999) fitted a deterministic ASPM model to the GLM-standardized CPUE and the survey biomass series obtained from data collected by the *RV Dr. Fridtjof Nansen* between 1994 and 1999 (these were hake-targeted surveys). She estimated only two parameters; namely R_0 (pristine recruitment) and h, and fixed M.

MFMR (2004, 2005) fitted a deterministic ASPM model to the GLM-standardized CPUE and the monkfish-directed survey biomass series between 2000 and 2003/2004 (as appropriate). MFMR (2004, 2005) estimated only the pre-exploitation spawning biomass, K^{sp}, and fixed the "steepness" parameter, h, the natural mortality, M, and the survey multiplicative bias, q^{survey}. Sensitivity analyses were conducted in all the above cases.

In this study, a stochastic ASPM model is fitted to the GLM-standardized CPUE (Table 2.2) and the monkfish-dedicated survey series between 2000 and 2004 (Table 2.3), with the above-stated Base-case assessment specifications. Posterior distributions for quantities of interest were obtained using the Markov Chain Monte Carlo (MCMC) algorithm, and historic recruitment variability (equation 3.4) was also taken into account. MCMC, involves the Metropolis algorithm, and permits the simulation of any distribution on a finite-dimensional state space specified by any unnormalized density. The principle is to build a succession of states, and once convergence is reached, the consecutive states are assumed to be drawn from the target probability distribution (Sénégas, 2002). The questions here therefore are: what is the status of the Namibian monkfish resource, when noise in the dynamics and estimation, given limited data, are taken into account, and how best should the resource be managed given the associated uncertainty?

4.2 Sensitivity Tests

The following sensitivity tests were carried out, in addition to the Base-case assessment above, to assess the status of the resource under these uncertainties.

1. High "steepness": "steepness" is increased from 0.7 to 0.9 because the overall potential yield predicted by an ASPM depends primarily on the "steepness" of the stock-recruitment curve h and on the natural mortality rate.
2. Low "steepness": "steepness" is decreased from 0.7 to 0.5. To effect this, the natural mortality M was treated as an input parameter, and was fixed to 0.25. This was because of difficulties in estimating M, given the data available, when h is 0.5.
3. Bias in historic CPUE. The change in the model to allow for this was effected as follows:

   $$CPUE_y^{bias} = qB_y^{\exp} \cdot e^{\delta(y-1991)} \qquad 4.1$$

   For this variant, the value of $\delta = 0.03$ was used to reflect possible undetected improvements in fishing efficiency over time. This modification continued into the future into the projections.
4. Higher variability for stock-recruitment fluctuations. The value for σ_R for the Base-case operating model was 0.15 for the years from 1965 to 1994, but was raised to 0.4 for the years from 1995 to the end of the projection period. In this variant assessment, σ_R remained the same, 0.15, for the years from 1965 to 1994, but was increased from 0.4 to 0.6 for the years from 1995 onwards.

5. Decrease in selectivity (*"Selectivity down 1"*) for the 1 and 2 year olds. For this variant, S_a was as follows:

Age	S_a
0	0
1	0.33
2	0.67
3	1
4	1
5	1
6	1
7	1
8	1
9	1

6. Decrease in selectivity (*"Selectivity down 2"*) for the older ages. The desire here was for the selectivity at age to decrease with increasing powers of 0.9 from the 6-year olds, but due to difficulties in convergence, S_a was as follows for this variant:

Age	S_a
0	0
1	0.5
2	1
3	1
4	1
5	1
6	0.90
7	0.85
8	0.85
9	0.85

The values selected for these tests constitute initial and very rough estimates of the extent of uncertainty in areas of possible concern.

Checks were made to confirm that the MCMC algorithms had converged.

4.3 Results and Discussion

4.3.1 Base-case Operating Model

Model parameter estimates and the log-likelihood contributions of each abundance index (corresponding to posterior modes) from the Base-case assessment and the robustness test operating models are summarized in Table 4.1. The corresponding model fits to the GLM-standardized CPUE and the fishery independent survey indices are presented in Figure 4.1, which compares the observed values to those predicted by the model. A reasonably acceptable fit to both the abundance indices is shown, although the observed survey index has only five data points, and so has little influence. A downward trend can be observed in both the catch rates and the fishery independent abundance index in recent years (Figure 4.1). This is consistent with the MSY estimate (9363 tons; 95% probability interval [7434, 11624]) being less than most catches over recent years.

Figure 4.2 shows the posterior 95% probability intervals for the spawning biomass estimates (in terms of the pre-exploitation level), together with the MSYL. The model suggests that the current spawning biomass, B_{2004}^{sp}, is 35354 tons with 95% probability interval [19251; 50803], which is about 3% above MSYL and 32% of the pre-exploitation level. The 95% probability intervals for $B^{sp}_{2004}/MSYL$ and B^{sp}_{2004}/K^{sp} are [65%; 138%] and [21%; 42%] respectively. Hence, the resource seems to still be in a reasonably healthy state although the downward trend observed in the catch rates and the survey indices suggests that catches need to be reduced in future.

The catchability coefficient for the CPUE index, $\hat{q}^{CPUE}$, is 2.49×10^{-3} hr^{-1} (Table 4.1). The survey multiplicative bias estimate, $\hat{q}^{survey}$, is 0.58 (Table 4.1). This suggests that the application of the swept-area methodology to the survey results to provide biomass estimates in absolute terms results in underestimates of the biomass by about 40%.

The Base-case estimate of the (age-independent) natural mortality M is 0.40 yr^{-1}, with a 95% probability interval [0.19; 0.49], which is reasonably consistent with a slowish growing and longer-lived species such as monkfish, although it is rather higher than the ranges considered by both Maartens (1999) (0.09 to 0.20), and MFMR (2004 and 2005) (0.2 to 0.3). Figure 4.3 shows the estimated residuals about the stock-recruitment function; there is no clear pattern, apart from the increase in magnitude of residuals from 1994, which is related to the increase in the value input of σ_R after that time.

4.3.2 Sensitivity Test Operating Models

When the steepness parameter, h, is increased from 0.7 to 0.9, the overall fit improves by almost 2 log-likelihood points (i.e. from –85.6 to –87.3). This is due mainly to the improved fit to the CPUE series (-18.2 vs. –15.5 for h=0.7), since the fit to the survey abundance estimates hardly changes and the contribution from the recruitment residuals alters in the other direction. When h is increased to 0.9, the resource appears to be in even a better state, 33% (CV=0.20) above its MSYL, compared to 3% (CV=0.18) above MSYL for h=0.7. The MSY is estimated to be higher at 10572 (CV=0.12) tons.

Decreasing the steepness parameter to 0.5 (with the natural mortality fixed to 0.25) results in an overall fit somewhat worse than for the Base-case assessment (-83.9 vs. -85.6 for the Base-case). Again, it is only the change in the fit to the CPUE series that has induced this reduction in the quality of the overall fit. The resource in this case is about 29% (CV=0.15) below the MSYL and at about 27% (CV=0.15) of its pre-exploitation level. The estimated value of MSY is lower at 6796 (CV=0.07) tons.

The assessment with a bias in historic CPUE incorporated shows results that are a little more optimistic than the Base-case assessment, while increasing σ_R for the years from 1995 to 2005 from 0.4 to 0.6 does not give results very different from those given by the Base-case assessment. Decreasing selectivity-at-age for the 1- and 2-year olds, or for older fish, give slightly more optimistic views of the resource than that given by the Base-case operating model, but there is no major difference in the management quantity estimates for either of these two variants. Figure 4.4 shows depletion $\left(B_y^{sp} / K^{sp}\right)$ trajectories for the Base-case and six sensitivity test operating models –only that for $h = 0.5$ differs appreciably from the others.

Table 4.1: Management quantity estimates for the Namibian monkfish operating models for the Base-case and the operating model sensitivity tests. The first figure shown is the posterior mode, followed by the posterior CVs in parenthesis.

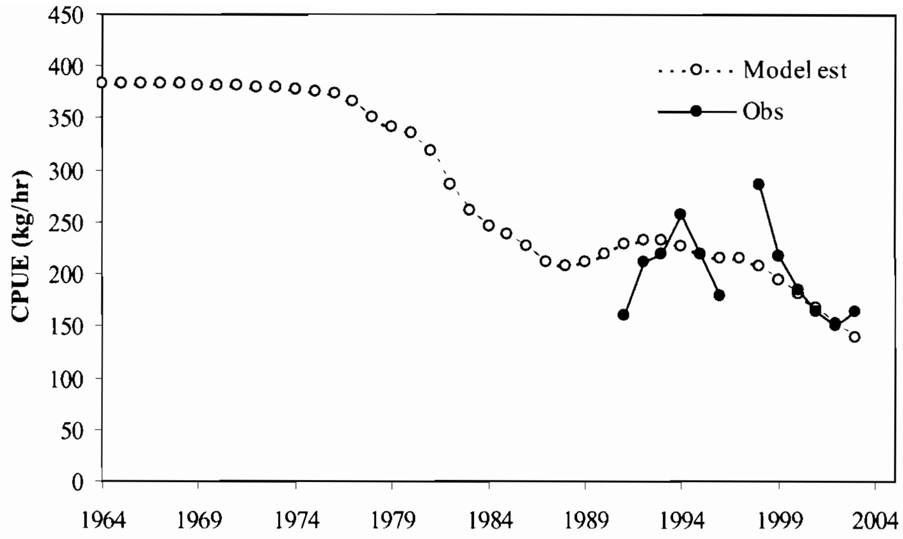
	Base-case		***h*=0.9**		***h*=0.5**	
-lnL: Total	-85.600		-87.328		-83.895	
-lnL: CPUE	-15.500		-18.246		-13.694	
-lnL: Survey	-4.000		-4.137		-4.097	
-lnL: SR Residual	-66.100		-64.946		-66.103	
K^{sp}	106746	(0.21)	103095	(0.20)	160949	(0.07)
$K^{\exp}$	144879	(0.15)	136671	(0.15)	193809	(0.07)
B^{sp}_{2004}	35354	(0.23)	34500	(0.26)	44295	(0.17)
$B^{\exp}_{2004}$	52782	(0.20)	51966	(0.22)	54746	(0.18)
B^{sp}_{MSY}	32955	(0.25)	25107	(0.26)	61671	(0.07)
$B^{\exp}_{MSY}$	52852	(0.14)	42086	(0.16)	78819	(0.07)
MSY	9363	(0.12)	10572	(0.12)	6796	(0.07)
B^{sp}_{2004} / K^{sp}	0.319	(0.17)	0.328	(0.17)	0.272	(0.15)
$B^{\exp}_{2004} / K^{\exp}$	0.357	(0.19)	0.373	(0.18)	0.279	(0.16)
$B^{sp}_{2004} / MSYL$	1.027	(0.18)	1.333	(0.20)	0.710	(0.15)
$B^{\exp}_{2004} / MSYL$	0.979	(0.19)	1.209	(0.19)	0.687	(0.16)
$MSYL / K^{sp}$	0.309	(0.03)	0.244	(0.06)	0.383	(0.00)
$MSYL / K^{\exp}$	0.365	(0.01)	0.308	(0.01)	0.407	(0.00)
M	0.402	(0.22)	0.377	(0.21)	0.250	(0.00)
$\sigma : CPUE$	0.162	(0.15)	0.158	(0.14)	0.200	(0.13)
$\sigma : Survey$	0.269	(0.07)	0.270	(0.07)	0.268	(0.05)
$q : CPUE(\times 10^{-3})$	2.000	(0.17)	2.576	(0.20)	2.146	(0.11)
$q : Survey$	0.581	(0.17)	0.600	(0.20)	0.544	(0.14)

Table 4.1: continued

	Base-Case		Bias in historic CPUE $CPUE_y e^{\delta(y-1991)}$ $\delta = 0.03$		$\sigma_R = 0.6$	
-lnL: Total	-85.600		-83.427		-83.418	
-lnL: CPUE	-15.500		-15.692		-18.852	
-lnL: Survey	-4.000		-3.999		-4.178	
-lnL: SR Residual	-66.100		-63.736		-60.387	
K^{sp}	106746	(0.21)	96738	(0.15)	104737	(0.21)
$K^{\exp}$	144879	(0.15)	133467	(0.12)	141545	(0.15)
B^{sp}_{2004}	35354	(0.23)	35775	(0.21)	34161	(0.25)
$B^{\exp}_{2004}$	52782	(0.20)	54457	(0.20)	51513	(0.22)
B^{sp}_{MSY}	32955	(0.25)	29566	(0.17)	32227	(0.24)
$B^{\exp}_{MSY}$	52852	(0.14)	48745	(0.12)	51672	(0.14)
MSY	9363	(0.12)	9250	(0.10)	9220	(0.12)
B^{sp}_{2004} / K^{sp}	0.319	(0.17)	0.363	(0.17)	0.318	(0.17)
$B^{\exp}_{2004} / K^{\exp}$	0.357	(0.19)	0.403	(0.18)	0.358	(0.20)
$B^{sp}_{2004} / MSYL$	1.027	(0.18)	1.188	(0.18)	1.023	(0.18)
$B^{\exp}_{2004} / MSYL$	0.979	(0.19)	1.104	(0.18)	0.981	(0.20)
$MSYL / K^{sp}$	0.309	(0.03)	0.306	(0.02)	0.309	(0.03)
$MSYL / K^{\exp}$	0.365	(0.01)	0.365	(0.00)	0.365	(0.01)
M	0.402	(0.22)	0.425	(0.13)	0.403	(0.20)
$\sigma : CPUE$	0.162	(0.15)	0.200	(0.20)	0.156	(0.16)
$\sigma : Survey$	0.269	(0.07)	0.275	(0.08)	0.266	(0.08)
$q : CPUE(\times 10^{-3})$	2.000	(0.17)	3.160	(0.16)	2.544	(0.19)
$q : Survey$	0.581	(0.17)	0.567	(0.16)	0.585	(0.19)

Table 4.1: continued

	Base-Case		**Decrease selectivity for the 1- and 2-year olds**		**Decrease selectivity for older fish**	
-lnL: Total	-85.600		-87.168		-87.283	
-lnL: CPUE	-15.500		-17.998		-18.027	
-lnL: Survey	-4.000		-4.113		-4.140	
-lnL: SR Residual	-66.100		-65.058		-65.116	
K^{sp}	106746	(0.21)	106227	(0.18)	112044	(0.19)
$K^{\exp}$	144879	(0.15)	137921	(0.14)	139672	(0.13)
B^{sp}_{2004}	35354	(0.23)	36338	(0.23)	37787	(0.25)
$B^{\exp}_{2004}$	52782	(0.20)	51722	(0.21)	52983	(0.21)
B^{sp}_{MSY}	32955	(0.25)	32667	(0.20)	34345	(0.22)
$B^{\exp}_{MSY}$	52852	(0.14)	49120	(0.14)	51884	(0.13)
MSY	9363	(0.12)	9687	(0.11)	9534	(0.11)
B^{sp}_{2004} / K^{sp}	0.319	(0.17)	0.336	(0.17)	0.330	(0.17)
$B^{\exp}_{2004} / K^{\exp}$	0.357	(0.19)	0.371	(0.18)	0.374	(0.18)
$B^{sp}_{2004} / MSYL$	1.027	(0.18)	1.085	(0.18)	1.067	(0.17)
$B^{\exp}_{2004} / MSYL$	0.979	(0.19)	1.043	(0.18)	1.007	(0.18)
$MSYL / K^{sp}$	0.309	(0.03)	0.308	(0.03)	0.307	(0.03)
$MSYL / K^{\exp}$	0.365	(0.01)	0.356	(0.00)	0.372	(0.01)
M	0.402	(0.22)	0.390	(0.18)	0.394	(0.19)
$\sigma : CPUE$	0.162	(0.15)	0.162	(0.15)	0.160	(0.14)
$\sigma : Survey$	0.269	(0.07)	0.270	(0.08)	0.269	(0.08)
$q : CPUE(\times 10^{-3})$	2.000	(0.17)	2.574	(0.18)	2.526	(0.17)
$q : Survey$	0.581	(0.17)	0.588	(0.18)	0.590	(0.18)



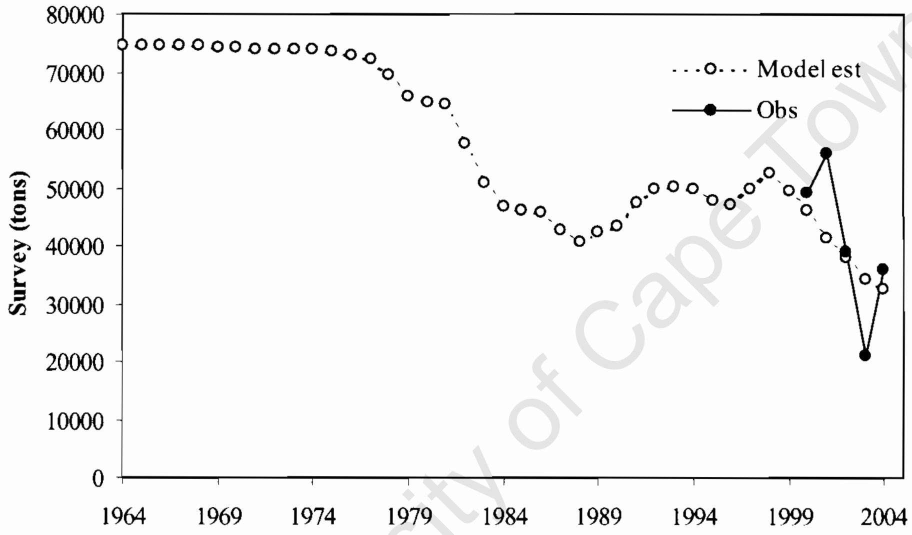


Figure 4.1: Base-case assessment model fits to the abundance indices (CPUE and survey) for the Namibian monkfish resource. The model trajectories shown are posterior modes.

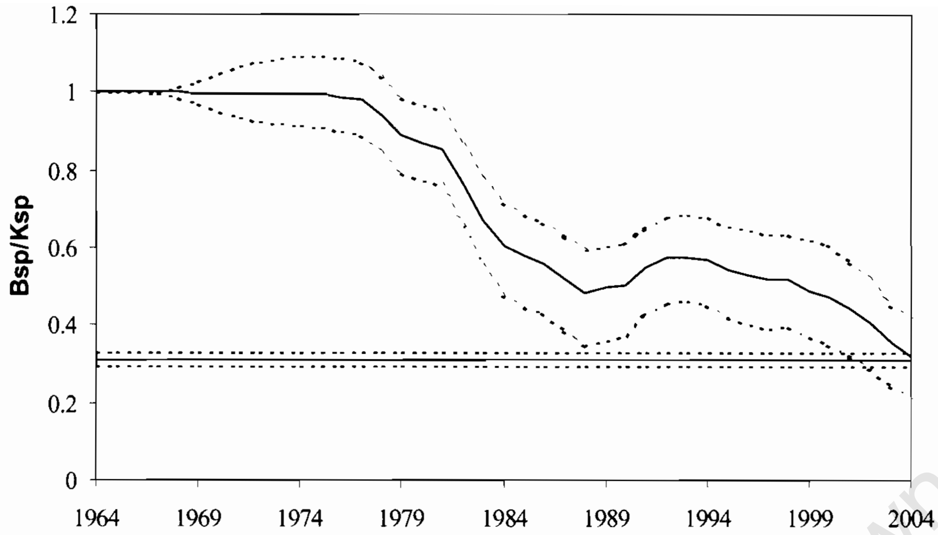


Figure 4.2: Estimates of the resource abundance as estimated by the ASPM (which incorporates fluctuation about the stock-recruitment relationship), expressed in terms of spawning biomass as a proportion of its pre-exploitation equilibrium level (B^{sp} / K^{sp}), for the Namibian monkfish resource. The 95% probability interval envelope determined from the Bayesian posteriors and the posterior mode for MSYL relative to K^{sp} are also shown.

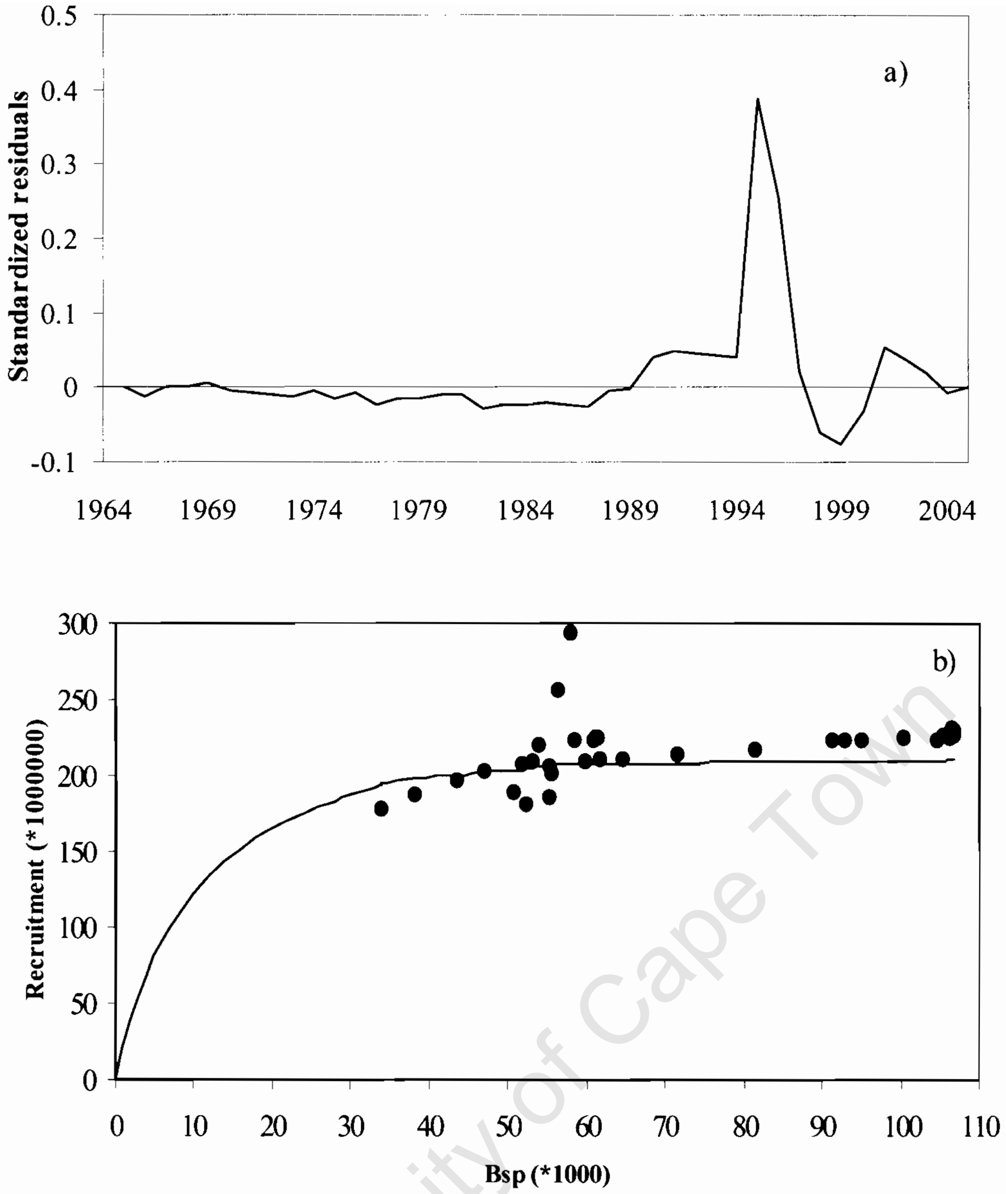


Figure 4.3: a) Time series of the estimated stock-recruitment residuals and b) the fit of the stock-recruitment curve to the stock recruitment pairs for the Base-case assessment of the Namibian monkfish resource (again posterior modes are shown).

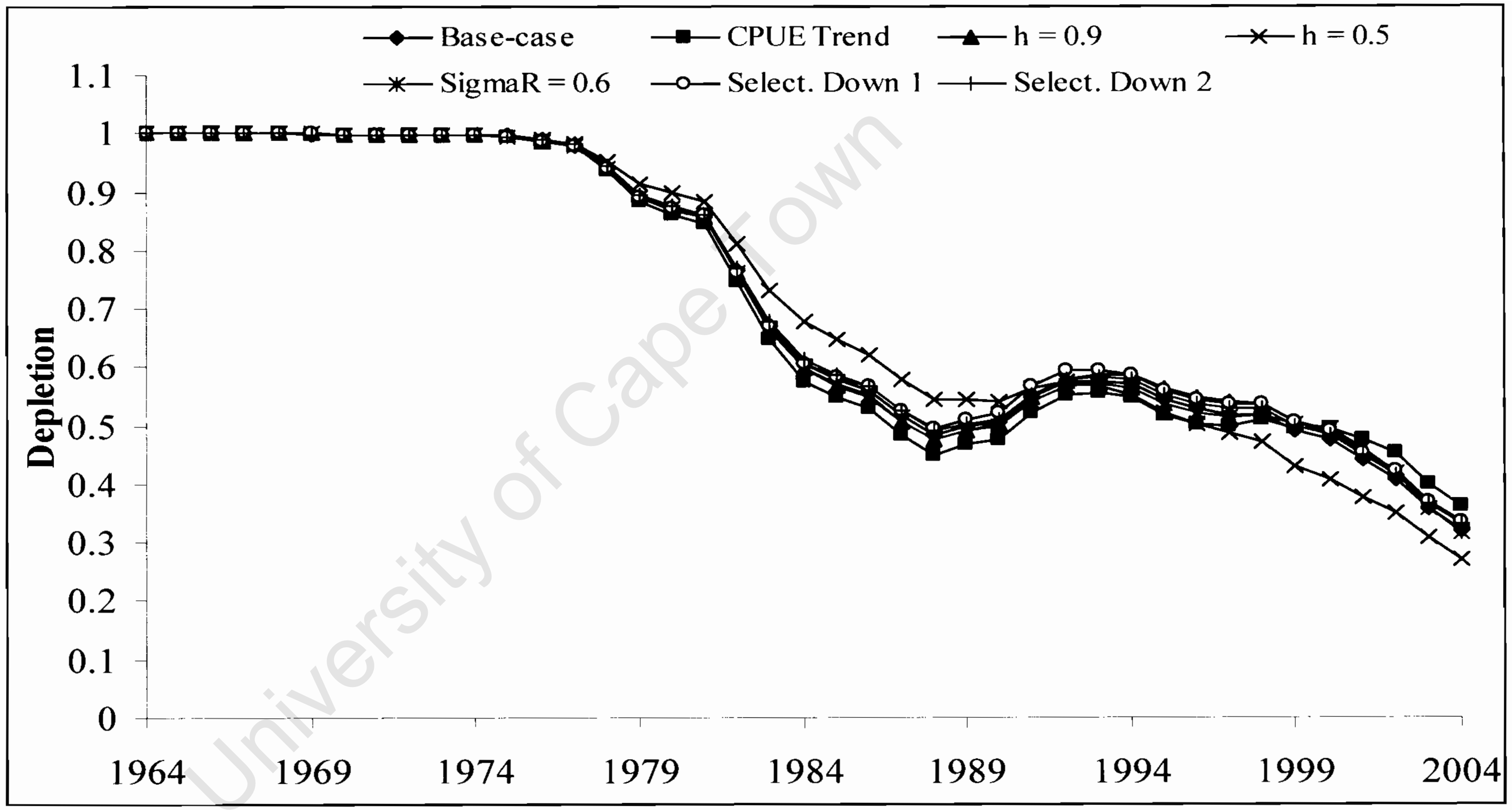


Figure 4.4: Median B_y^{sp} / K^{sp} for the Base-case and six other sensitivity test operating models.

5 An Operational Management Procedure for Namibian Monkfish

5.1 General Introduction

An "Operational Management Procedure" (OMP), alternatively called a "harvest algorithm" by Cooke (1999), is defined by Butterworth and Punt (1999) as a set of rules which specify exactly how the regulatory mechanism (e.g. a TAC or allowable fishing effort) is to be computed each year from specified stock monitoring data such as commercial CPUE and/or abundance indices from research surveys, where the performance of the rules have been evaluated by simulation. The simulations should cover a wide range of plausible scenarios with respect to the population dynamics of the resource being managed, involving realistic alternative assumptions about the dynamics (Cooke, 1999).

The evaluation of these rules provides the projected risks and rewards, and their different trade-offs for different OMPs (Cochrane *et al.,* 1997). The rules should also be checked to confirm that they provide adequately robust performance in the face of uncertainty about the dynamics of the resource (Butterworth and Punt, 1999; Cooke, 1999).

These rules can be based either on a simple measure such as the recent trend in an abundance index, or on fitting a population model, as is the case for the Namibian and South African hake (Rademeyer, 2003). Statistics such as the average annual catch, stock biomass relative to the pre-exploitation level (depletion) and inter-annual variability in catch, are used in the performance assessment of the candidate OMPs (Geromont *et al.*, 1999; Rademeyer, 2003).

The management procedure approach was originally developed in the International Whaling Commission (Kirkwood, 1992 and Kirkwood, 1997). Management procedures have been developed in Namibia to regulate the hake fishery and the seal fishery (Geromont *et al.*, 1999; Rademeyer and Butterworth, 2002; Rademeyer, 2003) and in South Africa for the hake, pilchard-anchovy pelagic and the west coast rock lobster fisheries (Butterworth and Punt, 1999; Geromont *et al.*, 1999; Johnston and Butterworth, 2005). Examples from elsewhere in the world are provided by some Australian fisheries, which have also been managed using this approach (Smith *et al.*, 1999), and for the North sea plaice (*pleuronectes platessa*) management procedures have been evaluated (Kell *et al.*, 1999).

The increasing popularity of the OMP approach stems from its potentially considerable benefits. An OMP should be agreed upon by all involved stakeholders (scientists, industry, managers) and put in place for a number of years before being revised if necessary (Cochrane *et al.*, 1997). The approach thus provides a transparent and objective way of setting TACs (Rademeyer, 2003). The relative performance of candidate OMPs can be assessed and the anticipated performance relative to specified management objectives can be determined (Butterworth and Punt, 1999). The uncertainties are taken into account through sensitivity and robustness testing under the OMP approach

(Rademeyer, 2003). The other advantage of an OMP approach is its "feedback-control" nature, i.e., as future information (data) become available, the OMP is able to self-correct for the consequences of having to base previous management decisions on unavoidably inexact assessments (Johnston and Butterworth, 2005). This is especially necessary in the context of management decisions for a longer-lived species like monkfish, where it is difficult to effectively assess the risk associated with a single decision for one year; this rather needs to be done for a process of the continued application of some TAC-setting formula over time (Butterworth and Rademeyer, 2005).

5.2 Measures of Candidate OMPs Performance

The statistics used here to measure the candidate OMPs' performance are the same as used by Rademeyer (2003) for southern African hake resources. The projection period considered here for reporting performance statistics is 20 years.

Catch-related:

- Average annual catch over the projection period ($C^{ave} = \frac{1}{20}\sum_{y=2005}^{2024} C_y$)
- The Average Annual Variation (AAV) in TAC from one year to the next, ($AAV = \frac{1}{20}\sum_{y=2005}^{2024} \left|C_y - C_{y-1}\right| / C_{y-1}$). This gives an indication of the fishery stability associated with the candidate OMP under consideration.

Risk-related

- Spawning biomass change over the projection period, i.e. $B^{sp}_{2024}/B^{sp}_{2004}$
- Final spawning biomass level as a proportion of the corresponding pristine level: B^{sp}_{2024}/K^{sp}
- Final spawning biomass as a proportion of the Maximum Sustainable Yield Level (MSYL): $B^{sp}_{2024}/B^{sp}_{MSY}$.

The results are reported in the form of medians and 95%-iles of the distributions over replicate trials.

5.3 Candidate OMPs for the Namibian monkfish

The Baseline OMP

The OMPs considered to provide the TAC recommendation for the Namibian monkfish resource are based on the Schaefer surplus production model in combination with an $f_{0.n}$ harvesting strategy.

The Schaefer surplus production model used here for the OMP algorithm, from e.g. Johnston (2004) is as follows:

$$B_{y+1} = B_y + rB_y\left(1 - \frac{B_y}{K}\right) - C_y \qquad 5.1$$

with

$$B_{1974} = K \qquad 5.2$$

where

B_y	is the total biomass in year y,
C_y	is the catch in year y, and
r, K	are estimable parameters of the model.

The parameter estimates are obtained using maximum likelihood when fitting the model to the CPUE and the survey abundance estimate series. The contributions from each of the abundance indices to the negative of the log-likelihood function (which is being minimized in the model fitting process) are as follows (omitting constants):

$$-\ln L^i = n\ln(\sigma^i) + \frac{1}{2(\sigma^i)^2}\sum_y \left(\ln(I_y^i) - \ln(q^i) - \ln(\hat{B}_y)\right)^2 \qquad 5.3$$

where

I_y^i	is the abundance index series i for the year y, and
σ^i	is the residual standard deviation, estimated in the fitting procedure by its maximum likelihood value:

$$\sigma^i = \sqrt{\frac{1}{n^i}\sum_y \left(\ln(I_y^i) - \ln(q^i) - \ln(\hat{B}_y)\right)^2} \qquad 5.4$$

where

n^i	is the total number of data points in the abundance series i, and
q^i	is the catchability coefficient (or survey multiplicative bias) for series i, estimated by its maximum likelihood value:

$$\ln \hat{q}' = \frac{1}{n'} \sum_{y} \left(\ln(I'_y) - \ln(\hat{B}_y) \right) \qquad 5.5$$

$f_{0.n}$ strategy

The $f_{0.n}$ strategy is defined (e.g. Hilborn and Walters (1992)) as a constant exploitation rate strategy with the fishing mortality rate set equal to the value where the slope of the equilibrium yield vs. fishing effort curve is a fraction $0.n$ of the initial slope, i.e.

$$\left.\frac{dC}{dE}\right|_{E=E_{0.n}} = 0.n \left.\frac{dC}{dE}\right|_{E=0} \qquad 5.6$$

and hence,

$$TAC_y(f_{0.n}) = \left(\frac{C_{0.n}}{B_{0.n}} \right) B_y \qquad 5.7$$

as per Figure 5.1.

Further rules

Further additional rules that were explored, to modify the outputs from this Schaefer-based algorithm, were:

a) the TAC may not increase to more than x tons,

b) any TAC increase is limited to z% per year, and

c) any TAC decrease is limited to ω% per year.

Thus the group of OMPs considered is distinguished by the choice of harvesting strategy $f_{0.n}$ coupled with a choice of the values for the parameters x, z and ω.

Following consideration of the initial results, it was decided that three choices of harvesting strategy be investigated in more detail, and the associated results are therefore those presented in this thesis. The three are: $f_{0.1}$, f_{MSY} and $f_{-0.1}$, with an absolute upper bound on the TAC of 14000 tons, together with any TAC increase from one year to the next limited to 5%, and decrease limited to 15%. The $f_{0.1}$ strategy is more conservative than the f_{MSY}, while the $f_{-0.1}$ strategy is less conservative.

For the baseline OMP, the f_{MSY} strategy was used, with an absolute upper bound of 14000 tons on the TAC, and an increase limit of 5% and decrease limit of 15% from one year to the next.

Why Not Others?

Initially, other harvesting strategies were also considered. These included greater extremes on both sides of the f_{MSY} strategy, i.e. $f_{0.3}$, $f_{0.2}$, $f_{-0.2}$, $f_{-0.3}$ and/or with the absolute upper bound on the TAC removed completely, increased to 15000 tons, or decreased to as low as 12000 tons. Changing the decrease limit on the TAC from one year to the next was also investigated, reducing this to 10%, and increasing it to 20%.

Comparisons of the performance statistics for these candidate OMPs with those of the three "chosen" ones indicated the following:

- The $f_{-0.3}$ and $f_{-0.2}$ harvesting strategies did not perform well in preventing the resource from going extinct, even with the TAC decrease limit from one year to the next set as high as 20% and/or the absolute upper bound on the TAC as low as 12000 tons.

- The $f_{0.3}$ and $f_{0.2}$ strategies performed well in preventing the resource from going extinct, but this was at the expense of under-utilization of the resource.
- Increasing the TAC decrease limit to more than 15% led to poor performance, as large decreases in TAC eventuated in the short period of time when this OMP tried to correct mistaken increases in TAC made earlier by the procedure. Reducing the TAC decrease limit to 10% led to resource extinction.

5.4 Robustness Tests

An important component of the OMP approach, consistent with application of a precautionary approach given scientific uncertainties, is to check that the candidate OMPs demonstrate robust achievement of objectives given possible errors in the data, assumed population model structure or implementation (e.g. the h value being different from the one assumed in the Base-case assessment) (Butterworth and Rademeyer, 2005). In addition to the Base-case assessment and the sensitivity tests in section 4.5, following robustness test were carried out on the candidate OMPs, to see if one of the candidate OMPs could perform better than the others given these uncertainties.

1. Episodic events: At some stage in the next 20 years 25% of the fish die, as a result of such an event. The event was assumed to occur midway through the projection period: i.e. $N_{2012,a} \rightarrow 0.75 \cdot N_{2012,a}$

5.5 Projection Procedures and Generating Future Data

5.5.1 Deterministic vs. Stochastic Simulations

The terms above are the two ways of classifying simulation models. The difference between the two lies in whether or not the model has a stochastic (or random) aspect. Deterministic simulations are completely defined by the model. Rerunning a simulation will not change the outcome. Stochastic simulations include randomness. Multiple runs of the same model will generate different values. This random element forces one to generate many outcomes to see the range of possibilities, with the number of possible outcomes to be generated being determined by the precision required for the results of interest.

5.5.2 Projection Procedures and Generation of Future Data

Procedures followed to project the true dynamics (the Operating Model) into the future to test a specific OMP are based on the ones outlined in Rademeyer (2003), and are:

1. From an assessment of the resource that serves as the Operating Model, the component of the numbers-at-age vector for the start of year y_1 ($N_{y_1,a}$: $a = 0,....,m$) are estimated by application of equations describing the operating model (i.e. equations 3.1 to 3.3), where y_1 is the year the projection starts, i.e. 2005 in this case. The recruitment for year y_1 is provided by application of the stock-recruitment relationship of equation

3.4. This will not be determined by the deterministic stock-recruitment relationship alone, but will be subject to fluctuation about the level indicated by that relationship. Log-normal fluctuations are introduced by generating ς_y factors from $N\left(0,(\sigma_R)^2\right)$, where $\sigma_R = 0.4$ for the Base-case Operating Model.

2. The information obtained in 1. is used to generate values of the abundance indices $I_{y_1-1}^{CPUE}$ and $I_{y_1}^{Survey}$. The commercial survey index is generated 1 year ahead of the commercial CPUE index because when deciding for the TAC for year *y*, data for CPUE for year *y* would not yet be available. Indices of abundance in future years will not be exactly proportional to true abundance, as they are also subject to observation error. Log-normal observation error is therefore added to the expected value of the abundance index evaluated, i.e.:

   $$I_y^i = q^i B_y^i e^{\varepsilon_y^i} \qquad \varepsilon_y^i \text{ from } N\left(0,(\sigma^i)^2\right) \qquad 5.8$$

   where

   B_y^i is determined from equations 3.15 and 3.16 as appropriate,

   I_y^i reflects the index from commercial CPUE or the surveys,

   q^i is as estimated for that assessment/Operating Model (equation 3.20), and

   σ^i is as estimated for that assessment/Operating Model (equation 3.19).

3. The OMP sets a total catch TAC_{y_1} (equation 5.7).

4. The numbers-at-age $N_{y_1,a}$ are projected forward under a catch TAC_{y_1} by means of the operating model to determine $N_{y_1+1,a}$. The age-specific selectivity given in section 4.1 remains unchanged. Equations 3.1 to 3.3 used for this purpose require specification of how the catch is disaggregated by age to obtain the $C_{y_1,a}$, with equation 3.13-3.14 used for this purpose

Steps 1-4 are repeated for each future year in turn for as long a period as desired, and at the end of that period the performance of the candidate OMP under review is assessed by considering performance statistics such as the average catch taken over the period and the final spawning biomass of the resource.

The variance-covariance structure in the estimates from the assessment fits is carried forward into the projections through the process of projecting realizations from the Bayesian posterior for the assessment.

5.6 Results and Discussion

5.6.1 Baseline OMP

Performance comparisons of the baseline OMP (i.e. the f_{MSY} strategy) for the Base-case and seven other robustness tests operating models are shown in Figures 5.2 to 5.5. Figure 5.2(a) shows the resource spawning biomass depletion in 2004 (B^{sp}_{2004}/K^{sp}), while depletion at the end of the projection period (B^{sp}_{2024}/K^{sp}) is shown in Figure 5.2(b). For comparisons, MSYL is also shown in Figure 5.2(c), as a proportion of the pre-exploitation spawning biomass (B^{sp}_{MSY} / K^{sp}).

Figure 5.3 shows the Average Annual catch Variation (AAV) (see section 5.1) over the 20-year projection period. Figure 5.4 presents the expected Average Annual catch over the projection period, while Figure 5.5 shows the time-series of projected TACs for the Base-case as well as for seven other robustness test operating models.

The values presented in all these figures are the distribution medians and 95% probability intervals. The median is favoured over the mean because it is less affected by outliers, in contrast to the case with the mean. It should also be noted that these results are for fully stochastic scenarios: this means that uncertainty in parameter estimates, and observation errors in future data are all included, and further both past and future recruitment variability is taken into account.

From Figure 5.2, the baseline OMP does not seem to be robust to changes in the recruitment "steepness" parameter, *h* and also to an increase in σ_R. The lower 95%ile depletion at the end of the projection period is poor for both when *h* is decreased to 0.5 and when σ_R is increased to 0.6. The baseline OMP also does not perform well when there is bias in historic CPUE, in terms of preventing large reductions by the end of projection period, but the results are not as poor as under $h = 0.5$ and $\sigma_R = 0.6$. Performance in terms of depletion in 2024 is relatively good for all the other robustness tests. One should also note that even if the lower 95%ile for the projected depletion shows an increase compared to the corresponding figure for the current depletion, it is possible that for some of the realizations the spawning biomass actually decreased during the projection period. The Average Annual Variation is desirably low for all the robustness tests, though can get rather high when $h = 0.5$ (see Figure 5.3). For all the operating models, the median annual catches show an initial decrease before they increase again eventually (see Figure 5.5). It should also be noted that the Average Annual Catches predicted for all the operating models are less than current catch (see Figure 5.4 and 5.5).

Figure 5.6 shows the time-series of depletion for the spawning biomass with the 95% probability interval envelope for the Base-case operating model in (a), and corresponding depletion "worm" plots showing some individual realizations in (b), for a 20-year projection into the future under the baseline OMP. Figure 5.7 shows similar time-series for annual catches. From these results, the likelihood of lower catches for the next 5 years, after which the catch generally increases again, is again evident.

5.6.2 Alternative OMPs

Figures 5.8 to 5.9 show a comparison of performances for the Base-case and seven other robustness test operating models under two other alternative candidate OMPs. Figure 5.8 shows a) the spawning biomass depletion at the end of the projection period, b) AAV and c) the Average Annual Catch over the projection period for the $f_{0.1}$ strategy, with $x = 14000$ tons, $z = 5\%$, and $\omega = 15\%$. Figure 5.9 shows similar statistics for the $f_{-0.1}$ strategy, again with $x = 14000$ tons, $z = 5\%$, and $\omega = 15\%$.

Neither these two candidate OMPs are robust to decreasing h to 0.5 or to increasing σ_R to 0.6. The $f_{-0.1}$ OMP shown does not perform well either (in terms of final depletion) when the bias in historic CPUE is considered, with some extinctions evident.

A harvesting strategy of $f_{-0.1}$ means more catches on average and as a result, a lower final depletion. A harvesting strategy of $f_{0.1}$ on the other hand means less catches on average and hence a somewhat higher final depletion.

Since variability in catch (AAV) is controlled mainly by values given to z and ω, which are the same for the OMP variants compared here, this remains roughly constant across candidate OMPs and robustness test operating models, except in cases where the resource appears heavily depleted and hence the OMP reduces catches drastically.

The baseline and the other two candidate OMPs might be considered to have failed under some of the robustness tests, in terms of preventing the resource from going extinct, as mentioned above. Although chances of these scenarios applying in reality seem rather slim, if management authorities consider them serious threats, increasing ω to 25% would give a safer option. Figure 5.10 shows performance statistics for the 20-year projection, under the most aggressive harvesting strategy of the three, $f_{-0.1}$, with $\omega = 25\%$ and the other control parameters unchanged. This prevents extinction, but comes at the price of lower average catches and of a higher AAV.

5.7 **Summary**

The candidate OMPs examined perform appreciably differently across a range of robustness tests. Although the f_{MSY} harvest strategy, with $x = 14000$ tons, $z = 5\%$ and $\omega = 15\%$ is put forward as the baseline OMP in this thesis, at the end of the day the choice of the OMP to be adopted lies with the managers' choice of trade-offs.

Should this be somewhat higher catches, with the higher risk of heavy resource depletion under the $f_{-0.1}$ strategy, with $x = 14000$ tons, $z = 5\%$ and $\omega = 15\%$, or lower catches with a lesser risk of such depletion if $f_{-0.1}$ is changed to $f_{0.1}$? The other alternative is opting for an even smaller resource depletion risk, but with lower annual average catch and higher inter-annual catch variation under an $f_{0.n}$ strategy with $x = 14000$ tons, $z = 5\%$ and $\omega = 25\%$. For presentation simplicity, only the more aggressive of the three harvest strategies, $f_{-0.1}$, with the above-mentioned set of control parameters is presented in Figure 5.10. Figure 5.11 compares the four candidate OMPs under the Base-case operating model.

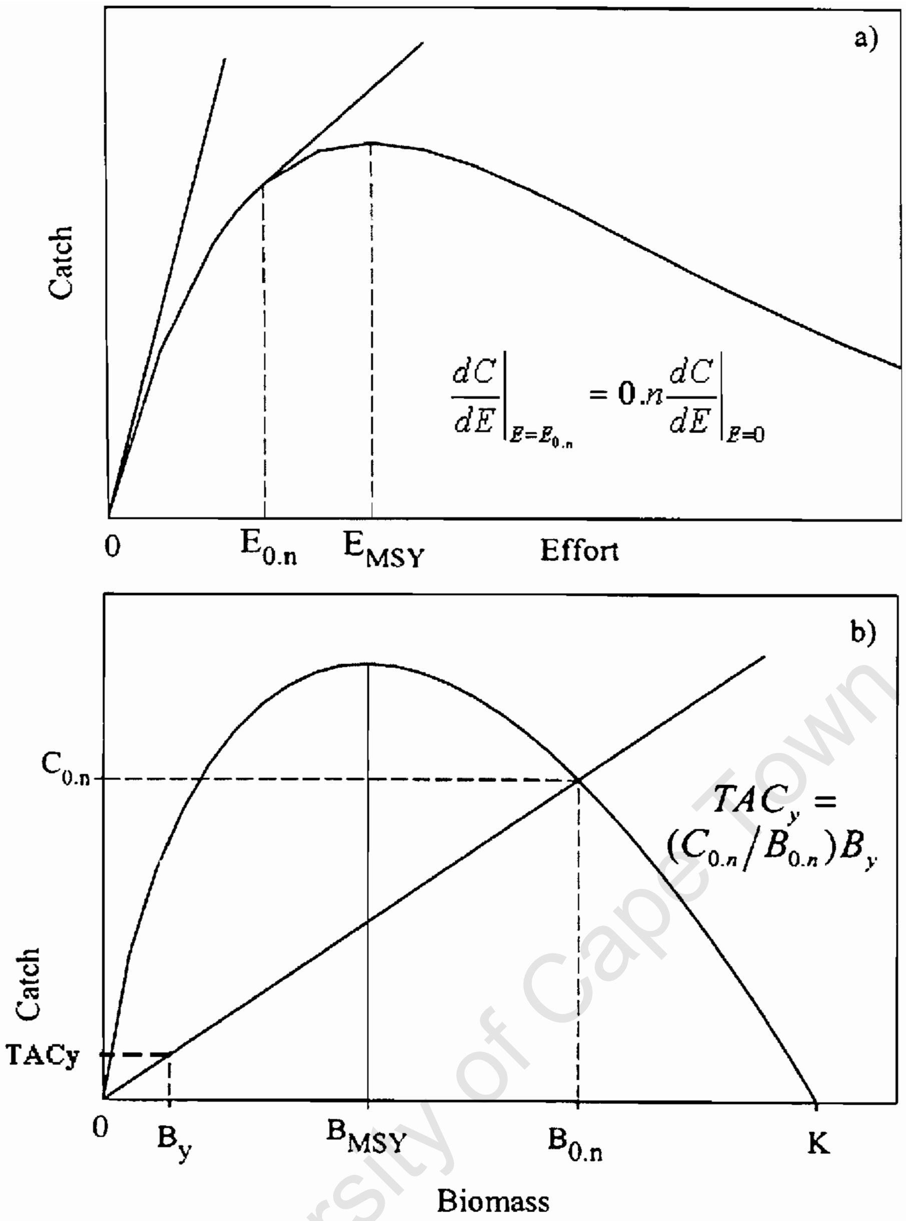


Figure 5.1: A graphical explanation of the $f_{0.n}$ harvesting strategy: a) shows how the effort level $E_{0.n}$ is obtained from a sustainable catch *vs.* fishing effort curve; which correspond to an equilibrium biomass $B_{0.n}$, and b) shows how the sustainable catch *vs.* biomass plot is used to convert this information into a TAC recommendation (from Butterworth and Rademeyer, 2005).

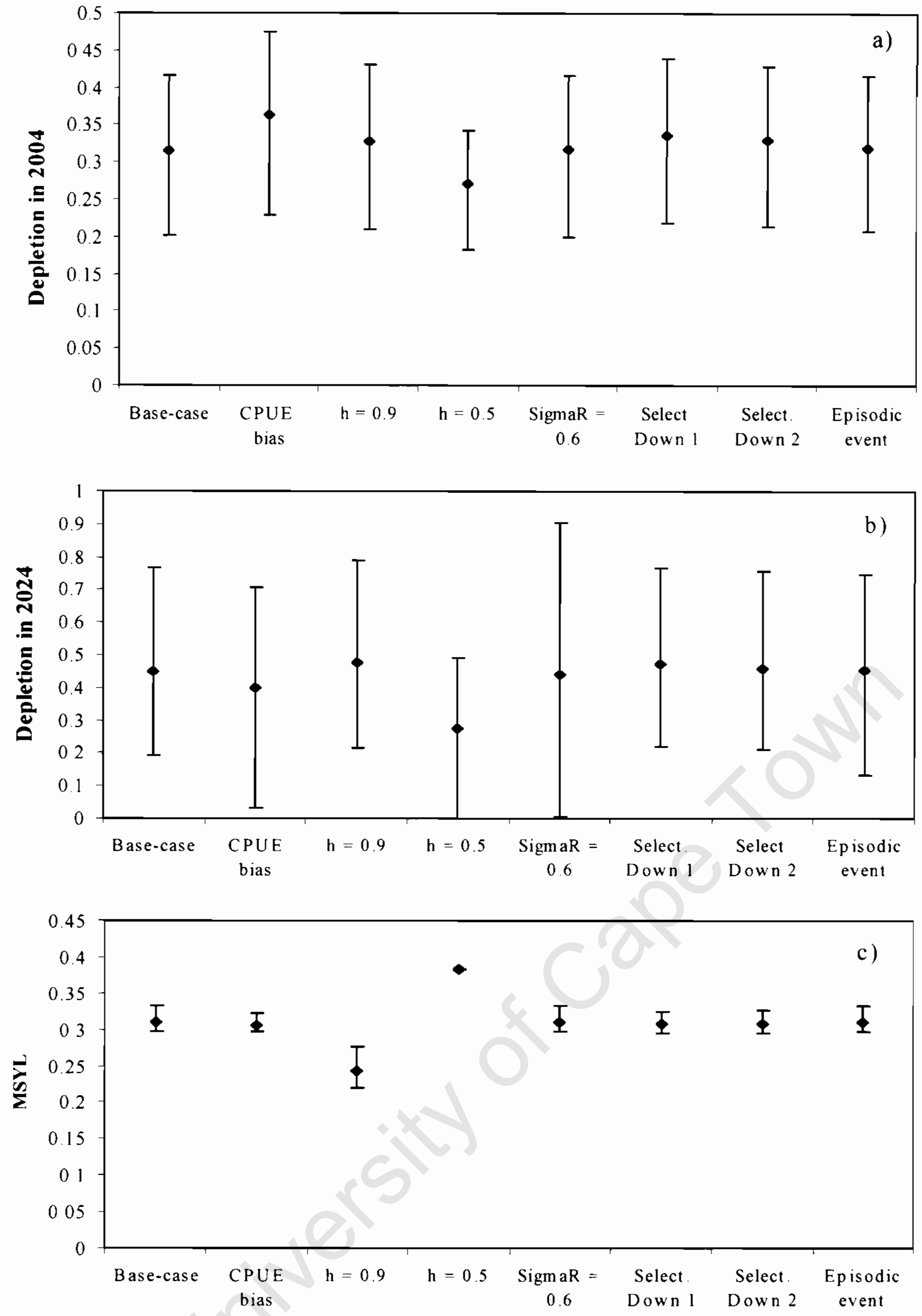


Figure 5.2: a) Initial (2004) and b) projected final depletion under the baseline OMP for the Base-case and seven other robustness test operating models. The estimated MSYL (see also Table 4.1) is shown in c). The bars show the 95% posterior probability intervals, with the central dot showing medians.

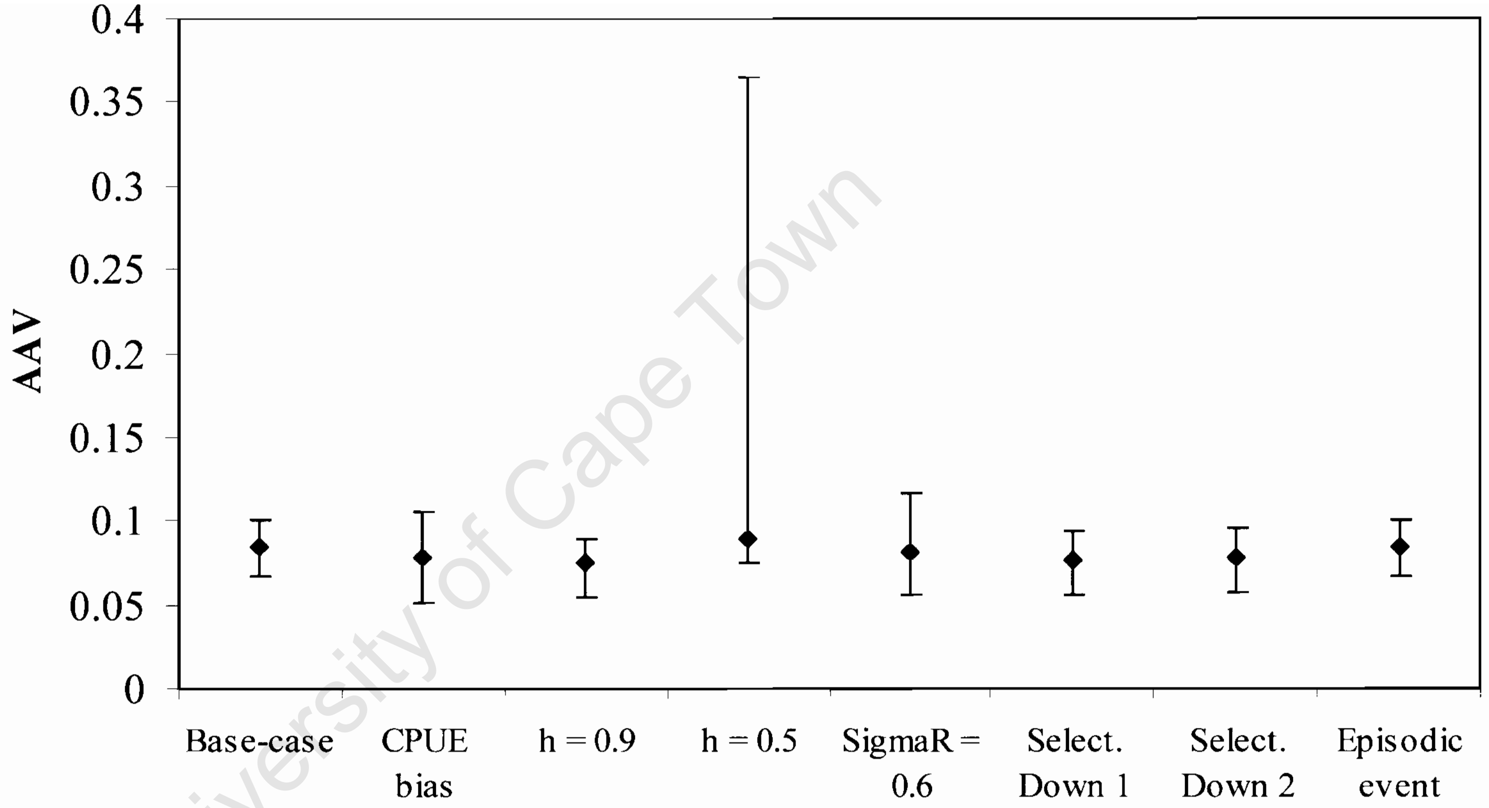


Figure 5.3: Average Annual Variation (AAV) in catch for the 20 years projection period under the baseline OMP, for the Base-case and seven other robustness test operating models. The bars show the 95% probability intervals, with the central dot showing medians.

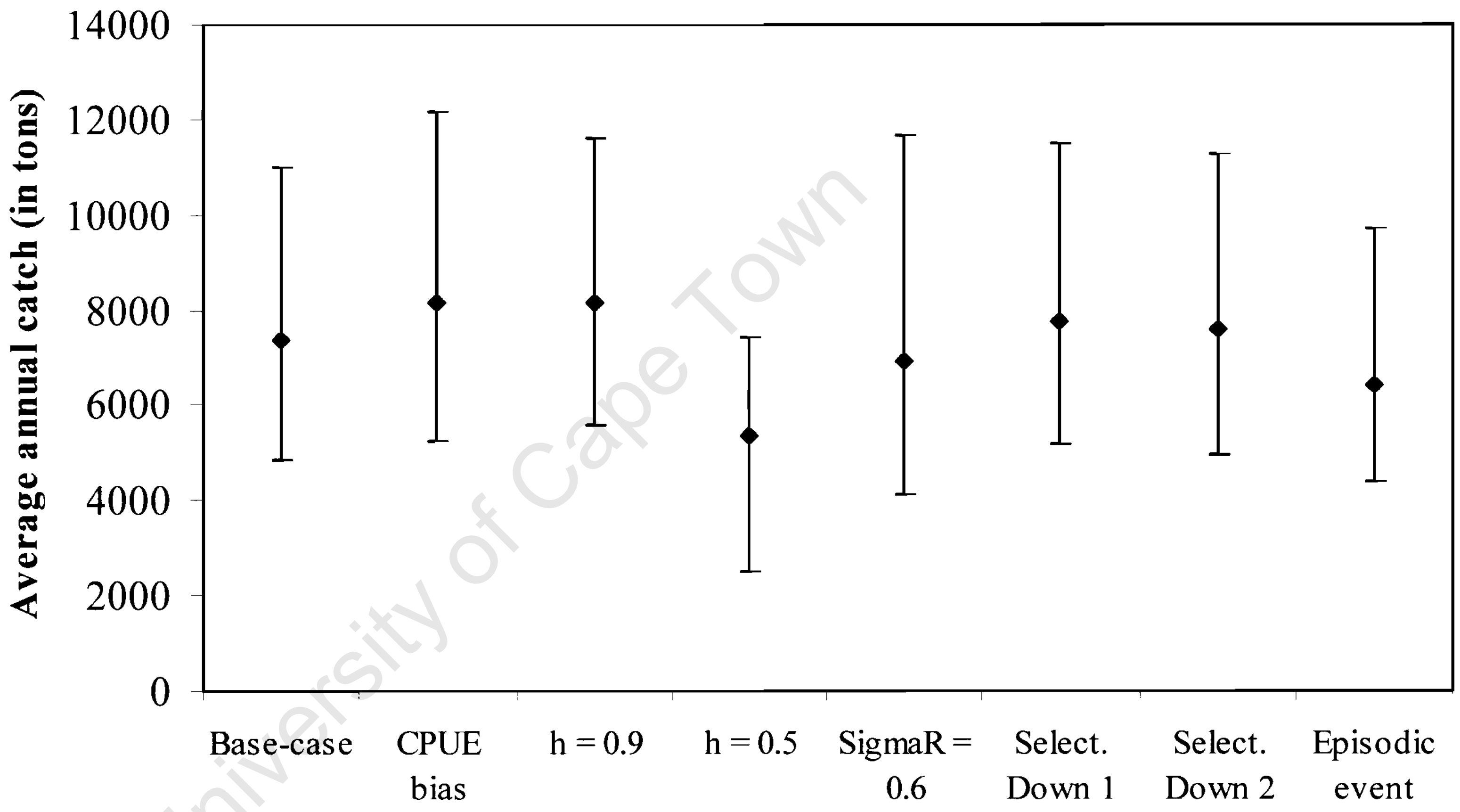


Figure 5.4: Average Annual Catch for the 20-years projection period under the baseline OMP, for the Base-case and seven other robustness test operating models. The bars show the 95% probability intervals, with the central dot showing medians.

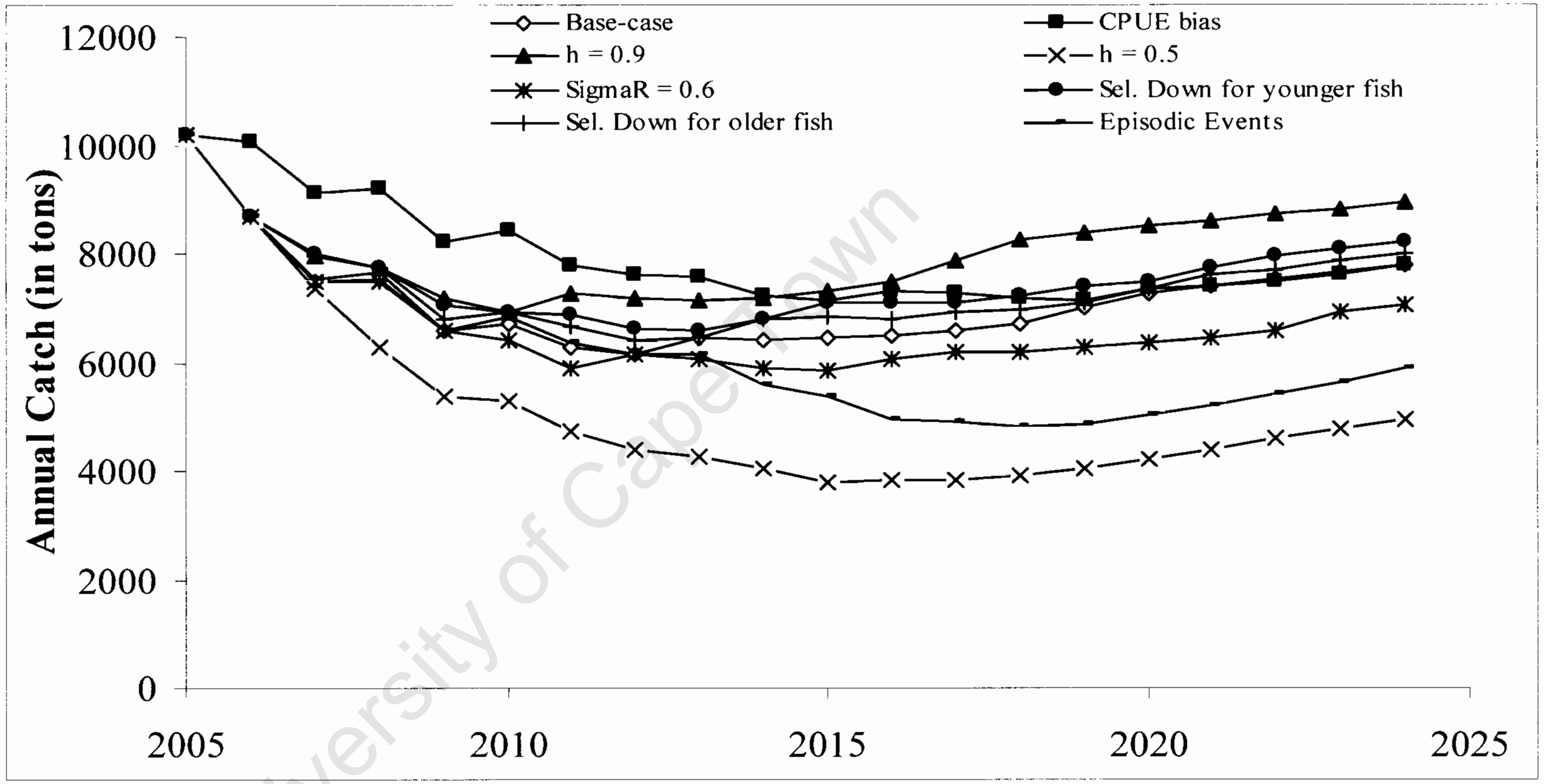


Figure 5.5: Median Annual Catch for the 20 years projection period under the baseline OMP, for the Base-case and seven other robustness test operating models.

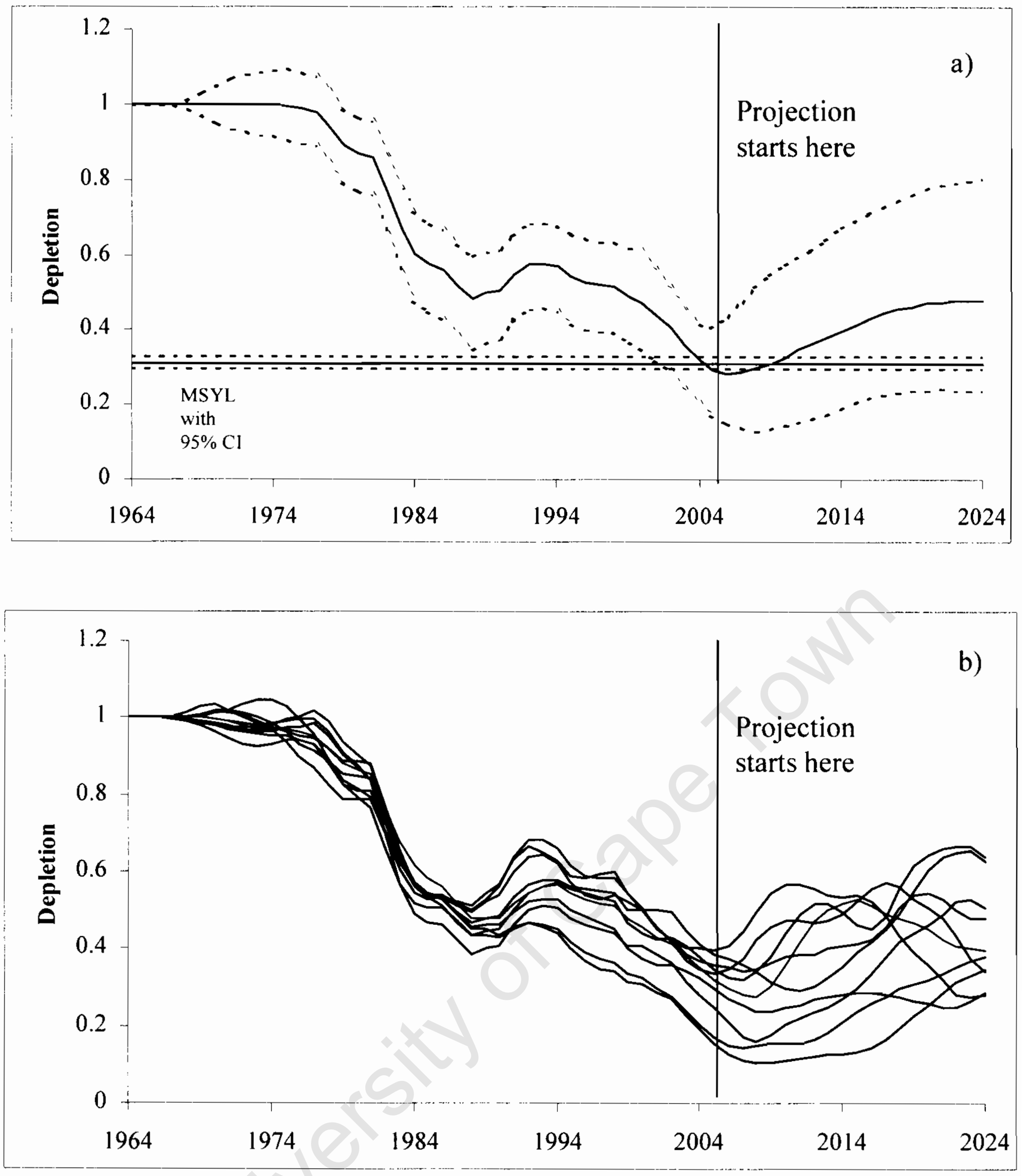


Figure 5.6: a) Depletion, B_y^{sp} / K^{sp} with 95% probability intervals (MSYL with its 95% probability interval is also shown) and b) "worm" plots showing the first 10 replicates, for the Base-case operating model projected 20 years into the future under the baseline OMP.

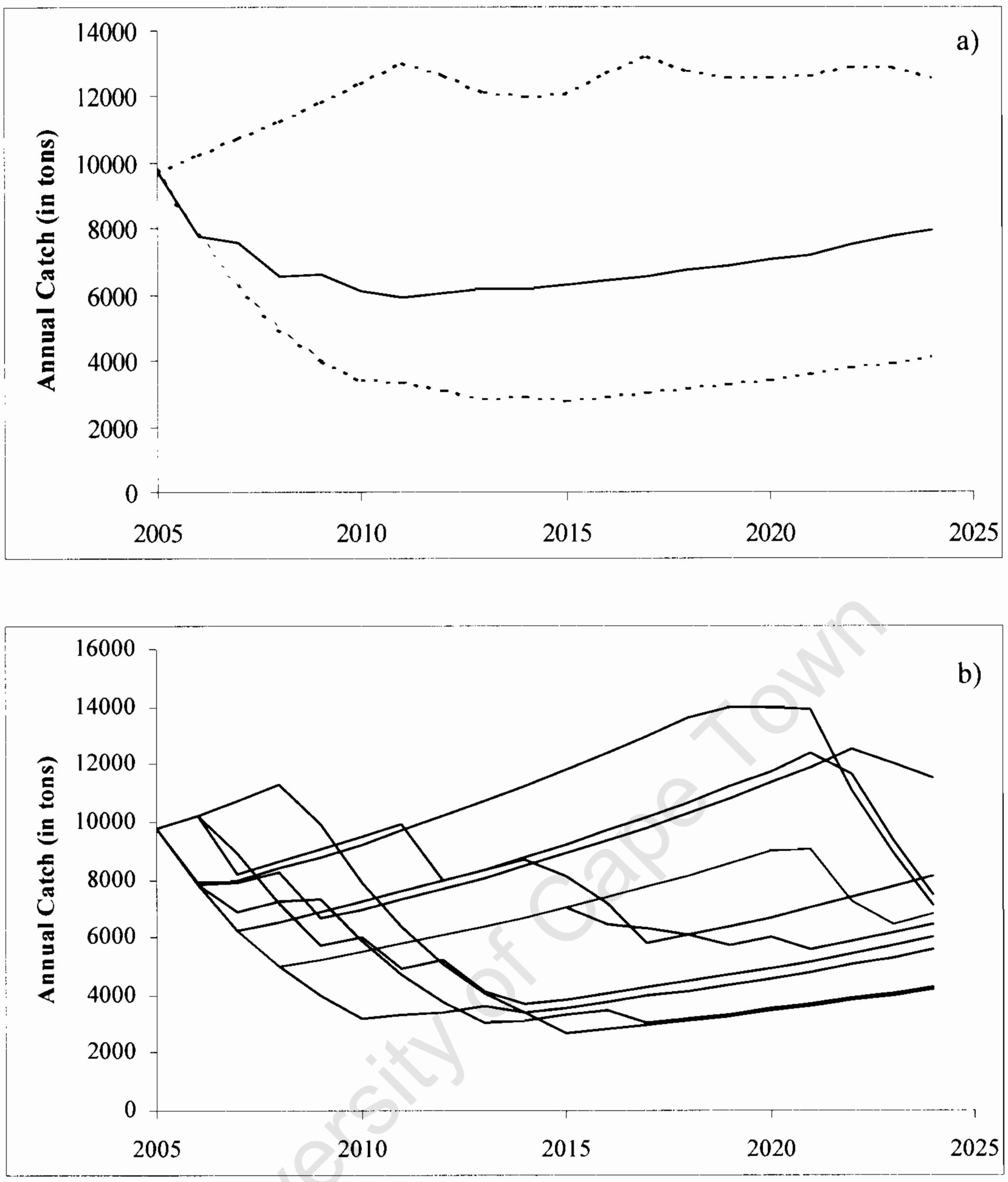


Figure 5.7: a) Annual catches with 95% probability intervals and b) "worm" plots showing the first 10 replicates, for the Base-case operating model projected 20 years into the future under the baseline OMP.

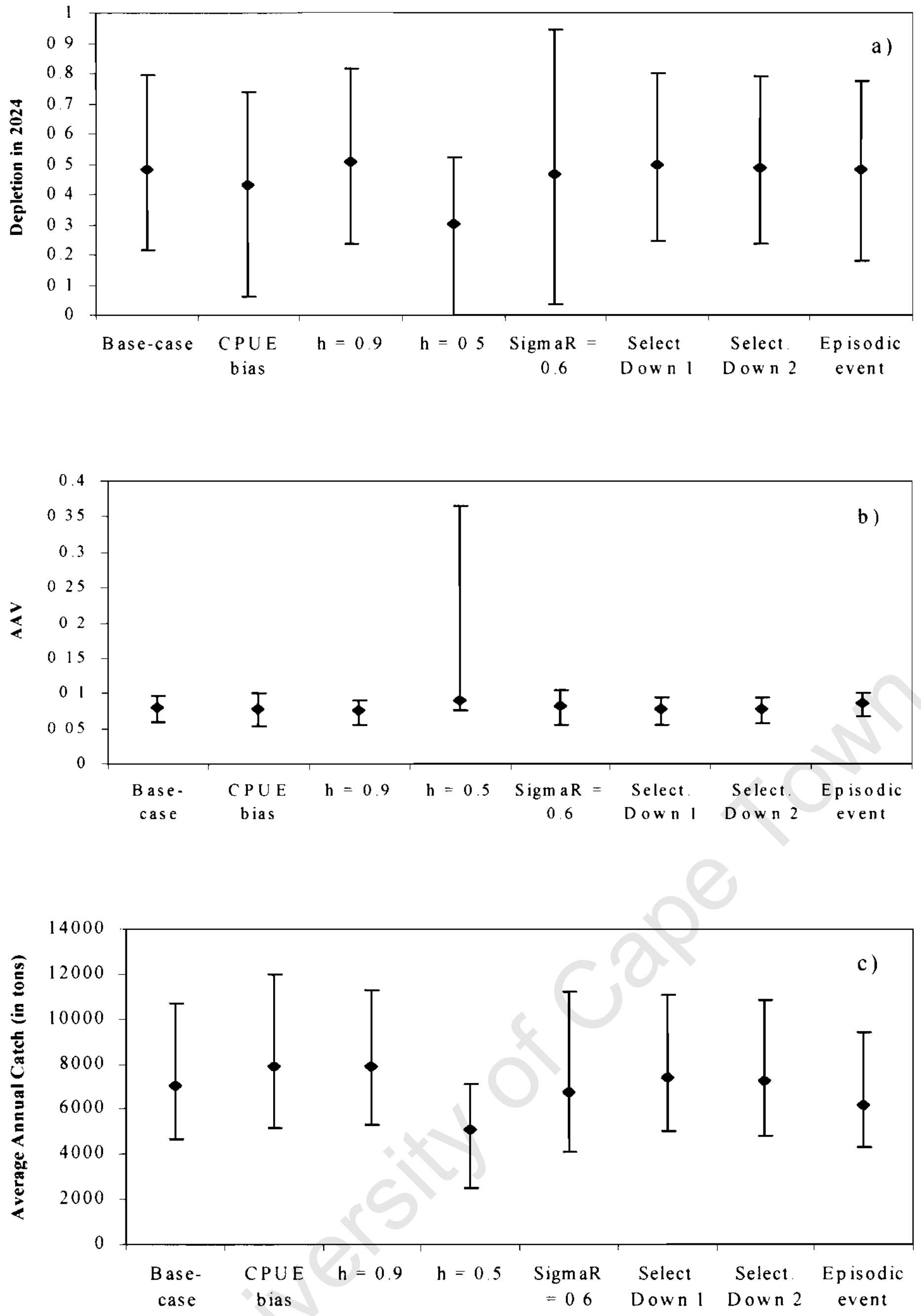


Figure 5.8: Medians for a) Final depletion at the end of the projection period, b) AAV, and c) Average Annual catch under the $f_{0.1}$ harvest strategy, with $x = 14000$ tons, $z = 5\%$ and $\omega = 15\%$, for the Base-case and seven other robustness test operating models.

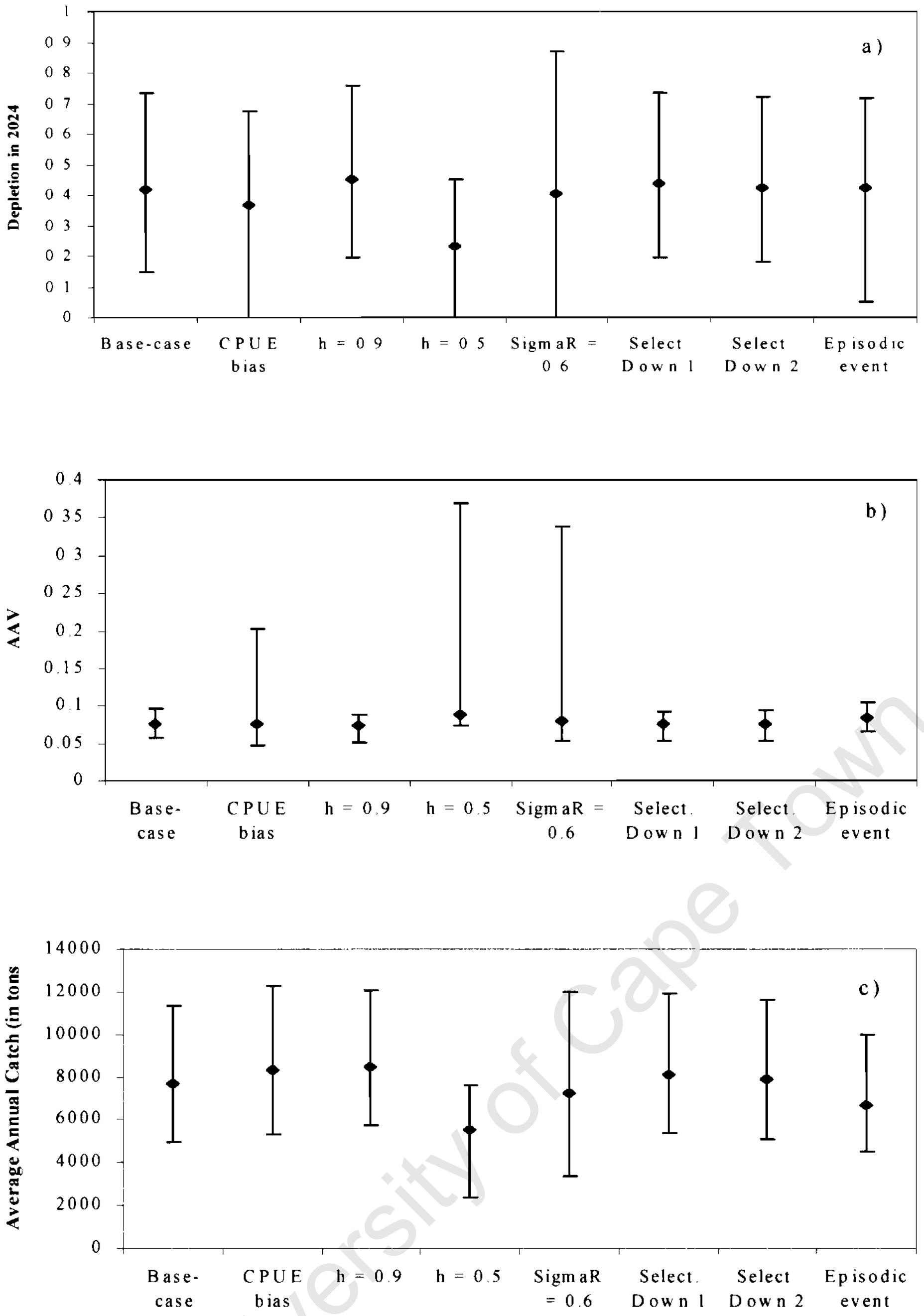


Figure 5.9: Medians for a) Final depletion at the end of the projection period, b) AAV, and c) Average Annual catch under the $f_{-0.1}$ harvest strategy, with $x = 14000$ tons, $z = 5\%$ and $\omega = 15\%$, for the Base-case and seven other robustness test operating models.

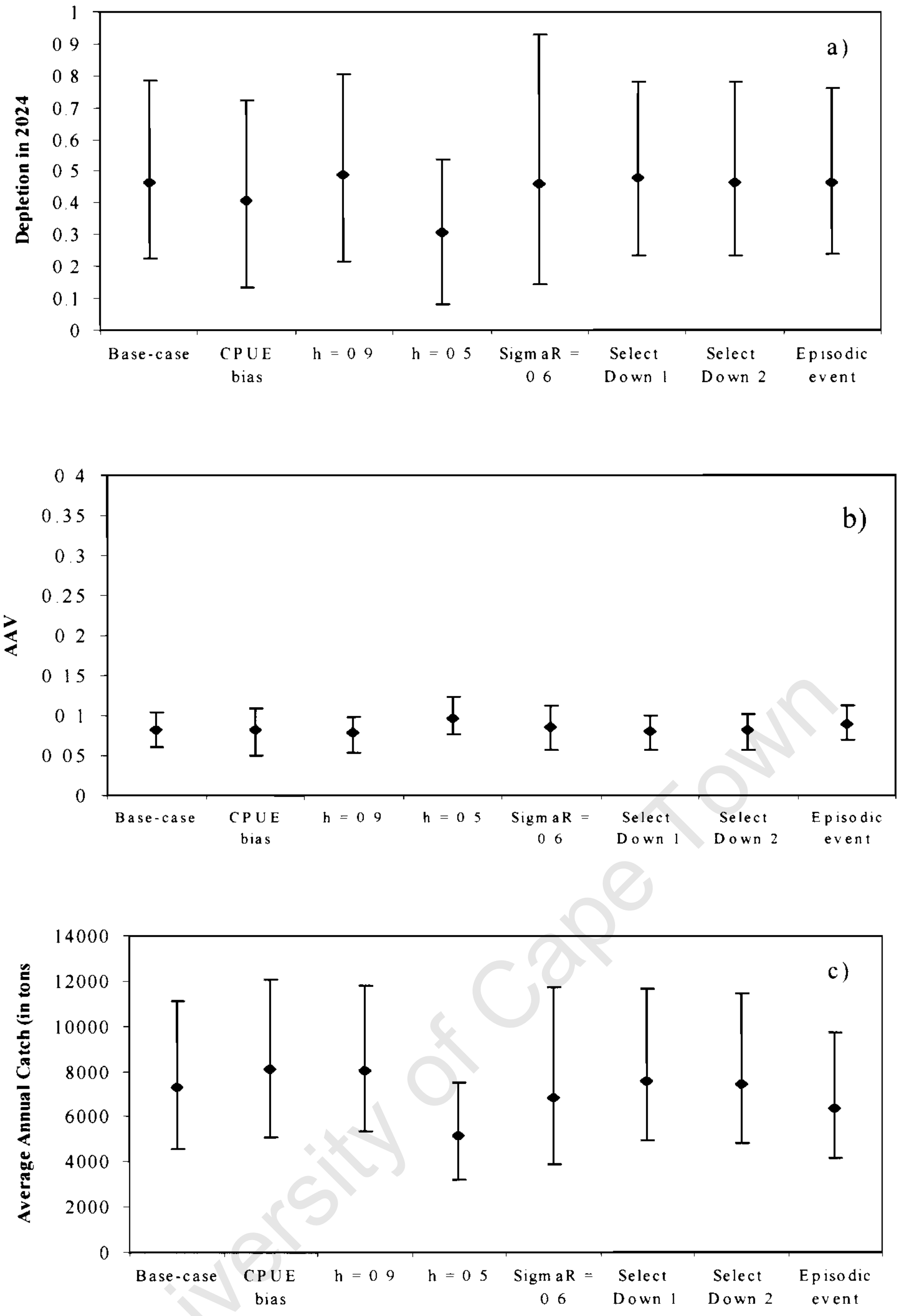


Figure 5.10: Medians for a) Final depletion at the end of the projection period, b) AAV, and c) Average Annual catch under the $f_{-0.1}$ harvest strategy, with $x = 14000$ tons, $z = 5\%$ and $\omega = 25\%$, for the Base-case and seven other robustness test operating models.

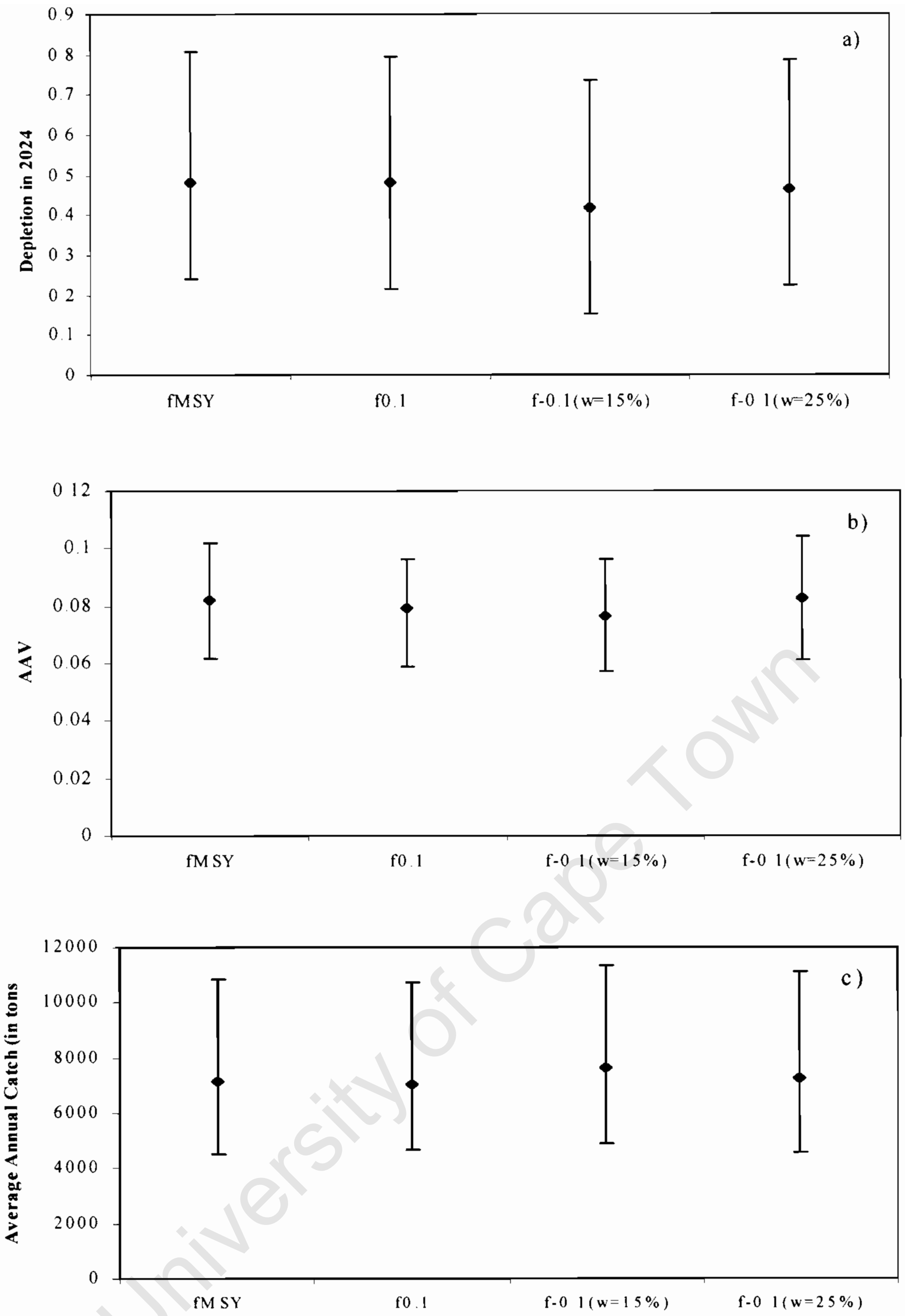


Figure 5.11: Medians for a) Final depletion at the end of the projection period, b) AAV, and c) Average Annual catch under four candidate OMPs for the Base-case operating model.

6 Overall Conclusion

The two main topics considered in this thesis are a Bayesian statistical approach to the assessment of the Namibian monkfish (*Lophius vomerinus*) resource, and the development of an Operational Management Procedure for the resource based on this assessment and its attendant uncertainties.

The Bayesian statistical approach was intended to account for and convey the full range of uncertainty related to parameter values. This was not entirely possible due to model convergence problems, caused by inadequate information in the available data. As a result, the "steepness" parameter, *h*, was fixed for the assessment, and the value for the recruitment variability parameter σ_R was set to a low value of 0.15 from 1965 to 1994, which is a less than a realistic level of variability in recruitment (Beverton and Holt, 1957). Sensitivity tests were run to allow other uncertainties to be considered.

Although information for this resource is limited, the Base-case model and sensitivity tests all estimate the resource to be, more or less, at 30% of its pre-exploitation level (Figure 4.4). This does not seem too unhealthy a state, so no drastic action seems required immediately and these assessments should provide a sufficient basis for managing this resource.

The OMP options presented in this thesis provide a range of choices from which managers can select depending on the desired trade-offs between conflicting objectives. The f_{MSY} harvesting strategy, with $x = 14000$ tons, $z = 5\%$ and $\omega = 15\%$ (the baseline OMP) represents a moderate risk of resource depletion, a comfortably low AAV and a moderate level of average annual catch. If f_{MSY} is changed to $f_{-0.1}$, one predicts higher catches, with a higher risk of resource depletion, while if f_{MSY} is changed to $f_{0.1}$, lower catches are likely, with a smaller risk of depletion. However, under any of the three harvesting strategies, with the maximum annual decrease parameter increased from $\omega = 15\%$ to $\omega = 25\%$, there is an even smaller risk of resource depletion together with lower annual average catch and higher AAV. It should also be noted that all the OMP options considered suggest that a decrease in the TAC in the short term is likely to be required.

6.1 Future Research

6.1.1 Age-dependent natural mortality

In the absence of enough information about the Namibian Monkfish resource, the natural mortality, M, was treated as age-independent in this analysis. The reality, however, is that the juveniles and very old fish are more likely to die of natural causes (predation, disease) than the middle-aged fish, i.e. M would be expected to be higher for the young and the old fish than for the middle-aged fish. Therefore efforts should be made to estimate age-dependent natural mortality, M_a. This may not be easy, even with much greater data availability (e.g. this has scarcely been possible for the South African hake resource, a major fishery in the region (Rademeyer and Butterworth, 2005)). Another approach therefore is to determine the effect of changing values of M_a on the performance of OMPs (robustness tests). If performance hardly changes with changes to values of M_a, the priority for improved estimates of such parameters would reduce.

6.1.2 Distinction of the two fishing fleets catching monkfish

Two different fishing "fleets" are currently exploiting the Namibian monkfish resource: the monkfish and sole directed "fleet", and the hake directed "fleet". The resource is however being assessed in this thesis as if it was being exploited by one "fleet" only (see section 2.1). Catch-at-length data for the two fisheries are available, and would allow for a distinction between the fishing selectivities of the two "fleets". This in turn would allow for the resource to be better assessed with the two "fleets" distinguished.

6.1.3 Fit the model to commercial and survey catches-at-age data

Not all "important" model parameters could be estimated from the information that was available for the Namibian monkfish assessment for this thesis. The model was fitted only to the CPUE and the survey abundance indices. If the commercial and/or survey catches-at-age could be made available, this would add more information about the resource to the data used for model-fitting purposes, and allow for more reliable and realistic biological parameter estimation.

6.1.4 Incorporate age data into the OMP

The OMPs developed in this thesis are based on a dynamic age-aggregated production model (Schaefer surplus production model) (see Chapter 5). The catch-at-age information is not taken into consideration. Some thought should be given to this issue, so that at least some age-data might be included in further OMP investigation in the future.

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