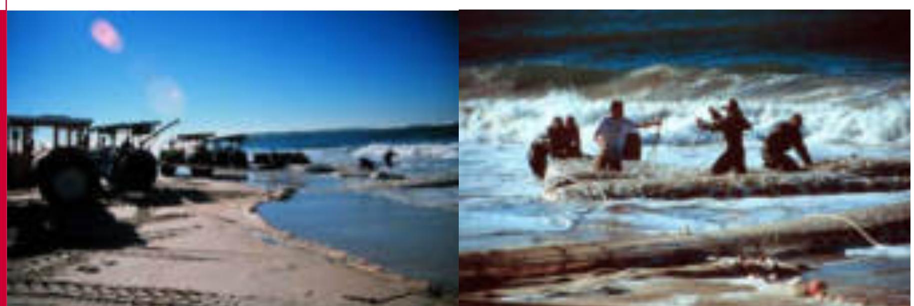
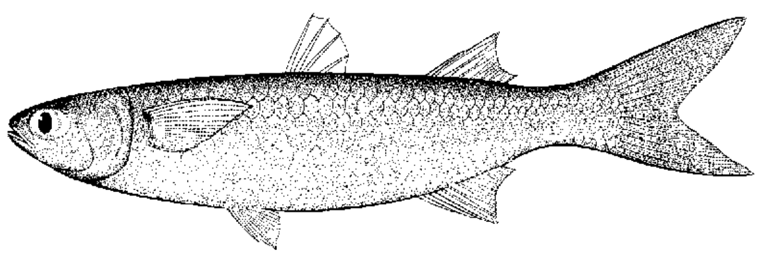
Stock Assessment of the Queensland–New South Wales Sea Mullet Fishery (*Mugil cephalus*)





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This publication provides an assessment of the state of the population of Sea Mullet, Queensland's most commercially valuable finfish resource, and recommendations for future research and data collection.

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1 EXECUTIVE SUMMARY

An analysis of the catch, fishing effort and age frequencies for the Queensland and New South Wales sea mullet (*Mugil cephalus*) stock was undertaken for the purpose of assessing the status of the fishery. In the period 1990–2003 logbook data indicated that an average of 3809 tonnes of sea mullet were landed in New South Wales annually, while the average annual reported harvest from Queensland was 2030 tonnes.

The catch-per-unit effort (CPUE) for the fishery was standardised using a general linear model that considered the influence of the number of days fished, the type of fishing gear, the State, fishing location, year, and month on catches. Given the different fishing gear used such as beach-haul-netting and estuarine-gill-netting, observed levels of fishing effort are generally difficult to interpret. Fishing effort and catch were therefore standardised and used in three stock assessment models (Paloheimo's catch-at-age model, an age-based model and a virtual population analysis, VPA) to assess the past and present condition of the entire stock. Paloheimo's catch-at-age model was used to simulate and forecast catch rates into the future, under different management scenarios and recruitment regimes.

The results suggest that the sea mullet stock has been heavily exploited since the fishery's introduction more than 100 years ago, so much so that over the last decade fishing has accounted for about two out of three deaths of those fish that have recruited to the fishery. Point estimates of current biomass are uncertain but clearly less than 60% of the virgin level. Recruitment to the fishery is a highly variable process, but appears to have dropped significantly around 1993 and not yet fully recovered, despite the reasonably constant catch rates. Furthermore, in recent years, both the Paloheimo catch-at-age model and the age-based model indicate that recruitment declined markedly in 2001 and 2002. If this finding is accurate, then catches in 2004 and 2005 would be expected to be below the long term average.

Results from the VPA suggest an annual recommended target catch of 3620 tonnes, for both States combined (see Table 5.5). This calculated target catch does not represent maximum sustainable yield, but a more conservative estimate to account for the large uncertainty.

Priority recommendations include:

- Expanding the Queensland Long Term Monitoring Program to capture the age, length and sex structure of the estuarine component of the fishery.
- Investigating the proportion of sea mullet that move from fresh water to the fishery each year (i.e. quantify the exploitable fraction of sea mullet) using annual otolith microchemistry. This data may also help identify the important estuaries or catchments for recruitment.
- Improving the commercial fishing logbooks to allow accurate reporting of target species, fishing search time, size of fishing operation, and zero catches.
- Reviewing levels of fishing if the reported landings or catch rates drop significantly within the next three years.

2 INTRODUCTION AND BACKGROUND

This document reports on the past and current status of the eastern Australian sea mullet stock from Queensland and New South Wales coastal waters. To comment on the status of the stock, information on the catch, effort and age frequencies of the sea mullet harvest were used in three mathematical models. In addition to providing information and advice for the management of the stock, the work formed an academic thesis constituting part of the senior author's (Paul Bell) Master of Science (Mathematics) program at the University of Queensland.

2.1 INTRODUCTION

The Queensland and New South Wales sea mullet fisheries are among the most important commercial fisheries in Australia. In both States, the annual catch of sea mullet is higher than that of any other species, and sea mullet is considered the mainstay of the fresh fish trade in Queensland (Virgona et al.1998). To maximise the long-term sustainability of the resource, it is important that sound scientific information is made available to individuals responsible for managing the fishery. This information may take many different forms, such as biological research and monitoring activity or research into fishing activity. In this case, the information being provided is a quantitative assessment of the fishery by mathematical modelling. This assessment is intended to extend and complement the already available (both recent and historic) scientific documentation on the resource [e.g. Smith and Deguara (2002) and Dichmont et al. (1999)].

The eastern Australian sea mullet population is considered a single straddling stock across Queensland and New South Wales waters. As such, this project is framed in a collaborative context, incorporating data and research from both States. It is subsequently imperative that any future management and/or research decisions made on the basis of this work are undertaken in careful consideration of the impact on and benefit to both States.

2.2 BACKGROUND

Dichmont et al. (1999), Halliday (1992), Smith and Deguara (2002) and Williams (2002) detailed comprehensively the population biology, economic value and management of Australia's east-coast sea mullet. The reader is referred to these studies for more details. Following is a brief summary of these studies.

2.2.1 DISTRIBUTION OF THE FISHERY

The straddling sea mullet population stretches along the eastern Australian coast, with most landings occurring between 19°S (≈ Townsville) and 37°S (≈ border New South Wales and Victoria). Harvest declines significantly in the southern extent of New South Wales, so much so that Victorian fishing activity was excluded from this analysis (Table 2.1 and Figure 3.4). The catch also declines in the northern extent of Queensland. The population is typically spread throughout freshwater, estuarine, and ocean beach waters.

2.2.2 LIFE AS A SEA MULLET

After hatching, the larvae drift in ocean waters until large enough to swim, at which stage they enter estuaries swimming against the tidal stream (Halliday 1992 and Virgona et al. 1998). Schools of fry do not seek a specific salinity level within estuarine waters but scatter from the estuary mouths all the way to freshwater (Thomson 1955). They typically remain in these waters until maturity. Pre-spawning fish aggregate at the mouths of estuaries before exiting to sea during late autumn or winter (Smith and Deguara 2002). Spawning fish swim northward along the ocean beaches during winter. These fish take part in what is generally known as the 'ocean beach spawning run', in which eggs are released, fertilised and hatched during the winter months. After spawning, the mature fish return to the estuaries.

In some summers, a 'hardgut' movement of fish along ocean beaches occurs. The fish that take part in this movement do not feed and have undeveloped gonads, hence the term 'hardgut' (Smith and Deguara 2002).

The movement of sea mullet was studied by Kesteven (1953) and Virgona et al. (1998) through tagging programs. These studies indicate that mullet generally move northward during both the spawning and hardgut runs. Not all mature fish participate in the spawning run each year but there is evidence of multiple movements, i.e. a single fish moving to ocean beach waters year after year (Virgona et al.1998).

Mullet typically mature from two to four years of age (Smith and Deguara 2002). This age range constitutes most of the catch taken during the spawning run. The size at which mullet first mature is typically between 250 to 450 mm total length (Smith and Deguara 2002).

The sex ratio of the population can vary greatly with time and location. Ocean beach catches typically comprise more males than females while estuarine catches contain a more balanced ratio.

2.2.3 ECONOMICS OF THE FISHERY

The Queensland sea mullet fishery is valued at around \$10 million per annum GVP[1] (Williams 2002) and has averaged a gross catch of 2396 tonnes each year in the years 1988 to 2002 (Table 2.1). The New South Wales fishery by comparison is valued at around \$11.4 million (Dichmont et al. 1999) and has averaged a gross catch of 3970 tonnes each year in the same timeframe. Victorian landings averaged only 20.2 tonnes (an average of only \$24 800 annually) in the last five financial years (Fisheries Victoria 2003), and were deemed small enough to be ignored in the assessment.

Table 2.1 Comparison of the 'value' of each State's sea mullet fishery. The Queensland and New South Wales averages are calculated from 1988 to 2002. Victoria is calculated on the financial years from July 1998 to June 2003.

State	Average tonnes per year	$ per annum GVP
Queensland	2396	10 000 000
New South Wales	3970	11 400 000
Victoria	20	24 800

Fishers target mullet for fillets, roe and gut. The market price of roed females, typically, far exceeds the price of males or immature females. This is due to the high overseas demand for mullet roe, which is considered a delicacy in many Asian countries. Male fish attract about \$0.5/kg while roed females have attracted up to \$6/kg (Williams 2002). Roed females are only caught during the spawning season, which takes place in April through August in Queensland, and March through July in New South Wales. Mullet fillets are among the cheapest (price per kilogram) of any finfish sold in Australia.

2.2.4 SECTORS AND GEAR

The fishery in each State can be split into two distinct commercial sectors; ocean-beach and estuarine. The ocean-beach sector targets mullet at the mouth of estuaries and along ocean beaches during the spawning season using highly efficient beach haul nets (Figure 2.1). This activity yields most of the total landings each year. Mullet are caught in the estuarine sector

[1]GVP: Gross value of production at prices paid to fishers at wharf (i.e. landing value).

mostly by gillnetting. Tunnel and ring netting methods are also used. In Queensland, the ocean beach component of the fishery dominates, accounting for around 72% of the catch each year. In New South Wales, the estuarine component has historically dominated, but has been overtaken by ocean beach landings over the last 15 years (ocean beach landings accounted for only 23% of the catch in 1988, but rose to a maximum of 61% in 1997). See Chapter 3 for more information on the different sectors in each State.

Figure 2.1 Commercial beach seine fishers catching sea mullet. In this operation a jet boat was used to deploy the large seine net around the school of mullet. Tractors were used to pull the laden cod end onto the beach. The photos were taken at North Stradbroke Island, southeast Queensland during the QDPI&F Long Term Monitoring Program.

2.2.5 RECREATIONAL CATCH OF SEA MULLET

Sea mullet are not targeted or caught in any great number by recreational fishermen because they cannot be taken easily by fishing line due to their diet, which consists predominantly of micro-crustaceans within the plankton (Smith and Deguara 2002). Because of this characteristic and the lack of data, the recreational catch was ignored in this assessment. However, it should be acknowledged that some numbers of recreational anglers in

Queensland and New South Wales do catch sea mullet using bait and cast nets.

In 2001 the Queensland recreational harvest of all mullet species was estimated to be about 1.85 million fish (calculated from 2001 recreational fisher diaries). No data on the different mullet species caught were available. In 1997, the use of bait nets and cast nets in Queensland recreational fisheries was studied (McPherson et al. 1999). The southern Queensland data suggested that bait and cast net catches constituted about one thirdof all mullets caught. This fraction was surprisingly high and may be a product of the small number of sampling locations and recreational fishers surveyed. Further catch surveys are required to quantify the mullet species composition in the relatively small recreational catch.

2.2.6 MANAGEMENT

In Queensland a limited entry ocean-beach licence regulates the targeting of the spawning run of sea mullet. There are currently 62 operative licences that allow their holders to deploy ocean beach haul (seine) nets from April to August each year (Williams 2002).

In 1995, New South Wales licensed the ocean beach sector of the fishery, restricting participation to fishers who could demonstrate historical participation. A similar restriction was placed on the estuarine sector in 1997 (Smith and Deguara 2002). The ocean beach sector in New South Wales is partitioned into one degree latitudinal bands that licence holders are designated. Various spatial and temporal closures in both the ocean beach and estuarine sectors exist and designed to minimise conflict between operators.

In both States the minimum legal size for sea mullet is 30 cm total length.

3 DATA

The objectives of the analyses were largely dictated by the quality, quantity and resolution of the available data.

3.1 AVAILABLE INFORMATION

An important early goal of the project was to catalogue the data and assess the quality and quantity of the information available. Broadly, the types of data that were considered for this assessment were biological, catch and effort, tagging and pricing data. A description of each type of data and the source of each type of data follows.

3.1.1 BIOLOGICAL

The biological data used for the assessment was acquired from different sources in both States and is quite comprehensive:

- Queensland 1995–1996: These data were sourced from excel files from the work conducted by Ian Halliday in his contribution to the FRDC report 94/024 (Virgona et al. 1998).
- Queensland 1999–2003: These data were sourced from the Long Term Monitoring database system (DPI&F).
- All New South Wales data were sourced from the New South Wales Long Term Monitoring program, which has been updated to include the New South Wales component of the data collected in the FRDC 94/024 project.

Important biological statistics in the data include:

Fork Length The length of each fish was measured as the distance from the tip of the snout to the caudal fork. The resolution is either at 5 mm (Queensland samples) or 1 cm (New South Wales).

Age The fish were aged by a count of otolith rings. The otolith is an ear bone that grows larger as the fish ages, and is marked with a distinct ring each year (similar to rings in trees). Ageing was done by taking a cross section of the otolith and counting the number of rings using a microscope. In the past, scale rings have been used for ageing (Grant and Spain 1975), though these have been shown to yield consistently different estimates of age compared to otoliths (Smith and Deguara 2002).

Weight The weight of each fish was measured in grams.

Sex The sex was recorded for most fish; note that it is difficult to distinguish sex in immature fish.

The long term monitoring program in New South Wales differs from the Queensland program. New South Wales' data also includes:

- sample weight relative to landing weight,
- fishing method and net size for each sample,
- samples from both estuarine and ocean beach-fishing, and
- sex for many measured fish lengths rather than just for those fish that had been aged.

There are no data from Queensland estuaries in the Long Term Monitoring database. As discussed in section 2.2.4, the estuarine component of the Queensland catch is small compared with the ocean beach component, whereas a significant catch is taken from estuaries in New South Wales. This explains the difference in monitoring between the two States. However, for modelling purposes (as detailed later), the New South Wales data have been drawn on heavily in order to include Queensland estuarine catches in the model. As discussed in Chapter 7, data from estuarine sampling in Queensland would be valuable for modelling the stock in future.

Though sex ratio information is available with the age samples, the sex records in the length data from New South Wales are valuable in that they provide a more robust indication of the behaviour of the sex ratio over time in different parts of the fishery. Note that the sex ratio is of special interest in the roe-driven mullet fishery.

3.1.2 CATCH AND EFFORT

The following sources of catch and effort data were used in this assessment:

- The Queensland compulsory logbook records begin in 1988. The data contain *daily* entries in which fishers have recorded their gross haul of mullet in kilograms. Note that some of the records cover more than one day though this is uncommon. The data used here were from 1988 to 30thJune, 2003.
- The New South Wales logbook records begin 1st July 1984. They contain *monthly* entries. The data used here were from 1st July 1984 to 30th June, 2003.
- The Queensland Fish Board historic catch data dates from 1936 through to 1981. These records do not contain information on fishing effort.

Each record in the logbook data contains information on some (usually all) of the major statistics below:

Catch — The weight of the landing in kilograms. Note that some Queensland records do not show the ‘whole’ weight but instead show the fillet or trunk weight (i.e. the weight of the landing once it has been partially or completely processed). A simple conversion factor was applied to these catches to scale them to equivalent whole weight. The conversion factors used in the commercial logbook database were:

- Fillet weight to total weight : multiply by 2.2
- Trunk weight to total weight : multiply by 1.4
- Gilled and gutted to total weight: multiply by 1.1

Date — This was given as a start and end date in the Queensland records, for example Start: ‘26/04/1996’ Finish: ‘26/04/1996’. The New South Wales records contain the month of operation, for example ‘199604’ meaning April 1996.

Location — The location of fishing operations was reported at a resolution of 30 minutes by 30 minutes ($30' \times 30'$) for most Queensland catches, though a resolution of 6 minutes by 6 minutes ($6' \times 6'$) was recorded for some catches. The location of ocean beach operations in New South Wales was reported at a one degree latitudinal resolution (recall the ocean beach fishery in New South Wales is partitioned into one degree ‘bands’). New South Wales estuarine catches were reported spatially according to the estuary in which the operation took place.

Gear Type The fishing gear used by the operation was recorded as text and/or code, for example 'Gillnetting'.

Boat ID Each record contains a vessel identification ('boat ID') specifying the vessel involved in the operation.

Days of Effort In the Queensland logbook database effort is recorded daily, and in some cases on individual seining operations. In New South Wales effort is recorded as the number of days fished per month.

3.1.3 TAGGING

Tagging studies were conducted by Kesteven (1953) and Virgona et al. (1998). Although not used herein, there may be ways of using the tagging data to estimate key population parameters in future assessments of the fishery (see Professor John Hoenig's review in Appendix 10.8).

3.1.4 PRICING

It was hoped that detailed data on the behaviour of the commercial market for mullet would be easily obtainable, but this was not the case. The mullet fishery is heavily market driven, and there is testimonial evidence that mullet fishermen will often deliberately not fish an available school, choosing instead to look for different species if the market price is too low. Such economic impacts would be useful to include when modelling the fishery.

3.2 DATA QUALITY I: BIOLOGICAL

A sea mullet is much easier to measure than it is to age. As such, the available biological data were made up of tens of thousands of fish length measurements from each year, with approximately 30% of these samples also containing age, sex and weight data.

Table 3.1 indicates the quantity of age and length data available from each State and location for each year. Not shown in Table 3.1 are the quantities of corresponding sex and weight data, which were present for most of the fish that were aged. Note that for every year since 1995, except 1997 and 1998, the data quality is quite robust from each State and includes age, length, sex and weight.

Table 3.1 A summary of the available biological data for eastern Australian sea mullet. Note that no data on mullet ages were available prior to 1995. The number of fish aged is shown in italics and the number of fish measured for length is shown in non-italics. Numbers underlined indicate data that were excluded from the analysis (see section 3.2.3).

Year	New South Wales Ocean-beach		New South Wales Estuarine		Queensland Ocean-beach		Queensland Estuarine	
1995	*496*	2493	*1371*	5408	*525*	2528	*556*	2165
1996	*474*	1202	*581*	3795	*475*	2401	*680*	3337
1997	*55*	10292	-	952	-		-	
1998	*818*	2961	*1405*	4507	-		-	
1999	*641*	4775	*408*	1654	*596*	2205	-	
2000	*684*	4389	*835*	3252	*600*	1798	-	
2001	*1121*	3941	*1448*	3676	*597*	2092	-	
2002	*737*	2440	*262*	543	*599*	2100	-	
2003	*217*	1657	-		*500*	1345	-	

3.2.1 SEX RATIO

The sex ratio of the catch differed between the estuarine and ocean beach sectors. Figure 3.1 shows the proportion of female fish observed for each length (relative to the total number of fish measured at each length for which sex was determinable). Proportions for lengths under 250 mm were set to an assumed value of 0.5 due to limited data at these lengths. Note that more fish at smaller lengths were male from ocean beach catches. Figure 3.1 also indicates that females are generally capable of growing much larger than males. The overall sex ratio varies from year to year (Figure 3.2). In the catches sampled, males generally outnumbered females in both sectors. Hwang et al. (1990) also observed this in their stock assessment of the Taiwanese mullet fishery.

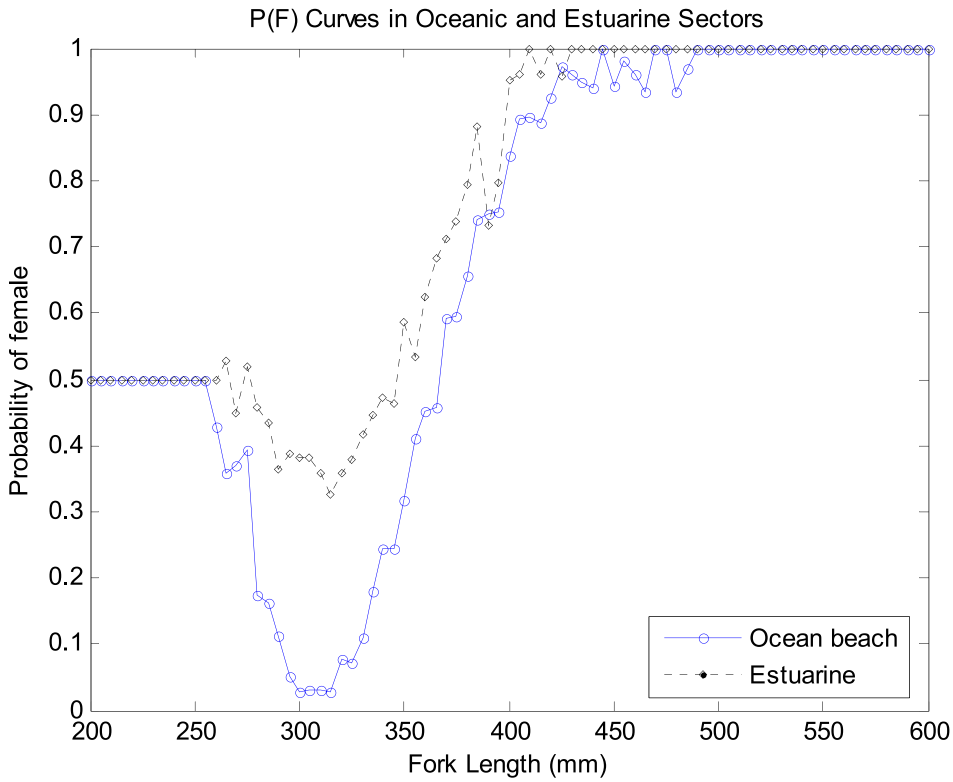


Figure 3.1 Sex ratios (i.e. the proportion of female fish caught) from the ocean beach (solid blue) and estuarine (dotted black) sectors for each length class.

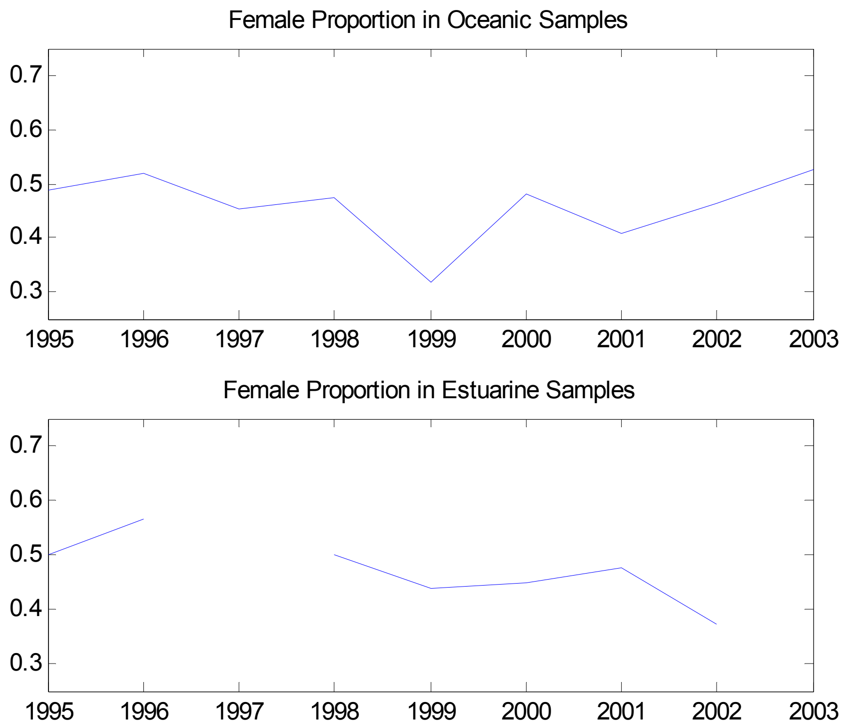


Figure 3.2 Female proportions in the ocean beach (oceanic) and estuarine sectors.

3.2.2 AGEING LOGIC

As described in section 3.1.1, age was measured by otolith rings. Historically, it has been thought that the first otolith ring is laid down when the fish is between 6 and 18 months old. More recent literature suggests that the timeframe is closer to 18 months. Smith and Deguara (2002) state that the first clear ring is not even visible commonly until around 22 months. We know that spawning occurs in winter and that all fish will be born during the middle of the year. Given that the first ring is not laid down until the fish is around 18 months old, a reasonable assumption is that the fish become 'one ring-olds' at the end of the calendar year following the year of birth. Note that by working this way the 'birthday', i.e. the day the fish move from one age class to the next, occurs at the very time that the catch is at its lowest during the year. As such, the uncertainty in ageing will be kept to a minimum during the dominant fishing (and sampling) activity occurring in winter. The simple statement for this logic is:

> 'Fish develop their first otolith annulus (ring) on December 31st of the calendar year following their year of birth. Subsequent rings are laid down on the same day each year until death.'

There has been no definitive study of the time between hatching and the formation of the first otolith ring. It is recommended that this process be verified in more detail.

In the catch-at-age analysis presented later, age classes were defined according to ring count directly, so any confusion about the ring-to-age conversion was generally avoided. From this point on, unless otherwise stated, 'age class one' refers to fish with one otolith ring, 'age class two' to fish with two otolith rings, and so on.

3.2.3 AGE AND LENGTH STRUCTURE

The age frequencies are shown in Appendix 10.1. Note that the age of each mullet was defined by its ring count (see section 3.2.2).

There was a very strong cohort of age class 4 in 1995 (Figure 10.1). Note that the cohort can be seen moving through the following years, with high proportions of class 5 in 1996, and class 7 in 1998 for the New South Wales ocean beach sector (Figure 10.2).

The age frequencies from Queensland in 1996 contain a marked deviation from the pattern in other years and in New South Wales in 1996, particularly in the large (45%) age class one observed in Queensland's estuarine fish. This difference was considered too distinct to be explained by random variation. The Excel file containing the Queensland age data in 1996 appears to have been modified under some ring-to-age algorithm that may have distorted the data slightly. It was decided to exclude the Queensland 1996 age data from the analysis.

The age data play a vital role in indicating the change in age structure of the population over time. Even before a quantitative assessment is made, one can immediately see a concerning shift in age structure in recent years (2001 to 2003), in which the demographic seems to be shifting sharply toward a higher proportion of older fish. It will be shown in the catch-at-age results presented later that this shift is likely to have been caused by poor recruitment in recent years.

Length frequencies are shown in Appendix 10.2. Note that the Queensland length frequencies were measured at a 5 mm resolution. However, this resolution does not appear to have been used during the entire sampling process, as illustrated in Figure 10.3. For simplicity, the length frequencies have been rounded to whole centimetres so that visual comparison is easier. However, the non-rounded data were used in the catch-at-age analysis.

The length frequencies from New South Wales in 1997 are included in Appendix 10.2. Note the unusual estuarine component with large fish in comparison to ocean beach activity (Figure 10.4). Coupled with an almost complete lack of age data in 1997 (55 fish aged in total), it was decided to completely exclude biological information from 1997 in the analysis.

Notice the distinct age and length differences between the ocean beach and estuarine samples. The estuarine sea-mullet were generally much younger and smaller. This is not surprising because mullet are known to recruit to and develop in estuaries before moving out to the ocean to spawn when mature, and therefore the differences between sectors were expected.

3.2.4 MISSING DATA

As shown in Table 3.1, there were several spatio-temporal regions in which there are no data available. The following assumptions were used in the analysis:

1997	The almost complete lack of age data in 1997 was considered too severe for cohort behaviour in that year to be captured accurately in the catch-at-age analysis. As such, no growth data from 1997 were used.
1998 Queensland ocean beach	New South Wales ocean beach sampling in 1998 was assumed for this component.

2003 estuaries There were no estuarine data at all in 2003. New South Wales estuarine samples from 2002 were used for both States in 2003. This is probably the most influential data correction because it implies that the length structure is not changing in estuaries between 2002 and 2003.

Queensland estuaries Where estuarine data from Queensland were missing, the age-length key and length frequency distribution from New South Wales estuarine sampling in the same year were used.

Summer All Queensland monitoring and most New South Wales monitoring samples are taken in winter so there is little information about the structure of the sea mullet population in summer. Estuarine samples were therefore used for this component.

3.3 DATA QUALITY II: CATCH AND EFFORT

3.3.1 LOGBOOKS – RECORDS OF THE CATCH AND EFFORT

Logbooks contain records of the fishing activity on a monthly basis in New South Wales and on an operational (≈ daily) basis in Queensland. The integrity of the logbook records is generally thought to be very good. However, intentional and unintentional misreporting of catch is a fundamental uncertainty that cannot be dealt with easily. For simplicity, the analysis assumes that all records were accurate.

It is very common for a fisher *not* to make a logbook data entry when they have spent the day fishing but not caught anything. This is a serious problem as it leads to the implication that a catch is landed whenever a fishing operation takes place, which will indicate a higher abundance than what is present in reality. This is a significant issue for sea mullet and other schooling fish, such as tailor and spotted mackerel.

The fishing gear recorded in the Queensland logbook database contains errors in some places. These have been addressed by the application of a conversion algorithm by Dichmont et al. (1999).

It is known that licence holders in the ocean beach sector will often work together to maximise efficiency and ensure a fair share of landings. This practice has developed to counter the fact that licences are generally spatially specific, and that landings can often be extremely localised (one fisherman taking the bulk of the catch despite several nets being cast along the coast by other licence holders). The effect of this activity on conceptual fishing effort is difficult to determine. It is generally thought that the effect should be minimal since the same number of licence-days and the same amount of catch is recorded regardless of whether the fishermen work together or not.

Some of the New South Wales records exceed 31 days of effort (recall that the New South Wales logbooks contain monthly records). This presumably results either from the effect of teaming (i.e. the days of effort are multiplied by the number of vessels in the team that month) or from logbook entry error (i.e. the fisherman logs several months of work in a single month). In this instance effort was truncated to the maximum number of days in the month (i.e. 31 for January, 30 for April, etc).

3.3.2 CATCH DATA

Long-term trends in total reported mullet landings from Queensland and New South Wales peaked in 1995 at approximately 7900 tonnes (Figure 3.3). For the period 1990–2003, inclusive, the average total reported landings of sea mullet from New South Wales was 3809 tonnes and from Queensland was 2030 tonnes.

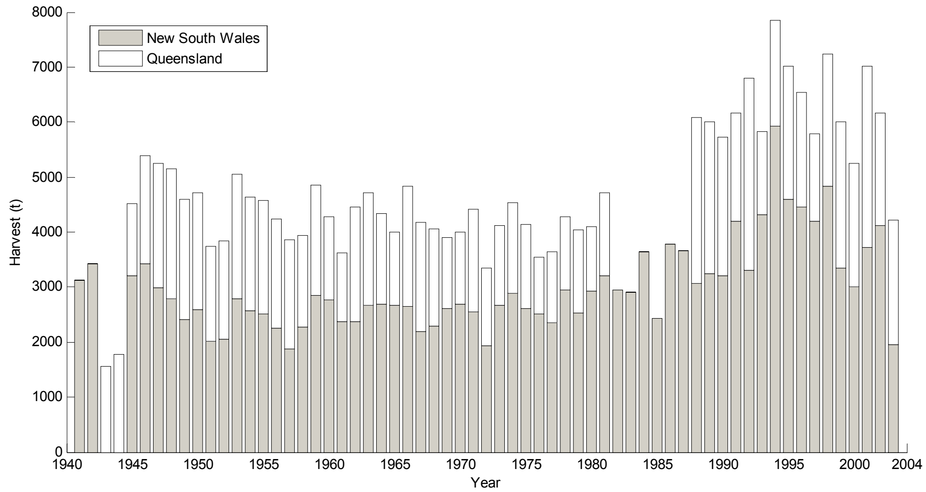


Figure 3.3 Total reported annual harvest (tonnes) from Queensland and New South Wales waters. No records were available on total catch in 1943 and 1944 from New South Wales and between 1982 and 1987 from Queensland. No breakdown of ocean beach versus estuarine catches was available prior to 1984. Data for 2003 may have been incomplete for one or both States at the time the logbook data were requested for this study.

In Queensland, most of the catch was landed from the southeast corner of the State between 26^o and 28^{o}S, while large catches of mullet are taken from an extended section of the New South Wales coastline between 29^o and 34^{o}S (Figure 3.4).

Due to the marked difference in the harvest age-structure between ocean beach and estuarine sea-mullet, it was decided to identify each entry in the logbook records as having taken place in one of these two sectors in order to accurately apply stock removal to the correct population in the catch-at-age analysis. This was accomplished for the records in each State as follows:

Queensland The Queensland operations are recorded in spatial logbook grids at a resolution of 30 minutes by 30 minutes (6 minutes by 6 minutes in some cases). Each grid was flagged as either ocean beach, estuarine, or both (the 30′×30′ grids often contain both ocean beaches and estuaries). The flags were attached to each record using simple database queries.

New South Wales The spatial resolution of the New South Wales logbook data is recorded on one degree latitudinal bands across the coastline, but also recorded are the names of coastal regions (i.e. Clarence River, Tuggerah Lakes, etc) where fishing operations occur. A simple string comparison test was applied to the recorded name to assign sectors to each New South Wales record.

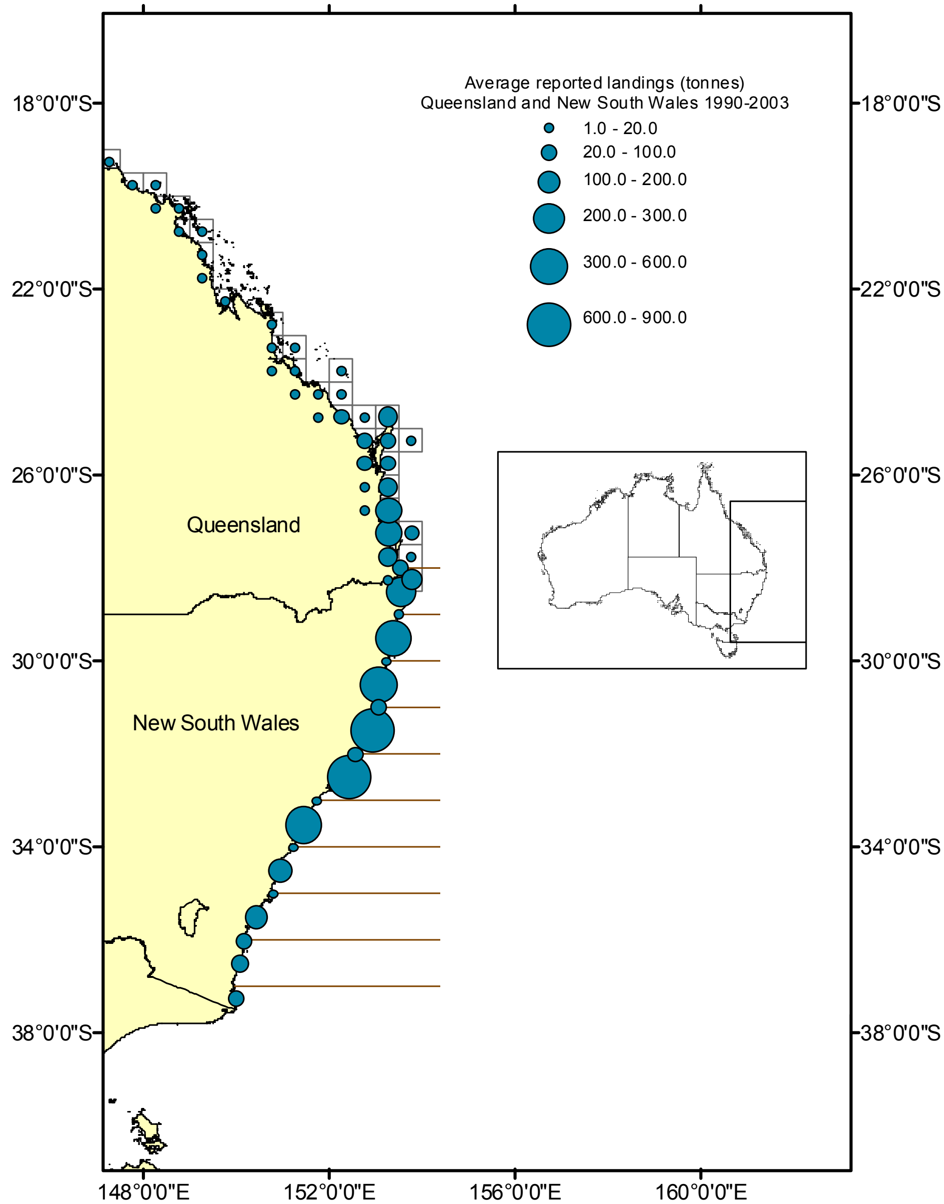


Figure 3.4 The average reported logbook landings for mullet from Queensland and New South Wales for the period 1990–2003, inclusive. The Queensland CFISH logbook database records catch and effort on a 30 minute by 30 minute grid system (although finer scales of 6 minute by 6 minute have been adopted in recent years). The New South Wales logbook database is mainly based on one degree latitudinal bands across the coastline, although some regional names are also used to spatially define landings. Average reported landings of less than one tonne have been omitted for clarity.

The New South Wales data indicate that catches from the ocean beach sector increased markedly from 1985 to a peak in 1994 of about 3500 tonnes (Figure 3.5). In recent years (1995–2002) landings from the estuary and ocean beach have been similar in New South Wales. In contrast, the ocean beach sector has consistently dominated estuarine landings in Queensland by a ratio of about 20:1 (Figure 3.6).

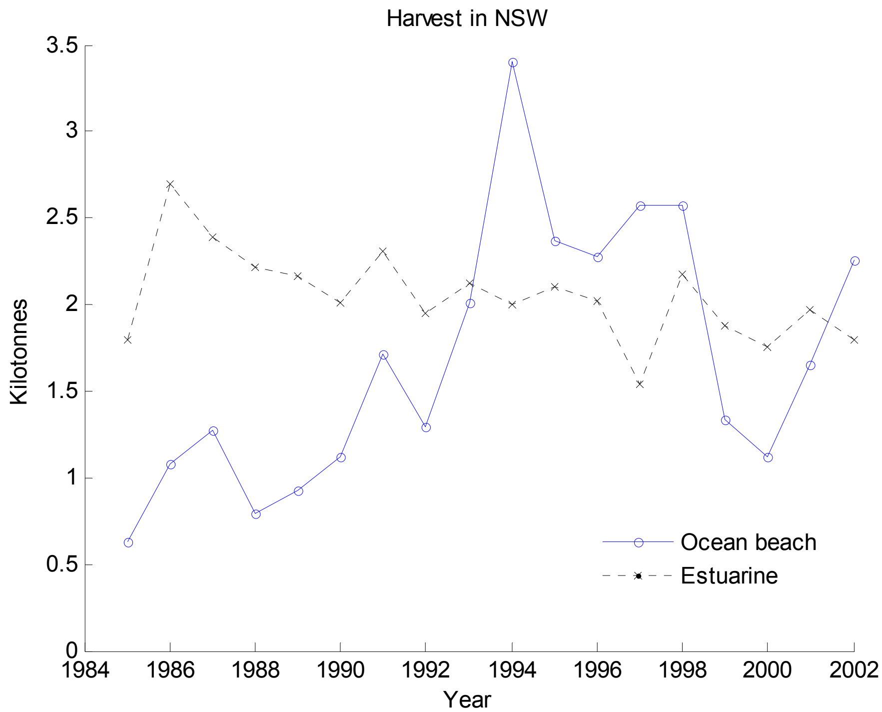


Figure 3.5 Total annual harvest from ocean beach (oceanic) and estuarine waters in New South Wales.

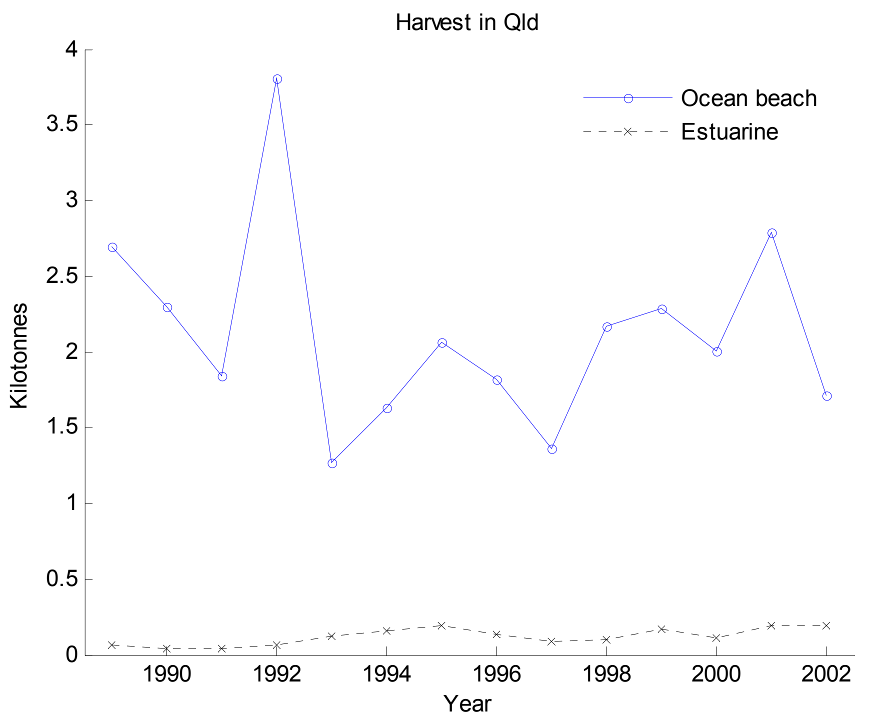


Figure 3.6 Total annual harvest from ocean beach (oceanic) and estuarine waters in Queensland. The catch records for which the sector is uncertain have been added to oceanic catch.

All Queensland monitoring and most New South Wales monitoring samples are taken in winter so there is little information about the age structure of the sea mullet catch in summer. Rather than assuming that ocean beach catches in summer (which may be targeting the hardgut run) will have the same demographic as the winter spawning run, the model applies estuarine biological data to these catches. As such, the two distinct catch sectors are redefined into two domains, 'IN' and 'OUT', referring to in and out of the open ocean beach season. That is:

IN Operations between April and August in Queensland and March and July in New South Wales count as exploiting the 'IN' population (which is drawn from the fish taken during the spawning run migration).

OUT Anything outside 'IN'. All estuarine catch falls into this category, as do ocean beach operations carried out during summer. The population being exploited is drawn from the estuarine fish.

3.3.3 EFFORT DATA

What work do mullet fishers do to catch fish? When fishing in estuarine waters for mullet and other species, searching for fish and setting/hauling nets could be considered the 'hard part'. It is generally thought that in the ocean beach haul net sector that the real work in catching mullet is in searching for mullet schools. The act of actually encircling the net around the school and hauling the net in is really just a consequence of the spotting effort.

Fishing operations in which mullet were caught were either:

1. Directed specifically at taking mullet. It is likely that records of ocean beach operations in winter in which large catches were taken can be classified as generally falling into this category.
2. Directed at mullet as well as other species (the fisher is not targeting a specific species).
3. Not directed at mullet at all. Mullet landed under these circumstances are referred to as 'by-product' or incidental catch.

There are many algorithms that can be applied to catch records to distinguish genuine targeting effort from 'accidental' effort. For example, one could say that if the landing was less than 50 kg, the fisherman was unlikely to have been targeting mullet assuming he had some degree of experience. However, this introduces uncertainty. What if the fisherman was a seasoned veteran and spent all day fishing but caught less than 50 kg because of a lack of fish? In this analysis all operations are assumed to have the same targeting status. This decision is not based in lethargy but in a reluctance to confound the data by introducing a targeting algorithm, which may only increase uncertainty and/or error in the results.

Schooling is a phenomenon which gives rise to the problem of hyperstability, in which catch rates remain high while the fish abundance drops (Hilborn and Walters 1992). This is because species which school are easier to catch than those that do not. As such, the CPUE is a poor index of abundance for schooling species because one observes a high catch rate in schooling species even when the population is in decline. When abundance is low the fish reform into high-density schools (Hilborn and Mangel 1997). The ocean beach sector directly targets schools of spawning migrating mullet (schools also form during the hardgut run), making this issue a very real problem in the definition of effort in this fishery.

In addition, fishing activity becomes more efficient with time. Boats are upgraded with better fishing gear, more powerful propulsion systems and so on. This process is called 'technology creep'. It presents a problem when defining effort because it means a day of fishing now is not equivalent to a day of fishing 50 or even 20 years ago. The most important technology upgrades the fleet has undergone include:

- Jet boats introduced, increasing effective effort by possibly 20% (Dichmont et al. 1999). This mainly occurred prior to and in 1986.
- CB radios and other communication devices. This occurred prior to 1986 but has improved over time (Dichmont et al. 1999).

The catch-at-age analysis makes use of catch records from 1988 to present, as such the above technology is not deemed to have had any serious effect on the data being used. It is assumed in the model that no other significant technological creep has occurred since 1988. Note that in order to include historic catch data one would need to account for technology creep mathematically.

The impact of targeting, lack of zero reporting, misreporting, hyperstability and the other factors mentioned above complicate the definition of effort. For example, genuinely non-targeting operations that are treated as normal targeting operations will cause the model to predict that fewer fish are available than in reality (i.e. no real effort went into catching the fish in reality, but the model is claiming that the effort was at the standard targeting level regardless, thus under-estimating abundance). By comparison, the missing records in which genuine fishing effort yielded no catch (lack of zero reporting) will cause the model to predict higher availability than reality (i.e. the model claims that catch is always landed whenever a fishing operation takes place, thus over-estimating abundance).

There are several possible ways to define effort. These include:

1. Measure effort as the number of operation days for all types of fishing activity.

$$\text{effort} = \text{number of operation days}$$

2. Including an ‘effort shift’ parameter that could increase or decrease the effective effort in each record depending on its perceived susceptibility to the uncertainties above.

$$\text{effective effort} = (\text{operation days}) \times E_{\text{SH}}$$

   A careful study would be required to accurately quantify how severely the uncertainties above distort each record in the logbook. That is, accurately defining the E_{SH} parameter would be very difficult.

3. It could be assumed that licence holders will operate their vessels whenever they can. Effort could thus be defined each year as the

$$(\text{number of registered vessels}) \times \\ (\text{number of open season days - number of bad weather days during open season})$$

   Effort outside the licensed fishery would need separate consideration.

In this analysis un-standardised effort was measured in operation-days for all types of fishing activity.

Aside from the issues in effort definition discussed above, there remains a need to determine how different *types* of effort compare to each other in their ability to yield catch. It is expected that more fish will be taken from a haul net operation in winter than from a gillnet in summer — the question is how much more? What other circumstances or factors contribute to the effectiveness of each type of effort? These questions are addressed by standardisation of the catch and effort data (see section 4.2.4).

3.3.4 CATCH RATES

Trends in un-standardised catch rates (or catch-per-unit-effort, CPUE) can be observed in Figure 3.7 and Figure 3.8.

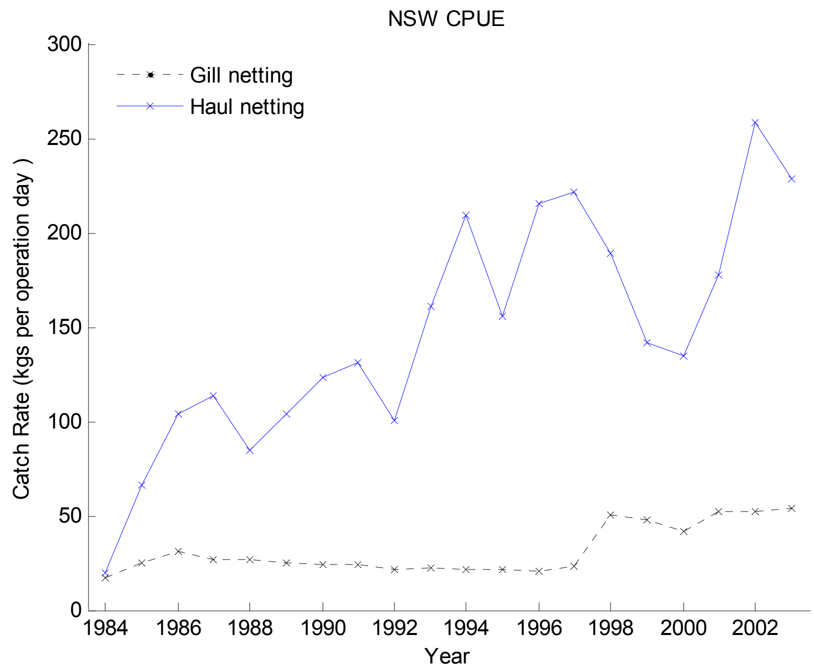


Figure 3.7 Un-standardised catch rates from New South Wales.

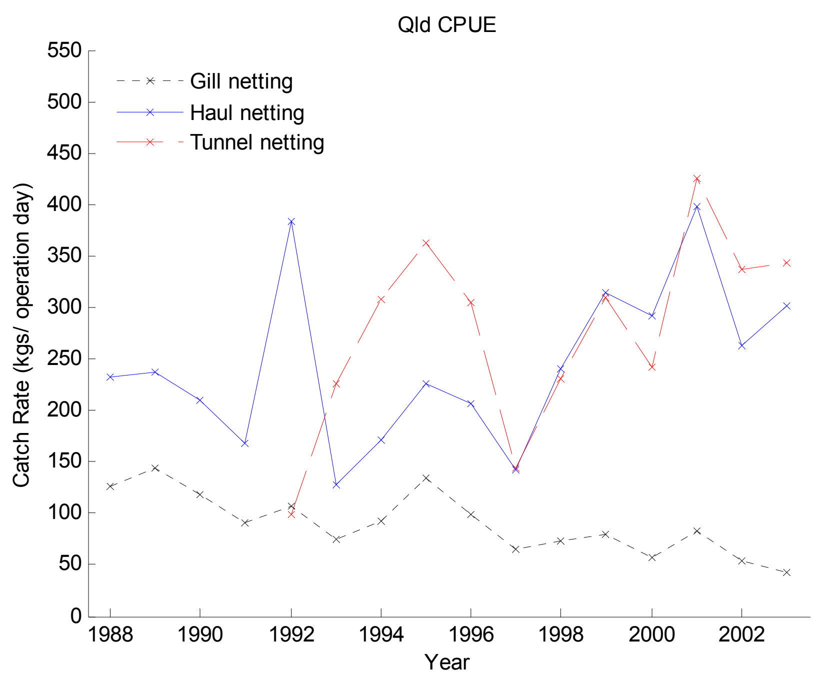


Figure 3.8 Un-standardised catch rates from Queensland.

Figure 3.7 and Figure 3.8 can be misinterpreted unless one is careful to consider the contribution of each type of effort. Gill and haul netting typically account for more than 99% of the catch in New South Wales and more than 90% in Queensland. As such, the difference between these lines (gillnetting and haul netting respectively) is of the most importance.

Notice how the gillnetting catch rate makes a marked jump in 1998 in the New South Wales records while the Queensland gillnet catch rate is in steady decline. This is a serious anomaly in the data sets between the two States. Smith and Deguara (2002) examined the catch data in New South Wales, and offer some telling facts that may account for this:

> "… the format of monthly fisher returns was altered in 1997–98. These changes are likely to have affected catch and effort statistics, although the nature of the effects are unclear".

Smith and Deguara (2002) employed a detailed algorithm to isolate experienced, targeting fishers in order to compute the trend in CPUE in estuaries, and arrived at the conclusion that catch rates in most estuaries are steady or in mild decline in New South Wales. As such, the increase in apparent catch rate in New South Wales in 1998 is deemed not to have resulted from an increase in abundance but from a change in the format of effort reporting. See 4.2.4 for details on how this problem was dealt with in the standardisation process.

4 STOCK ASSESSMENT METHODS

Three quantitative mathematical models were applied to assess the sea mullet stock in its entirety. These were:

1. Paloheimo's catch-at-age model (Hilborn and Walters 1992) with a few modifications. This model used catch, effort and biological data from 1995 to 2003, as 1995 is the first year that age frequency data were available. In the model, a single estimate of the instantaneous rate of natural mortality (M = 0.33 per year) was used. As catch and standardised effort were available for all of these years, standardised catch-per-unit effort (CPUE) was incorporated in the model.
2. An age-based model similar to that applied to the Queensland tailor fishery (Leigh and O'Neill 2004). This model used annual reported catch from both States from 1945 to 2003. It also considered a range of natural mortality rates (M = 0.33, 0.40 and 0.5 per year). CPUE did not correlate with the changes in the population that were apparent from the age frequency data (Figure 10.1) and therefore was not included in this model.
3. The virtual population analysis (VPA) model from Punt (1992). This model used the catch and standardised effort data from 1995 to 2003, and a single estimate of the rate of natural mortality (M = 0.33 per year). This model was used to estimate a total allowable catch (TAC) for the fishery.

4.1 MODELLING THE SYSTEM

The mullet fishery forms a very complex system, driven not only by population behaviour and fishing activity but also by environmental and economic forces. The quantitative assessment of such a rich system could thus be approached on many different levels of complexity. Major components and considerations include:

- Population dynamics (i.e. behaviour of the fish)
  - Spawning, recruitment, growth and death
  - Movement (e.g. spawning runs)
  - Location influences
- Fishing activity
  - Timing of fishing
  - Location of fishing
  - Economic influences on fishing
- Environmental effects
  - Seasonal and annual climate change (e.g. rainfall)
  - Agriculture and pollution
  - Ecosystem interactions

The most important biological feature of any fishery is the dynamics of the fish population (Hilborn and Walters 1992). The behaviour of the mullet stock itself is the major component of the work herein. Given the known biology, mullet have different age and length frequencies in different locations. Though the impact of the movement of sea mullet was considered from several angles, this assessment does not seek to quantify movement directly. However, temporal effects on abundance were considered.

Obviously, the behaviour of the fishing activity that exploits the mullet population needs consideration in any quantitative assessment. Dividing the assessment and fishing activity into spatial regions was an important priority identified early in the project. Given the strong export market for roe and the low fillet value per unit weight, economic forces are deemed to have a significant impact on the behaviour of the sea mullet fishery. However, adequate data on this component of this system was not available for this assessment.

4.2 MODIFIED PALOHEIMO'S CATCH-AT-AGE MODEL

Essentially, this model estimates parameters of interest (e.g. recruitment) by minimising the difference between the observed and predicted catch at each age. The observed catch is calculated from the available data using the methods discussed in section 4.2.3. The model uses a modified Paloheimo's catch-at-age equation to predict the catch. Paloheimo's catch-at-age analysis for multiple cohorts is described in Hilborn and Walters (1992). Only the modifications to this analysis are discussed here (in section 4.2.1). The estimated values are then used to calculate current and virgin biomass.

4.2.1 MODIFIED PALOHEIMO'S CATCH EQUATION

In Paloheimo's derivation, the annual fishing mortality rate is assumed to be proportional to the fishing effort. However, a modification has been made to include the selectivity (section 4.2.5) or vulnerability of a fish to fishing at a particular age. The relative number of fish of age a that are killed by fishing in year j is proportional to the selectivity of the age class. That is,

$$F_{ja} = qE_jS_a \tag{4.1}$$

where F_{ja} is the fishing mortality in year j for fish of age a, q is the catchability co-efficient, E_j is the fishing effort in year j and S_a is the selectivity of fish at age a.

In the interest of linearising the catch-at-age equation, Paloheimo (1980) and Hilborn and Walters (1992) used an approximation that was reasonable whilst the instantaneous rate of total mortality (Z) was low. The following slightly different approximation was used as it more closely approximates the left hand side without over-estimating for lower values of Z (see Appendix 10.4 for the rationale behind this modification).

$$\log_e\left(\frac{1-e^{-Z}}{Z}\right) \approx -\frac{Z}{2.05} \tag{4.2}$$

Upon close examination of the age frequencies (Appendix 10.1) it was noted that fish in age-class zero were seldom caught anywhere in the fishery. The proportion of zero ring-old fish caught compared to the number of zero ring-olds in the population is deemed so small that in this model, recruitment to the sea mullet fishery first occurs at age class one. In their virtual population analysis of the Taiwanese sea mullet fishery, Hwang et al. (1990) also exclude fish in age class one, claiming recruitment occurs at age class two. However, the catch of one ring-olds in the age frequencies herein is deemed significant enough for inclusion. Note that it is assumed that the one ring-old fish become recruited to the fishery on January 1st each year and so are vulnerable to fishing for the entirety of their first recruited year. This results in a modification to:

$$N_{1y} = R_y \tag{4.3}$$

where N_{1y} is the number of fish aged 1 in year y and R_y is the number of recruits for this age (i.e. the number of fish aged one that would continue to grow and age if there was no mortality in the intervening years).

With these modifications (equations 4.1, 4.2 and 4.3), Paloheimo's catch-at-age equation becomes

$$\log_e\left(C_{ja}\right) = \log_e\left(R_{j-a+1}\, q\, S_a E_j\right) - q\left(\sum_{k=j-a+1}^{j-1} S_{a-(j-k)} E_k + \frac{S_a E_j}{2.05}\right) - M\left(a - \frac{1.05}{2.05}\right) \tag{4.4}$$

where j is the year, a is the age of the fish, C_{ja} is the number of fish aged a caught in year j, and M is the instantaneous rate of natural mortality (year^{-1}). The equation is valid for $a \geq 1$. Note that cumulative mortality and recruitment begin at '+1' in the equation to account for the fact that individuals are recruited to the fishery at age class one and not at age class zero as in the un-modified version.

4.2.2 FITTING THE MODEL

A regression on the catch-at-age equation was used to fit the model. The criteria for model fitting was log least squares as described by Haddon (2001). We minimised SSQ_C:

$$SSQ_C = \sum_a \sum_j \left[\log_e\left(C_{ja}\right) - \log_e\left(\hat{C}_{ja}\right)\right]^2 \tag{4.5}$$

where $\hat{C}_{ja}$ is the predicted catch and C_{ja} is the observed catch, a is the age and j is the year. We used a modified Paloheimo catch equation to formulate the logarithm of the predicted catch (see section 4.2.1). The Matlab function 'nlinfit' was used to minimise equation (4.5) by the Gauss-Newton method.

Note the imposition of lognormal errors on the catch predictions as opposed to normal errors. This makes logical sense because a given error in low catch predictions (older fish) is typically more detrimental than the same absolute error in high catch predictions (younger fish). By taking the logarithm, all errors become relative and comparable. Log-catch output also makes negative catch predictions impossible, which is desirable (Haddon 2001).

The number of fish in age class 9 and over was very small. In fact only around 50 of the 16 000 measured fish were in this age bracket. A problem arose when fitting to these ages because of the very low resolution. That is, the model fitting process, by applying logarithms, sees a relatively large error in predicting; for example, predicting one 10 ring-old fish against an observation of say two such fish. This is of course not desirable, so fish aged older than 8rings-old were omitted from the model fitting process. Note that the predictions were still made for these ages for the biomass calculation. The result of this is the removal of several data points from the model, but an improvement of the relative resolution of the data available for the other age classes (for which there was a large number of fish). If appropriate weighting of data points with low granularity were possible, the older classes may be able to be included in the regression. An algorithm for adequately weighting low observations was not explored.

4.2.3 OBSERVED CATCH

The observed catch (numbers of fish) for the model to compare against its predicted catch was constructed using the information available on growth and catch weight from each year. Remember that the catch data did not contain age information and so couldn't be simply aggregated within a given age class. The data available to be used in the calculation of catch at each age was:

1. weight of fish caught from the logbook data;
2. length frequencies from each zone from the biological data;
3. length at age relationship from the biological data; and
4. weight at length relationship from the biological data.

The biological data was used to form relationships that allowed logbook catches (weight of fish) to be transformed to catch-at-age (numbers of fish) as required for the model described in section 4.2.2. This section develops these relationships and describes how they were combined to transform the catch weights to numbers of fish caught.

4.2.3.1 DEFINITION OF A ZONE

The catch of 1 to 13 ring-old fish each year in each fishing domain (recall that 'domain' refers to the IN/OUT distinction discussed in section 3.3.2) is computed as follows:

$$C_{ja} = C_{ja,IN,Qld} + C_{ja,OUT,Qld} + C_{ja,IN,NSW} + C_{ja,OUT,NSW} \tag{4.6}$$

where C_{ja} is the catch of each age class in each year as required for equation 4.4, $C_{ja,d,s,}$ is the contribution from fish caught in the *d* fishing domain and in the *s* State, *d* is either IN or OUT, and *s* is either Qld for Queensland or NSW for New South Wales.

Fishing 'zones' are defined for convenience of explanation below for each State, domain and year. For example, the 1995-IN-NSW fishing zone is distinct from the 2001-OUT-Qld fishing zone. So,

$$(\text{year}, \text{domain}, \text{state}) \equiv (\text{zone})$$

or symbolically,

$$(\text{j}, \text{d}, \text{s}) \equiv (\text{z}).$$

4.2.3.2 RELATIONSHIP BETWEEN LENGTH AND AGE

Given the shortcomings of applying von Bertalanffy growth (see Appendix 10.3) and the huge variation of length at age (notice the large scatter in length for each age in Figure 10.5), an appropriate means of defining an age-length relationship was the next objective of the analysis. An age-length key was built such that each length class is defined in a row and each age class is defined in a column. The contents of the table were proportions indicating how many fish relatively, from each age, contribute to observations at each given length. Table 4.1 illustrates this principle.

Table 4.1 A hypothetical example of an age-length key.

Length (mm)	Age Class 0	Age Class 1	Age Class 2
300	0.5	0.5	0
310	0.4	0.4	0.2
320	0.3	0.4	0.3

Note that in an age-length key, all rows sum to 1. This is because each length must be divided into all age classes; *i.e.* the age range in the key covers all possible ages of the fish that have been aged.

In the ageing process, otolith rings were often counted more than once by different people to minimise errors in the process (*i.e.* multiple ageing of a single fish). This presented a problem in constructing the key, because a single fish that was aged three times at, for example, age class one and 300 mm intuitively should only count as heavily toward the count of fish in that cell as a similar fish aged only once. This issue was overcome by weighting the inputs to the age-length key according to the number of age readings performed on each fish. In the example above, the number of fish that contribute to the cell [(length 300), (age one)] was determined by:

Weighting from fish 1 + weighting from fish 2 = 1/3 + 1/3 + 1/3 + 1
= 2

Note that if one of the three age readings of the first fish indicated that it was in age class 2, the number of fish that contribute to the cell [(length 300), (age one)] would be 1.67. However, the number of fish that contribute to the cell [(length 300), (age 2)] would increase by 1/3. Mathematically, each cell of the age-length key is calculated as

$$ALK(x,a) = \frac{\sum_{k=1}^{n_{xa}} \frac{1}{n_k}}{n_x} \tag{4.7}$$

where $ALK(x,a)$ is the age-length key for a fish in length class x and of age a, n_x is the number of fish in length class x (not including multiple ageing), n_{xa} is the number of fish of age a in length class x (including multiple ageing), n_k is the number of times the k^{th} fish in length class x and of age a has been aged (irrespective of whether or not age equals a).

As discussed in section 3.2.3, there is a distinct difference between the age structure of sea-mullet taken from estuaries and from ocean beach waters. It is also clear that males and females follow very different growth rates as they age, with females growing to a much larger length. Considering these differences, it was originally intended to construct separate age-length keys for each sex, in each domain, in each State and in each year. The problem with this approach was that the aged fish are spread across so many age-length keys (64) that the actual number of fish contributing to each key was very small, and granularity became a problem.

The following points contributed to the final age-length construction:

- By combining males and females in a single age-length key, the female proportion information from section 3.2.1 would be implicitly captured in the model. That is, the fact that large fish in the key are mostly female will not matter provided that the sex ratio of the population does not dictate its survivability and behaviour over time. This assumption was made in the analysis.

- The probability of a fish of length x being age a was expected to be relatively similar regardless of State and domain. This statement does not imply that the age structures in each State and domain are the same, only that for any given length, the distribution of age likelihoods is expected to be similar regardless of where the fish was caught. Population distinction, particularly between the domains, is still well captured by the length.

It was decided that a sensible balance was to combine the fish according to State, sex and domain into 8 age-length keys (one for each year j except 1997 – $ALK(x,a)_j$), relying on the length frequency data to account for the structural differences in each domain and State.

4.2.3.3 RELATIONSHIP BETWEEN LENGTH AND WEIGHT

The relationship between length and weight was assumed to be a power function, as employed by Smith and Deguara (2002) and discussed by Haddon (2001):

$$W = \alpha L^{\beta} \tag{4.8}$$

where W is the weight, L is the length, α and β are constants. It is generally expected that β will be close to 3 (Haddon 2001) because growth in weight occurs in 3 dimensions while growth in length occurs in 1 dimension. To find α and β, a linear regression was applied to the log-transformed length-weight data available from all years:

$$\log(W) = \log(\alpha) + \beta \log(L)$$

It was decided that log-normal errors in the regression were sufficient (i.e. normal error distribution applied to the log-transformed regression). The regression parameters are provided in Table 4.2:

Table 4.2 Regression parameters for the logarithm of the length-weight relationship.

Parameter	Estimate	Standard Error
$\log(\alpha)$	−11.4150	0.0361
β	3.04791	0.00617

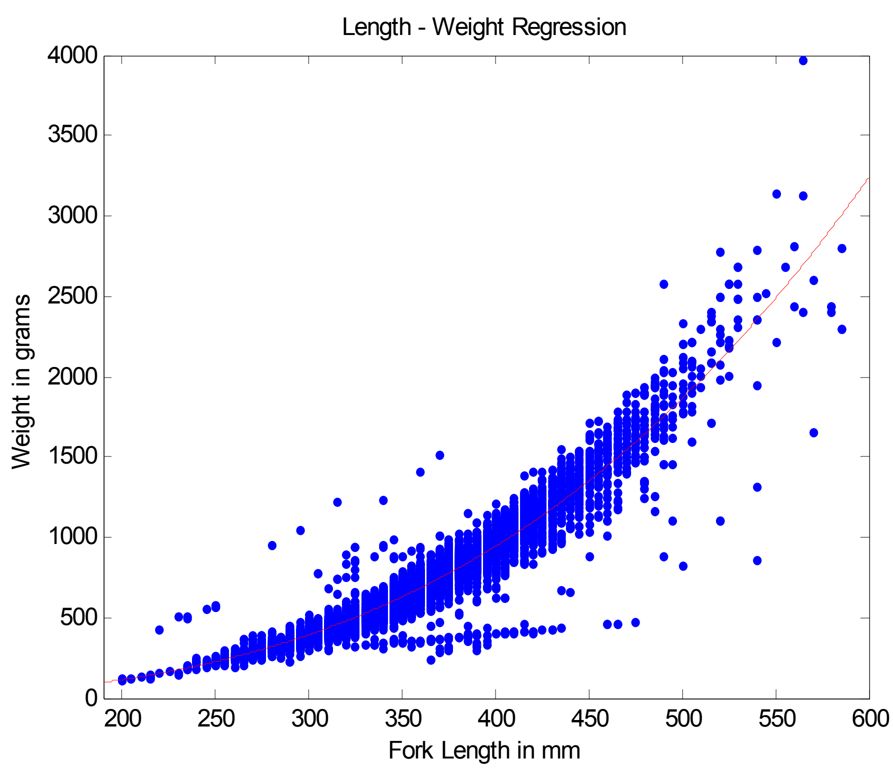


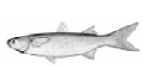
Figure 4.1 The observed relationship between length and weight (from the biological data source) and the estimated relationship (red line) as calculated by a regression.

Using the values in Table 4.2, equation 4.8 becomes:

$$W = 1.1029 \times 10^{-5} \times L^{3.04791} \tag{4.9}$$

4.2.3.4 CALCULATING OBSERVED CATCH-AT-AGE

The algorithm applied to obtain C_{ja} using the relationships described in sections 4.2.3.2 and 4.2.3.3 follows:



1. Estimate the number of fish caught in a zone by taking the weight of the catch in a zone and dividing it by the mean weight of the fish from the biological data in that zone. That is,

$$\overline{W}_z = \frac{\sum_{i \in z} n_{iz} \times W_i}{n_z}$$
$$f_z = \frac{GC_z}{\overline{W}_z}$$

where W_i is the weight of a fish in the length class i as calculated using equation 4.9, n_{iz} is the number of fish in zone z that are from length class i, n_z is the number of fish in zone z (i.e. $n_z = \sum_{i \in z} n_{iz}$), $\overline{W}_z$ is the mean weight of the fish in the zone, GC_z is the gross weight of the catch in the zone and f_z is the number of fish caught in the zone.

2. Estimate the number of fish caught in each length class represented in a zone by multiplying the number of fish caught in a zone by the proportion (or frequency) of the length in the zone. Note that 5 mm spacing of length classes is used. That is,

$$f_{xz} = f_z \frac{n_{xz}}{n_z}$$

where f_{xz} is the number of fish caught in zone z in length class x, n_{xz} is the number of fish in zone z in length class x.

3. Further split this into the number of fish from each age class by applying the age-length key (equation 4.7). That is,

$$f_{axz} = f_{xz} \times ALK(x,a)_j$$

where f_{axz} is the number of fish caught in zone z that are from length class x and age class a, $ALK(x,a)_j$ is the entry in the (x,a) cell of the age-length key for year j.

4. Estimate the number of fish caught in an age class for each zone by summing across all length classes in the zone and age class. That is,

$$f_{az} = \sum_{i \in az} f_{aiz}$$

where f_{aiz} is the number of fish caught in zone z that are from length class i and age class a (for all i represented in the zone and age class).

5. Finally, add together the results of all domains and States for each year to get the total number of fish of each age caught during the year (as in equation 4.6). That is,

$$f_{az} = f_{a,j,d,s}$$
$$C_{ja} = f_{a,j,IN,NSW} + f_{a,j,OUT,NSW} + f_{a,j,IN,Qld} + f_{a,j,OUT,Qld}$$

where $f_{a,j,d,s}$ is the number of fish caught in age class a from zone z where zone z is defined as year j, domain d and State s.

The observed catch of each age class in each year was computed and is presented in Table 4.3.

Table 4.3 The calculated number of fish caught in each age class in each year (C_{ja}). These age frequencies were used in all three models (modified Paloheimo, catch-at-age\and VPA).

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8
1995	813 370	2 131 900	1 805 400	3 379 500	1 800 400	785 890	98 752	15 597
1996	358 960	2 046 500	2 219 800	1 351 200	1 631 500	729 710	423 650	69 021
1997	—	—	—	—	—	—	—	—
1998	1 046 000	4 108 600	2 861 600	652 160	644 680	310 960	418 800	192 830
1999	614 370	3 733 200	3 268 800	1 153 200	311 660	123 450	83 999	75 268
2000	307 800	2 840 000	3 582 900	1 378 200	397 410	91 880	28 638	8 496
2001	539 730	3 958 800	3 724 700	2 335 600	553 450	97 784	12 961	1 932
2002	131 130	1 494 300	3 838 400	1 778 600	561 250	185 870	44 131	3 135
2003	237 880	1 010 000	1 395 800	1 702 200	694 210	255 630	81 667	52 632

4.2.4 STANDARDISATION OF EFFORT

A fundamental principle in fisheries science is that, under the ideal and correct definition of effort, the catch rate (catch-per-unit effort, CPUE) is proportional to the abundance of the population (Hilborn and Mangel 1997):

$$\frac{C}{E} = qB \qquad (4.10)$$

where *C* is the catch, *E* is the effort, *B* is the abundance measured typically as biomass but alternatively as number of individuals, and *q* is the catchability coefficient (Hilborn and Mangel 1997). This is a logical arrangement. If the available biomass were high, then one would expect to catch many fish with little effort. However, if the biomass were low, then one would instead expect to have to put more effort in to obtain the same catch, or expect a smaller catch from the same amount of original effort.

Two of the variables are to be measured directly, *C* and *E*. The catch records in the logbook data contain catch weight in kilograms making the estimation of catch in each State rather trivial. The real challenge lies in determining the amount of effort that went into achieving this catch. Ideally, the measurement of fishing effort needs to be such that it is directly proportional to the mortality it generates in the population (Hannesson 1993). This has proven very difficult to accomplish for the eastern Australian sea mullet fishery.

There is an intuitive difference in the CPUE one expects from fishing with various different gear, at different times of the year, in different locations and so on. For example, one would expect a higher catch from a day of ocean haul activity in May on a New South Wales beach than from a day of gillnetting in a Queensland estuary in August. As such, raw effort data (in this case, count of fishing days) cannot be directly summed each year and entered into equation 4.4 because of variations in the many different types of effort each year.

The effort was therefore standardised by generalised linear modelling of the catch data. This yielded a standardised catch rate for the entire fishery each year. The standardised catch rate was then converted into an effective standardised effort and used in the catch-at-age equation.

4.2.4.1 STANDARDISATION BY GENERALISED LINEAR MODELLING

A generalised linear model (GLM) was constructed to determine the relative catch rate in each year in the entire eastern Australian sea mullet fishery. Most of the theory behind the work presented in this section was sourced from O'Neill et al. (2003).

4.2.4.2 FACTORS INFLUENCING CATCH RATE

The following factors were considered likely to affect catch rates and were therefore included in the GLM analysis:

Fishing Gear Operations in which haul nets are used are known to land higher catch on average than gillnetting operations, for example.

Month Winter operations are more likely to yield high catch than those conducted in summer. Catch rates also differ between the winter months substantially.

Sector The fishing sector (oceanic/estuarine) an operation is conducted in is known to play a vital role in dictating the catch rate.

Location The geographical location in which a fishing operation is carried out is expected to dictate catch rate. Note that this distinction is aimed mainly at latitudinal differences since longitudinal differences are mainly accounted for by the sector factor.

Lunar Phase There is evidence that lunar phase impacts catch rate in some fisheries (Courtney et al. 1996).

Wind The capability of fishing vessels on any given day is known to be dictated in part by the wind direction and strength.

State The mullet population does not recognise State borders. So, there should be no real difference in fishing in Queensland compared to New South Wales that is not captured in the *Location* factor. However, State is considered a possible factor in the model in order to assess the impact of the differences between reporting format in each (recall the general mismatch of un-standardised catch rates between the two States discussed in section 3.3.4).

4.2.4.3 GENERALISED LINEAR MODELLING

Equation 4.10 can be extended to incorporate the impact of each of the factors described in section 4.2.4.2 as follows:

$$C = q_0 e^{\alpha} \times B_0 e^{\beta} \times E^{\gamma} \qquad (4.11)$$

where q_0 and B_0 are base values for q and B, and

α is a vector of effects defined by:

$$\boldsymbol{\alpha} = \phi_{GEAR} + \omega_{LOCATION} + \varphi_{STATE} + \delta_{SECTOR} + \lambda_{MONTH} + \vartheta_{LUNAR} + \upsilon_{WIND}$$

β is a vector of effects for each year:

$$\boldsymbol{\beta} = \theta_{YEAR}$$

and γ is a scalar value accounting for number of days fished (O'Neill et al. 2003).

The terms ('factors') in $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ take on different values for each category they encompass. For example, ϕ_{GEAR} might be

$$\phi_{GEAR} = \begin{cases} 1.0 & \text{for gillnetting} \\ 2.6 & \text{for tunnel netting} \\ 2.1 & \text{for haul netting} \\ \quad \vdots & \end{cases}$$

and so on depending on how conducive each of the gear types is toward attaining high catch.

Equation 4.10 can be log-transformed into a linear equation:

$$\log(\mathrm{C}) = \eta + \boldsymbol{\alpha} + \boldsymbol{\beta} + \gamma \log(\mathrm{E}) \tag{4.12}$$

where $\eta = \log(q_0 B_0)$.

Equation 4.12 represents the realisation of what this segment of the work has searched for, that is, a mathematically valid means of determining an expected catch from a given effort and the factors thought to influence catch rate. The next question is: 'What values should the terms in $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and the parameters η and γ take?' This question is answered by applying multiple linear-regression to equation 4.12.

The regression was carried out using the generalised linear modelling framework in the software package Genstat 7 (GENSTAT 2003), setting the link function to 'Identity' and the error distribution to 'Normal'. In this way, lognormal errors are imposed on the system, so that equation 4.11 including error is:

$$\mathrm{C} = q_0 e^{\alpha} \times \mathrm{B}_0 e^{\beta} \times \mathrm{E}^{\gamma} \times e^{\varepsilon} \tag{4.13}$$

and equation 4.12 including error is:

$$\log(\mathrm{C}) = \eta + \alpha + \beta + \gamma \log(\mathrm{E}) + \varepsilon \tag{4.14}$$

where

$$\varepsilon = N\left(0, \sigma^2\right)$$

This error assumption arrangement is a common technique in dealing with catch and effort data (O'Neill et al. 2003).

Note that in Genstat explanatory variables that are continuous are called 'variates'. Explanatory variables that are discrete or categorical are generally referred to as terms. For example, fishing gear is a term, whereas wind, being measured in kilometres per hour, is a variate.

The logarithm of catch is defined as the response variable in the regression, with the terms and variates in α, β and the logarithm of effort defined as predictor variables (logarithm of effort is a variate which influences catch).

4.2.4.4 EXTRACTING THE STANDARDISED CATCH RATE EACH YEAR

The regression analysis yields a set of best-fit parameters for each of the terms and variates. Genstat is capable of applying these estimates using the ‘predict’ command to compute the output from the model under various variate constraints. To find the relative catch rate each year, the ‘predict’ command was executed, setting the log(effort) variate to zero, and the year factor to ‘*’. The other terms and variates remain unspecified. The model then applied its estimates for the parameters to arrive at the overall catch predictions each year. Note that log(effort) is set to zero so that effort itself is unity (exp(0)). Predicted catch at one unit of effort is then of course by definition the catch-per-unit effort or catch rate. Example code for the predict command is given below :

```
> predict [print=predictions, description; combinations=estimable] year, logeffort; levels=*,!(0)
```

Note that the model predictions are logarithms of catch rate, so the antilog was taken to obtain the relative catch rate predictions.

4.2.4.5 RUNNING THE MODEL

The factors and covariates discussed in section 4.2.4.3 were run in various combinations of interactions to test for significance and to find the most appropriate model. For example, to test the behaviour of catch rate trends in both States simultaneously, the State.year interaction was examined, under which the factor sets became:

$$\boldsymbol{\alpha} = \left[\phi_{GEAR} + \omega_{LOCATION} + \varphi_{STATE} + \delta_{SECTOR} + \lambda_{MONTH} + \vartheta_{LUNAR} + \upsilon_{WIND}\right]$$

$$\boldsymbol{\beta} = [\theta_{YEAR} + \tau_{STATE.YEAR}]$$

Under this regime, the model fits a parameter for every interaction of year and State (1995.New South Wales, 1995.Queensland, 1996.New South Wales and so on) as opposed to fitting one parameter for each year and one parameter for each State.

4.2.4.6 NEW SOUTH WALES AFTER 1997

Originally, the multiple linear-regression was carried out using the entirety of the catch and effort data from both States. The catch record anomaly in the New South Wales records discussed in section 3.3.4 was immediately apparent in the original output from the regression; causing a sharp increase in catch rate for the entire fishery in 1998. To counter this, catch data from New South Wales from 1998 onward were excluded from the regression analysis, leaving only the behaviour of the Queensland fishery from 1998 onward to dictate the model output in those years.

4.2.4.7 WIND AND LUNAR PHASE

Wind and lunar phase records can only be applied to the Queensland records. This is because the New South Wales catch records are monthly (the lunar phase and wind is obviously not constant for the whole month). This was discovered to be too restrictive in the linear modelling, and lunar and wind effects were consistently flagged as insignificant ($F > 0.05$). None of the results shown below contain wind or lunar phase effects.

4.2.4.8 EFFORT OFFSET

Allowing the linear model to modify the γ parameter implies that catch may not be directly proportional to effort. For example, if $\gamma = 0.5$, the implication would be that catch is actually proportional to the square root of effort.

It was considered prudent to also run the regression under the assumption of ideal effort, whereby the value of γ is forced to equal 1. In Genstat, this was accomplished by removing log(effort) from the variate list and re-adding it to the model as an offset variable.

4.2.4.9 PROGRESSIVE REGRESSION OUTPUT

The estimated catch rates in each year from some (not all) of the progressive regression runs are shown below:

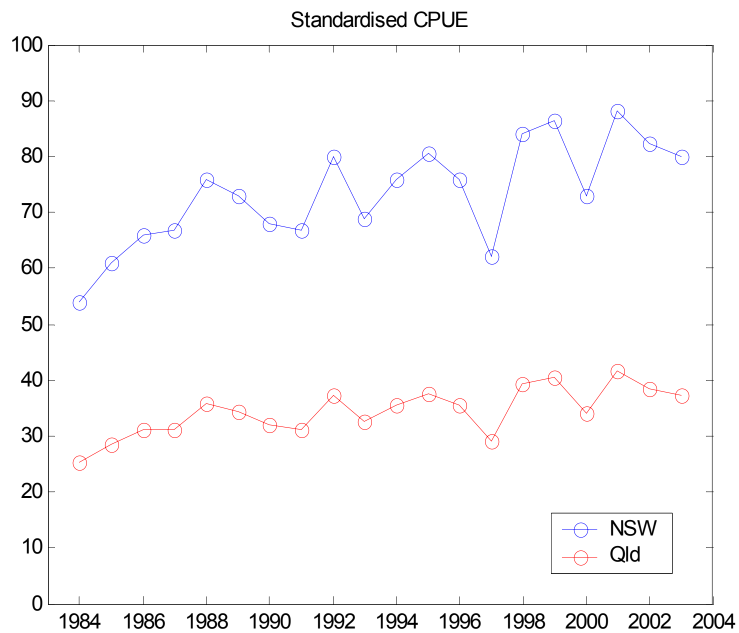


Figure 4.2 Standardised catch rates of sea mullet from Queensland and New South Wales. No interactions, all years included. Factors and variates: logeffort + year + month + State + sector + location + gear.

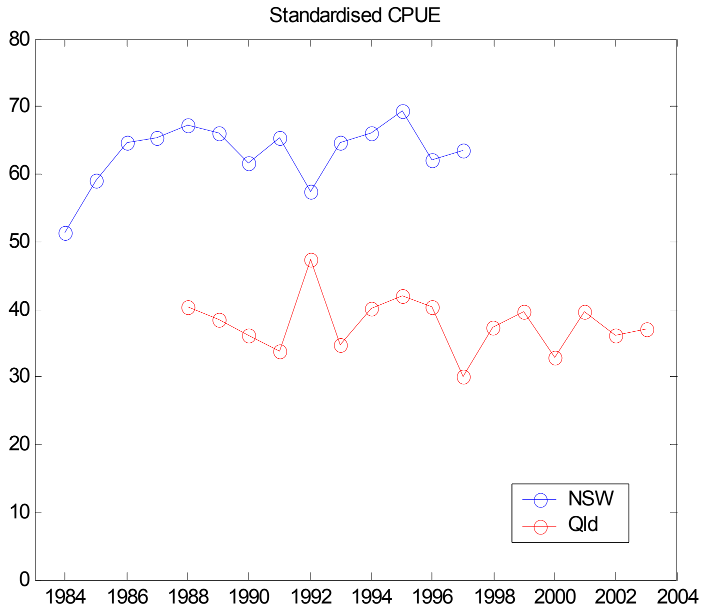


Figure 4.3 Standardised catch rates of sea mullet from Queensland and New South Wales. Interaction of State and year, all Queensland years, New South Wales stops at 1997. Factors and variates: logeffort + month + year*State + sector + location + gear.

4.2.4.10 FINAL RESULTS

The output observed from the above regression runs (and many others) were examined until a final linear model was decided upon. The regression output from the final model is shown in Appendix 10.5. The corresponding standardised catch rates are shown in Figure 4.4:

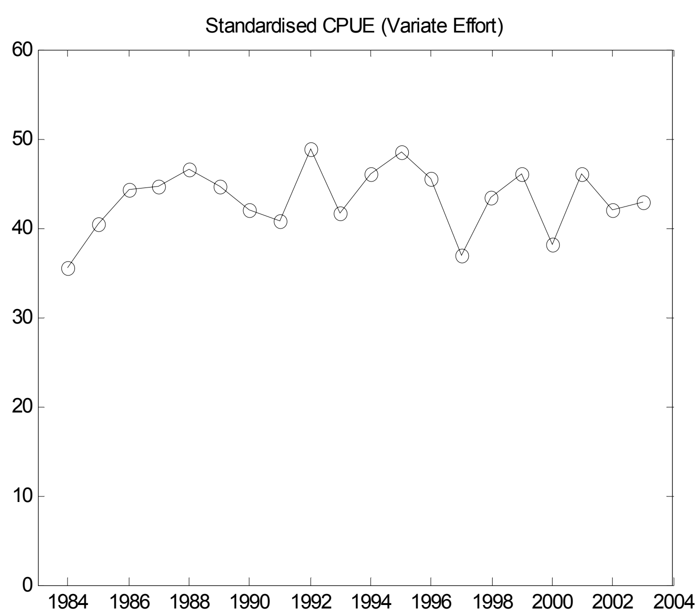


Figure 4.4 Standardised catch rates of sea mullet from Queensland and New South Wales. Final Model: No interactions, all Queensland years, New South Wales stops at 1997. Factors and variates: logeffort + year + month + sector + location + gear.

The regression was run again, with log(effort) imposed as an offset variable. The result (Figure 4.5) was almost identical:

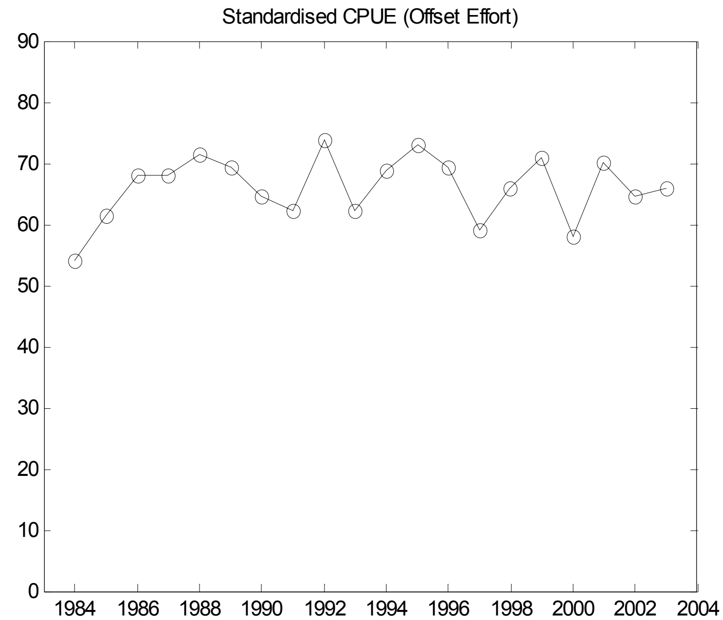


Figure 4.5 Final Model: No interactions, all Queensland years, New South Wales stops at 1997. Factors and variates: year + month + sector + location + gear. logeffort is an offset.

Note the similarity in shape in comparison to Figure 4.4. However, the scale is different because the offset treats catch directly proportional to effort, whereas with a variate model, catch is a nonlinear function of effort.

4.2.4.11 STANDARDISED EFFORT

Having obtained a representation of how the corrected, effective catch rate has changed over time, the next task was to apply this information to the catch-at-age model. Given that catch and effort are separated in the catch-at-age equation (equation 4.4), the standardised catch rate was used in equation 4.4 by claiming that:

$$\text{Standardised Effort in year } j = \frac{\text{Gross Catch in year } j}{\text{Standardised Catch Rate in year } j}$$

The effort variable thus becomes a relative value, which is comparable between years, and can no longer be thought of as representing a simple measurable value (such as boat-days). Note that making the effort variable relative between each year rather than having it represent a distinct value is fine because effective scaling to common units is accomplished by the catch-at-age model fitting the catchability coefficient. For example, multiplying E by 1000 in each year and dividing q by 1000 would yield the exact same output from equation 4.4 because q and E are always multiplied together. This would not be true if catch rate (C/E) were used as predicted-against-observed (response) output in the catch-at-age model because q and E must be separated in this case. Figure 4.6 shows the standardised effort.

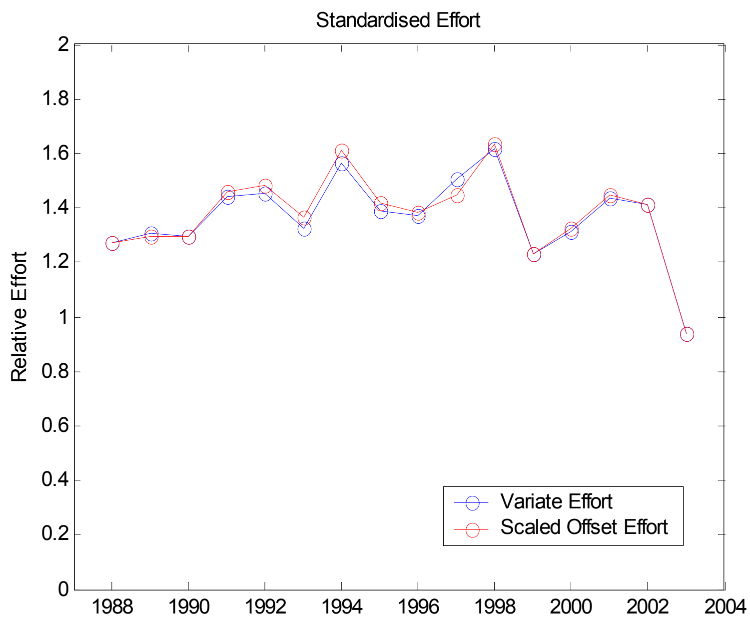


Figure 4.6 Relative standardised effort. The red line indicates the comparative behaviour of the model under the assumption of ideal effort definition.

Note the low effort value in 2003. This is expected as fishing activity in 2003 ends on June 30th in the model. So, the total effort from that year was less than other years (though not half because most of the ocean beach haul is taken between April and June). The final effort values put into the model came from the scaled offset effort results from the multiple linear regression.

4.2.5 SELECTIVITY

Selectivity is a term used to describe how vulnerable a particular fish (usually categorised by age) is to fishing. For example, an old fish that is likely to be large will be more susceptible to being caught in a net than a juvenile which may be able to escape the net if the mesh size is large enough for it to fit through. The older fish is said to have a higher selectivity. In practice, selectivity is relative so that one may define, for example, fish in age class 9 to be fully selected (selectivity $S_9 = 1$), while age class 2 may be only partially selected ($S_2 < 1$).

It is logically expected that at any given time the number of zero ring-olds in the population exceeds the number of one ring-olds, which in turn should exceed two ring-olds and so on. The age frequencies in Appendix 10.1 are fishery dependent, so the quantity of each class observed depends on the selectivity of sea mullet at age. Thus a low selectivity of zero and one ring-olds explains the relatively low number of these age classes in the samples.

Early in the model development, it was assumed that all fish in age class three and over were fully selected ($S = 1$) and only the selectivity of one and two ring-olds were to be estimated. It was pointed out that selectivity of some of the older age classes was unlikely to be 1 and so a sigmoidal function for selectivity was suggested. The equation was taken from Haddon (2001):

$$S_a = \frac{1}{\left(1+\left(\frac{1}{19}\right)^{\left(\frac{a-a_{50}}{a_{95}-a_{50}}\right)}\right)} \tag{4.15}$$

where a_{50} and a_{95} are the ages at which 50% and 95% of the fish are selected respectively. Variation of a_{50} and a_{95} can completely dictate the shape of the selectivity curve. If the two values are close together we get a ‘step’ function. If there is a sizable difference between them the curve smoothes itself out. a_{50} and a_{95} are parameters that are estimated in the model. There are still only two selectivity parameters but the model is now able to capture a selectivity lower than 1 for older age classes.

4.2.6 ESTIMATING TOTAL MORTALITY (*Z*)

Catch curves from the growth data were constructed to assist in the estimation of biomass and to anchor certain parameter assumptions in the catch-at-age analyses.

Catch curves are built from the age frequencies (Appendix 10.1) and provide a means of assessing the total instantaneous mortality rate (Z) and how it behaves over time. Broadly speaking, the theory of catch curve analysis involves the application of linear regression to the observed logarithmic proportions of fully selected age classes in order to assess the constancy of mortality over time (Hilborn and Walters 1992). The decline of fish can be modelled as

$$N_{a+1} = N_a e^{-Z} \tag{4.16}$$

where N_a is the number of fish aged a in a given year and Z is the instantaneous rate of total mortality. It follows then that Z can be obtained by

$$Z = -[\log(N_{a+1}) - \log(N_a)]$$

Instead of using actual observed numbers, proportions are used in this analysis. Catch curve analysis can be conducted via two common methods, construction of cross-sectional curves and longitudinal curves.

4.2.6.1 CATCH CURVES

Cross-sectional catch curves were constructed from the aged fish within each year. In this analysis, sets of cross-sectional catch curves were defined by taking the logarithm of the age proportions in each State for each year. That is, the catch curve function for each year and in each State is

$$f(a)_{j,s} = \log_e\left(\frac{n_{a,j,s}}{n_{j,s}}\right),$$

where $n_{a,j,s}$ is the number of fish at age a in year j and State s and $n_{j,s} = \sum_a n_{a,j,s}$.

Longitudinal catch curves were constructed by taking proportion data for single cohorts. For example, to build a catch curve for the cohort that was recruited in 1995, one would take the proportion of one ring-olds observed in 1995, the proportion of 2 ring-olds in 1996, and so on. However, care is needed when comparing the proportion of observations in different years of sampling. Simple proportions taken each year cannot capture changes in abundance from year to year. Thus all proportions were multiplied by an index of abundance (in this case standardised catch rate) in the longitudinal catch curves. Note that this is not a problem in the cross-sectional case because each curve is built from data sampled in a single year. Mathematically,

$$f(a)_r = \log_e\left(\frac{n_{a,r+a-1}}{n_{r+a-1}} \times CPUE_{r+a-1}\right),$$

where $n_{a,j}$ is the number of fish at age a in year j, n_j is the number of fish in year j and r is the year that the cohort of interest was recruited to the fishery (remember that, in this fishery, fish are recruited when they are one ring-olds).

Note the psuedo-linearity in the latter part (age class > 3) of the curves in Figure 4.7 and Figure 4.8. If it is assumed that the proportion of numbers in one age class to the next is constant, then Z must be constant for all ages. This constancy translates to a straight-line observation in the fully selected section of the catch curves. The slope of the straight line corresponds in magnitude with Z (Hilborn and Walters 1992). Note that this is not seeking to prove a constant Z value; in fact the catch-at-age analysis is designed and intended to account for fluctuations in Z. Rather, this segment is concerned only with determining an approximate average Z value that can be used to estimate the ratio of current biomass to virgin biomass.

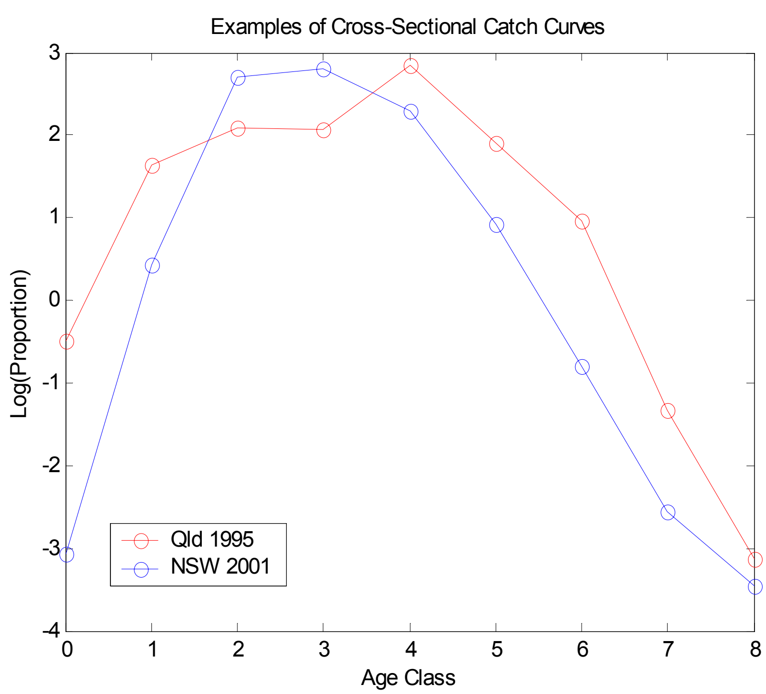


Figure 4.7 The logarithm of age samples in each State and year were calculated and used to construct cross-sectional catch curves.

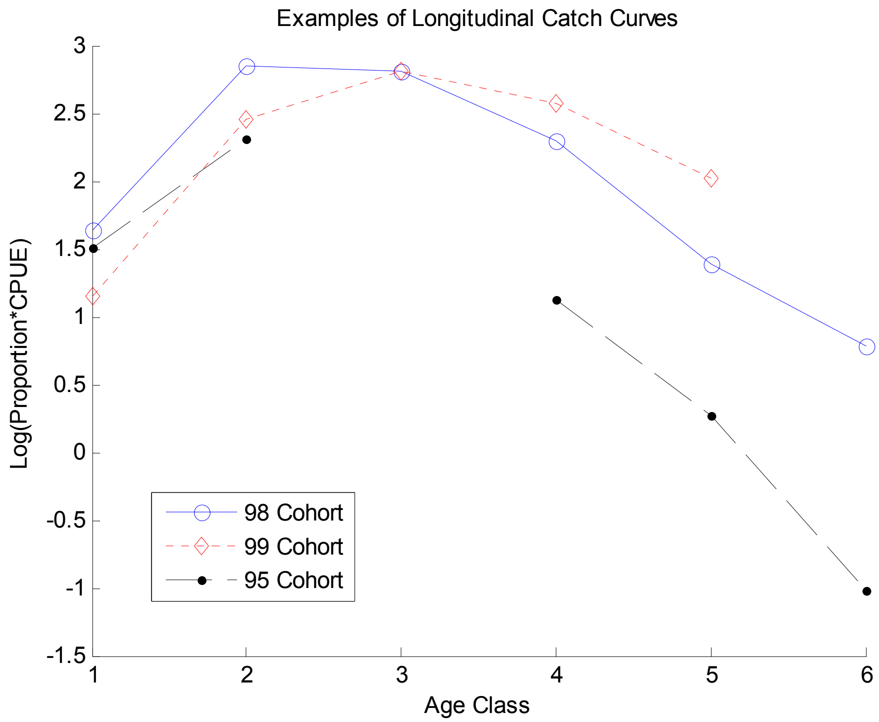


Figure 4.8 Longitudinal catch curves. The gap in the dotted line coincides with the lack of age samples in 1997 (hence no information on age class 3 for the 95 cohort).

Fully selected ages were deemed to most likely constitute the classes from 4 rings upward (early output from the catch-at-age analysis confirmed this). As such, linear regression was applied to the cross-sectional and longitudinal catch curves for age classes 4 through 7. Age classes 8 and up were excluded due to granularity problems. When fitting a linear regression to logarithmic data, building points from data with low resolution (in this case sampling only say one fish in age class 8) is unwise unless the points can be weighted appropriately.

The regression on the cross-sectional catch curves was found to indicate a significantly different Z value between years (Appendix Table 10.9). This was attributed to the unusually strong cohort of age class 4 in 1995 (these fish were recruited in 1992), which create a noticeable ‘bump’ in what was hoped to be a relatively straight line each year.

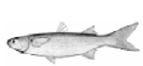
The results of the longitudinal regression were more sensible. The multiple regression of these curves was conducted in consideration of two paradigms. First, the additive effects of cohort and age were considered. That is,

Model 1: $$\log_e(\text{Proportion} \times \text{CPUE}) = \boldsymbol{\alpha}_{COHORT} + \beta a$$

where $\boldsymbol{\alpha}$ is the regression intercept for each cohort, and β is simply Z, the regression slope, which is applied to all cohorts across the ages a. The result of this paradigm is illustrated in Figure 4.9 (left plot) and in Appendix 10.6.1.

Second, the interaction of age and cohort was considered. That is,

Model 2: $$\log_e(\text{Proportion} \times \text{CPUE}) = \boldsymbol{\alpha}_{COHORT} + \boldsymbol{\beta}_{COHORT}\, a\,.$$



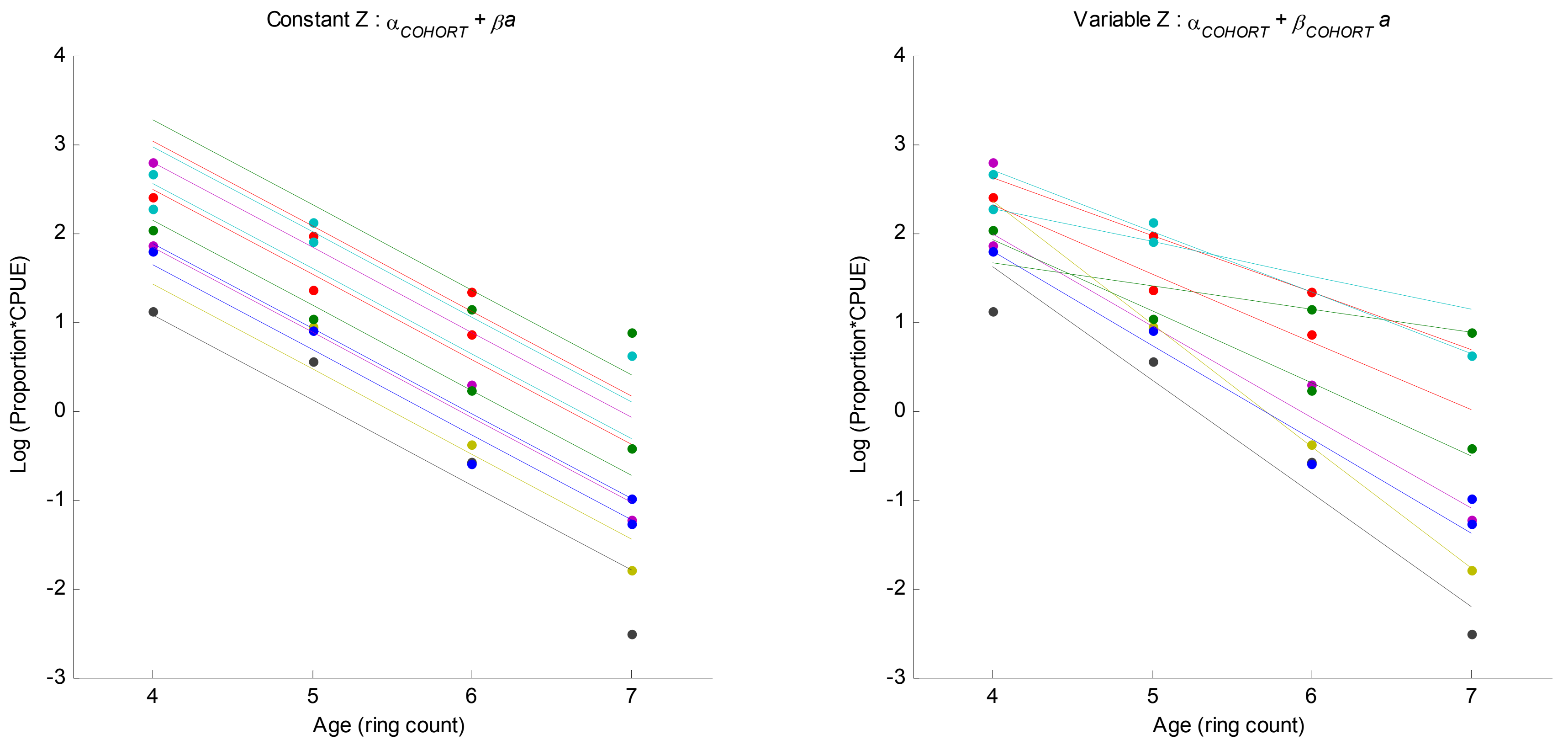


Figure 4.9 In the left plot, the slope of the curves (*Z* estimate), from each cohort, are assumed identical. Thus, one estimate of *Z* is obtained by this regression. The results from this regression are in Appendix **Table 10.4** and **Table 10.5**. In the right plot, the slope of the curves (*Z* estimate), from each cohort, are assumed to differ. Thus, 12 estimates of *Z* are obtained by this regression, one for each cohort. The results from this regression are in Appendix **Table 10.6** and Ta**ble 10.7**.

In this case, α was the regression intercept for each cohort. However, β is now a vector of slopes, one for each cohort. The result of this paradigm is shown in Figure 4.9 (right plot) and in Appendix 10.6.2.

In model 2, the slope and constant were permitted to be individually defined for each cohort. The ten estimates of Z for each cohort (Model 2, Appendix Table 10.7) were significantly different (Table 4.4) from the overall average Z (Model 1, Appendix Table 10.5).

Table 4.4 Significance of each of the catch curve models.

	F value	Degrees of freedom	P value
Model 1 or 2	2.47	9, 34	0.03
Cross sectional with States	0.28	1, 23	0.60
Longitudinal with States	0.36	1, 33	0.55

For both the cross sectional (model 1) and the longitudinal (model 2) catch curves, the slopes were not significantly different between States (Table 4.4). Therefore, this aspect was excluded.

The results of the regression (Appendix Table 10.5) on the longitudinal catch curves indicate that the total annual mortality rate in recent years is:

$$Z_{cc} = 0.95 \text{ year}^{-1}$$

4.2.7 ESTIMATING NATURAL MORTALITY (M)

The instantaneous rate of natural mortality (M) is assumed constant and is *not* estimated in the model. Instead, stand-alone estimates of M were obtained from two different sources

1. in their cohort analysis of the Taiwanese sea mullet fishery, Hwang et al. (1990) employ a natural mortality of $M = 0.33$ year^{-1}, and
2. the Hoenig estimator (Hoenig, 1984).

The Hoenig estimator provides a rough estimate of M when there is some certainty of the age of the oldest fish observed in sampling. Given that several thousand fish have been aged in the past nine years, it was decided to make use of the Hoenig estimate which takes the form:

$$\log_e(M) = 1.44 - 0.984 \log_e(t_{\max})$$

Two individuals out of over 16,000 aged fish have been observed at 13 rings. Substituting 13 in for $t_{\max}$ gives $M = 0.3383$ year^{-1}. Note that the 13 ring-old fish observed in nature are actually (according to our algorithm for ageing) a little older than 13 years. Such error is deemed small compared to the uncertainty of the ages and the 'approximate' nature of the Hoenig estimation equation.

Given the two sources above, the value of M assumed in the model was 0.33 year^{-1}.

4.2.8 RECRUITMENT

Recruitment to the fishery was modelled in two different ways:

Annual Recruitment The recruitment in each year was estimated separately. Note that we have several data points for most cohorts moving through the model. For example, we know the catch of age class one in 1995, class two in 1996, class four in 1998 and so on. The catch curve analysis (in particular, the problems discovered when attempting to fit cross-sectional catch curves) clearly indicates that recruitment is highly variable, further endorsing this approach.

Constant Recruitment The recruitment is assumed to be constant regardless of stock size or fishing pressure. This recruitment regime was useful in assessing the relative significance of the annual recruitment regime.

The model needs to estimate the number of fish in older age brackets in the first year of the age-based model (1995). The diagram below illustrates this principle:

Age	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	R_{95}	R_{96}	R_{97}	R_{98}	R_{99}	R_{00}	R_{01}	R_{02}	R_{03}
2	$N_{2,95}$								
3	$N_{3,95}$								
4	$N_{4,95}$								
5	$N_{5,95}$								

Figure 4.10 Diagram based on catch-at-age discussion by Haddon (2001). The R and N variables must be estimated in the model, while the remaining cells are computed from the estimates by forward projection of cumulative mortality on the cohorts.

This was accomplished by estimating recruitment in 1991 to 1994 (along with recruitment from 1995 to 2003) and applying fishing and natural mortality to the cohorts up to 1995. In order to cut down on the number of parameters being estimated, only 2–5 ring-old fish in 1995 were treated this way. Using equation 4.15, estimates for age class six and older were obtained by applying the catch curve total mortality estimate to the estimates for five ring-olds. That is,

$$\begin{aligned} N_6 &= N_5\, e^{-0.95} \\ N_7 &= N_6\, e^{-0.95} \end{aligned} \tag{4.17}$$

and so on. This is deemed acceptable since the selectivity of 6 ring-old fish is thought to be (and turns out to be) very close to one.

4.2.9 MODELLING THE MISSING DATA

It has been explained that age frequency data from 1997 was deemed not suitable to be included in the model. However, a means by which the model could predict and respond to fishery behaviour in 1997 was desired nonetheless. One suggestion was to interpolate the growth data available in 1996 and 1998 to construct a probable age structure in 1997. This was attempted but proved problematic due to the uncertainty about the proportion of the population that would be newly recruited in 1997, and the selectivity of each age class.

It was decided that an additional data point could be obtained by computing the gross predicted catch in 1997 for comparison to the observed gross tonnage (5.56 kilo-tonnes), making the observed gross tonnage of landings in 1997 an extra response value in the regression. Gross catch in 1997 was computed in the model by multiplying predicted numbers by weight-at-age estimates.

Weight-at-age can be computed in a number of ways. For example, one could combine equations 10.1 and 4.9 to obtain weight as a function of age. However, since this assessment seeks to avoid a von Bertalanffy growth definition, weight at age was computed by finding the mean weight at age for each age class in the biological data. That is,

$$\overline{W}_a = \frac{\sum_{i=1}^{n_a} W_{ai}}{n_a} \tag{4.18}$$

where $\overline{W}_a$ is the mean weight for age class a, W_{ai} is the weight of the i^{th} fish in age class a, and n_a is the number of fish in age class a. No functions were constructed for weight as a function of age in this work.

The weight-at-age relationship is approximate. It is used only in constructing predictions for the gross catch in 1997 (1 of the 65 data points in the model), and to convert predicted numbers-at-age into biomass (section 4.2.10). The 'hard work' in setting up the model itself is done by the more formal age-length keys, length frequencies and length-weight relation.

4.2.10 CURRENT AND VIRGIN BIOMASS

The expected biomass of the population can be calculated by taking the model estimates of numbers-at-age (which are computed by applying cumulative natural and fishing mortality to each cohort) multiplying by the weight-at-age approximation each year and summing for age. That is,

$$B_j = \sum_a N_{ja} \times w_a \,, \tag{4.19}$$

where $w_a = \overline{W}_a$ (as calculated in equation 4.18), j is the year and a is the age class (1 to 13). Note that this is *recruited* biomass, the 0 ring-old fish are not accounted for in this quantity.

The effective exploitable biomass is computed by multiplying the contribution of each age class by its selectivity. So equation 4.19 becomes,

$$B_{j_{EXPLOIT}} = \sum_a N_{ja} \times w_a \times S_a \,, \tag{4.20}$$

Current effective exploitable biomass can be estimated relative to the biomass of the virgin population using the following steps.

1. Assume that recruitment and total mortality is generally constant for the entire history of the fishery so that at the beginning of any year under a total annual mortality of Z the biomass is

$$B_{Now} = R \times w_1 + R \times w_2 \times e^{-(M+S_1F)} + R \times w_3 \times e^{-(2M+S_1F+S_2F)} \ldots \tag{4.21}$$

   where $F = Z_{cc} - M$.

2. In an unexploited population with the same assumption about recruitment, total mortality is M. Thus,

$$B_{Virgin} = R \times w_1 + R \times w_2 \times e^{-M} + R \times w_3 \times e^{-2M} \,\mathrm{K} \tag{4.22}$$

3. Dividing equation 4.21 by equation 4.22 eliminates recruitment,

$$\frac{B_{Now}}{B_{Virgin}} = \frac{w_1 + w_2 \times e^{-(M+S_1F)} + w_3 \times e^{-(2M+S_1F+S_2F)} \,\mathrm{K}}{w_1 + w_2 \times e^{-M} + w_3 \times e^{-2M} \,\mathrm{K}} \tag{4.23}$$

In addition to needing the weight-at-age computations from section 4.2.9, the selectivity at age is needed to actually compute the ratio. Selectivity estimates are provided by the output from the catch-at-age analysis in Chapter 5. The ratio of B_{Now} to B_{Virgin} is computed in that Chapter.

Obtaining confidence intervals for the biomass estimate is a bit more difficult than computing the expected biomass estimate itself. One cannot simply apply the equations to the 95% limits of the recruitment, selectivity and catchability estimates. Instead, using the Matlab function ‘mvnrnd.m’ on the covariance matrix for the parameter set (obtained from the Jacobian from the regression), one can obtain a set of (log)-normally distributed *sets* of parameter values, to be used in the prediction of biomass. One thousand simulations were run in which recruitment, catchability and selectivity were randomly generated according to the distribution dictated in the covariance matrix and processed to obtain biomass. The median, 2.5th and 97.5th biomass percentiles were recorded for each year. Again, this process is carried out *after* the model has yielded estimates of recruitment, catchability and selectivity.

4.2.11 SURPLUS PRODUCTION AND CONJUNCTION WITH CATCH-AT-AGE

The catch-at-age analysis does not make use of the catch and effort data available from the late 80s, and only superficial use of the data in the years 1991 to 1994 (to generate numbers at age in 1995). A surplus production model was investigated through which it was hoped to accurately model the dynamics of biomass prior to 1995. The model is based on the modified Schaefer equation (Hilborn and Walters 1992):

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t \tag{4.24}$$

where B is the biomass, r is the growth rate, C is the catch and K is the carrying capacity of the population (virgin biomass).

The surplus production was attached to the catch-at-age model and fitted simultaneously. Unfortunately this construction did not converge during the model fitting process despite various efforts to reduce the number of parameters estimated; K for example was computed from the catch curve results during model fitting. The failure of this model construction is put down mainly to the lack of contrast in the catch rate data during the years 1988 to 1994 (which the surplus production model depends heavily upon for convergence). For this reason, results from the surplus production model are not presented herein.

4.3 STATISTICAL CATCH-AT-AGE MODEL

This catch-at-age analysis was developed separately from the modified Paloheimo approach to estimate the number of fish in each age class (0–13 years) present in the population in each year and incorporates information on historical catches from 1945 to 2003.

4.3.1 FORMULATION OF MODEL

The model and notation are similar to those of Haddon (2001, Chapter 11 pp 329–372). That is,

$$N_{a\,y+1} = N_{a-1\,y}\left(1 - S_{a-1}U_y\right)e^{-M},$$

where $N_{a\,y}$ is the number of fish of age *a* in the population at the beginning of year *y*, S_a is the proportion of fish of age *a* that are selected by the fishery (see equation 4.15), U_y is the harvest rate in year *y* (probability that a selected fish is caught), and *M* is the instantaneous rate of natural mortality, assumed constant and measured in year^{-1}. The final age group is actually a 'plus group' of all fish aged 13 or more.

Recruitment of one ring-old fish was estimated separately for each year 1990–2002 from the age frequencies (Figure 10.1). The data did not permit the estimation of recruitment numbers prior to 1990, or after 2002. That is, it was decided that there were not enough 7 ring-olds in 1995 to estimate recruitment in 1989, 8 ring-olds in 1995 to estimate 1988, etc. Nor were there enough zero or one ring-olds in 2002 or 2003 to estimate recruitment in 2003. Recruitment was assumed to be constant over all years prior to 1990, and recruitment in 2002–03 was assumed equal to the 2002 level. In the presentation of results (section 5.2), recruitment is taken to occur at age one rather than zero, because negligible numbers of zero-ring-old fish are caught in the fishery (Figure 10.1); this is a difference only in terminology, not methodology.

4.3.2 MODEL PARAMETERS AND INPUTS

The following parameters were estimated by the model:

- N_0, the historical number of recruits of age zero to the virgin population (millions of fish)
- a_{50}, the age at which 50% of fish are selected by the fishery (yr)
- a_{95}, the age at which 95% of fish are selected by the fishery (yr)
- $N_{0\,y}$, the numbers of zero-year-old recruits for years y = 1990, 1991, …, 2002 (13 parameters).

Various levels of the instantaneous natural mortality rate *M* were tried, between 0.33 and 0.50 per year. This range illustrated the range of outcomes from the model. The catchability parameter *q* was set to $(\prod_y \text{CPUE}_y)/(\prod_y B_y)$, where CPUE_y is the catch rate or catch-per-unit effort in year *y*, B_y is the mid-year biomass in year *y*, and the product is taken over all years from 1992 to 2003.

The data input to the model were:

- annual catch weight (1945–2003)
- annual catch rate (1984–2003); although, as explained in section 4.3.3, this was found not to be useful and was omitted from the analysis
- weight-based relative age frequency sampled from the catch (1995–96, 1998–2003)
- mean weight-at-age of fish (1995–96, 1998–2003).

4.3.3 FITTING THE MODEL

The model could be fitted by matching the expected to the observed catch rate and age composition. Catch rates from 1984 to 2003 were available, and age compositions from 1995–96 and 1998–2003.

Catch rate can be assumed to follow a lognormal distribution, giving rise to the log-likelihood

$$L_{\text{CPUE}} = -n_{\text{CPUE}} \log_e \sigma_{\text{CPUE}} - \frac{\sum_y (\log_e \text{CPUE}_y - \log_e \text{pred.CPUE}_y)^2}{2\sigma_{\text{CPUE}}^{\;2}},$$

where n_{CPUE} is the number of years of catch-rate data, CPUE_y is the observed catch rate for year y, pred.CPUE_y is the catch rate predicted by the model, and σ_{CPUE} is the standard deviation of the lognormal distribution.

In practice the catch rate information was not found useful due to hyperstability issues, and was omitted from the analysis.

Age composition in year y was measured by the cumulative distribution function, $\text{cdf}_y(a)$, which is the proportion by weight of fish in the catch of age $\leq a$. The mean absolute difference between distribution functions was assumed to follow a half-normal distribution, giving the log-likelihood

$$L_{\text{age}} = -n_{\text{age}} \log_e \sigma_{\text{age}} - \frac{\sum_y \left(\sum_a \left|\text{cdf}_y(a) - \text{pred.cdf}_y(a)\right| \big/ A\right)^2}{2\sigma_{\text{age}}^{\;2}},$$

where n_{age} is the number of years for which ageing data are available (the sum over y is over those years), A is the number of age-classes (the sum over a is over these age-classes), pred.cdf_y is the age composition in year y predicted by the model, and σ_{age} is the standard deviation of the half-normal distribution. Some constant terms have been omitted from these log-likelihoods. The negative of the log-likelihood was minimised by the Matlab polytope (or simplex) routine `fminsearch`.

4.4 VIRTUAL POPULATION ANALYSIS

Virtual Population Analysis (VPA), also known as cohort analysis, is a time dynamic model, which calculates past stock abundances based on past catches. This analysis was completed using the stock assessment program PC-VPA (Punt 1992). The program is a stand-alone package written in Turbo Pascal (version 5). The special feature of this program is that it is designed to calculate total allowable catch (TAC) by shrinking recent recruitment estimates towards the historic mean (Butterworth et al. 1989). This is an alternative method where no information on the stock-recruitment relationship is present in the data.

4.4.1 THE MODEL AND INPUT PARAMETERS

The VPA runs by calculating the number of fish alive in each cohort (age class) for each past year. Each cohort is analysed separately. Thus the VPA relies on a very simple relationship for each cohort. This is that the number alive at the beginning of next year is equal to the number alive at the beginning of this year minus the deaths incurred during the year due to fishing and natural mortality. In this analysis of the sea mullet resource, a Laurec-Shepherd ad hoc tuned VPA is used as described in Punt (1992, 1997).

The input parameters to the VPA software include the age at which recruitment into the fishery occurs, the age at 50% maturity, natural mortality for each age and the shape of the selectivity curve. The base case for sea mullet was chosen as:

- age at recruitment was three+ ,

- age at 50% maturity is three+,
- natural mortality is 0.33 per year,
- the selectivity ogive (γ) in Equation 1 of Punt (1992) is zero, and
- the initial and final beta (β) values were those giving a flat selectivity function once full selection occurs.

5 MODEL RESULTS

5.1 MODIFIED PALOHEIMO'S CATCH-AT-AGE MODEL

5.1.1 RECRUITMENT

The results of the Paloheimo catch-at-age analysis under the two recruitment regimes (i.e. annual or constant recruitment) are shown in the diagram below:

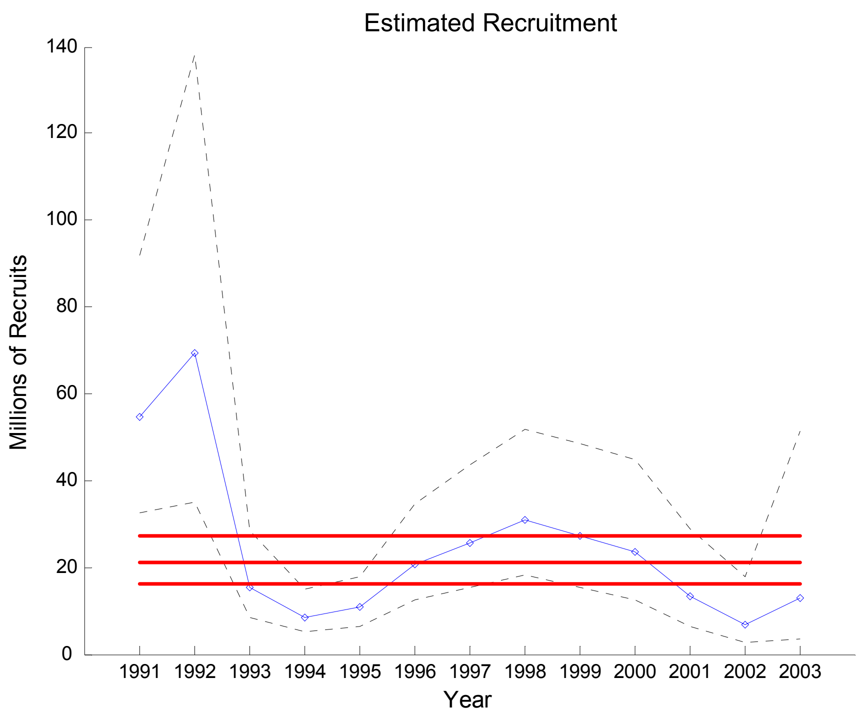


Figure 5.1 Estimated recruitment to the sea mullet fishery. The blue line represents the annual recruitment estimate with 95% confidence intervals shown in black. The solid red line represents the constant recruitment estimate with 95% confidence intervals shown as dotted red lines.

5.1.2 BIOMASS

The biomass estimates (derived using the algorithm described in section 4.2.10) are shown in Figure 5.2 and Figure 5.3. Recall that the weight-at-age relation and logic (which was used to estimate biomass) are approximate. As such, these biomass behaviour plots are intended as a rough indication only.

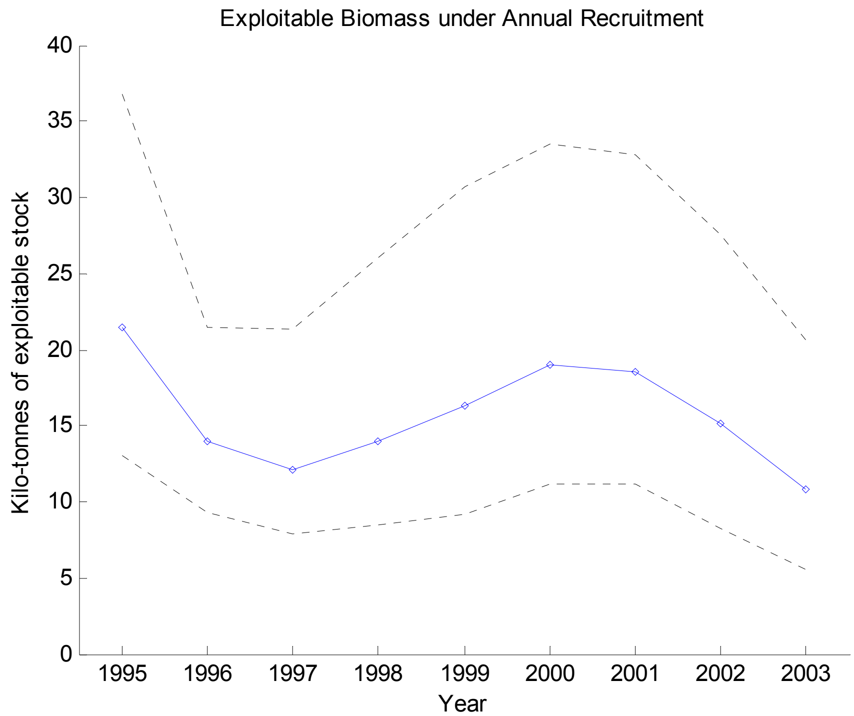


Figure 5.2 The blue line shows the median exploitable biomass in each year derived from 1000 simulations of randomly generated parameter values (based on parameter covariance matrix). The dashed lines show the 95% percentiles.

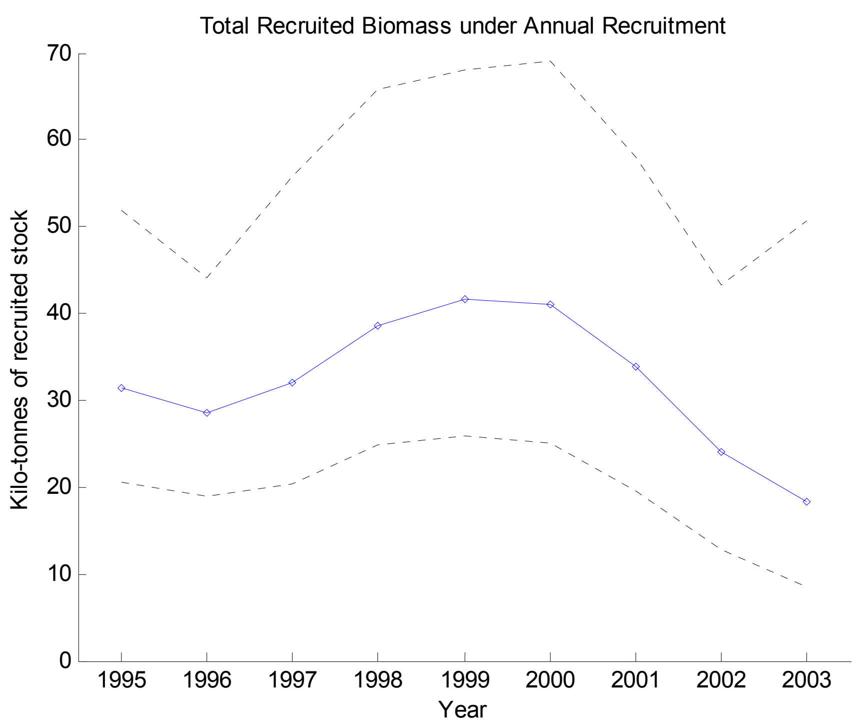


Figure 5.3 The blue line shows the median total biomass in each year derived from 1000 simulations of randomly generated parameter values (based on parameter covariance matrix). The dashed lines show the 95% percentiles.

5.1.3 CATCHABILITY AND SELECTIVITY

The catchability and selectivity parameters, for each of the two recruitment regimes, are provided in Table 5.1 and Table 5.2.

Table 5.1 Parameter estimates and 95% confidence limits for selectivity and catchability for the annual recruitment regime

Parameter	Lower Confidence	Estimate	Upper Confidence
q	4.1619×10^{-6}	5.0788×10^{-6}	6.1977×10^{-6}
a_{50}	1.7768	2.1618	2.5469
a_{95}	2.5441	3.2880	4.0320

Table 5.2 Parameter estimates and 95% confidence limits for selectivity and catchability for the constant recruitment regime.

Parameter	Lower Confidence	Estimate	Upper Confidence
q	4.2844×10^{-6}	5.6246×10^{-6}	7.3839×10^{-6}
a_{50}	2.0399	2.613	3.186
a_{95}	2.958	4.0388	5.1196

The estimated selectivity parameters yield a separate curve under each of the annual and constant recruitment regimes (Figure 5.4).

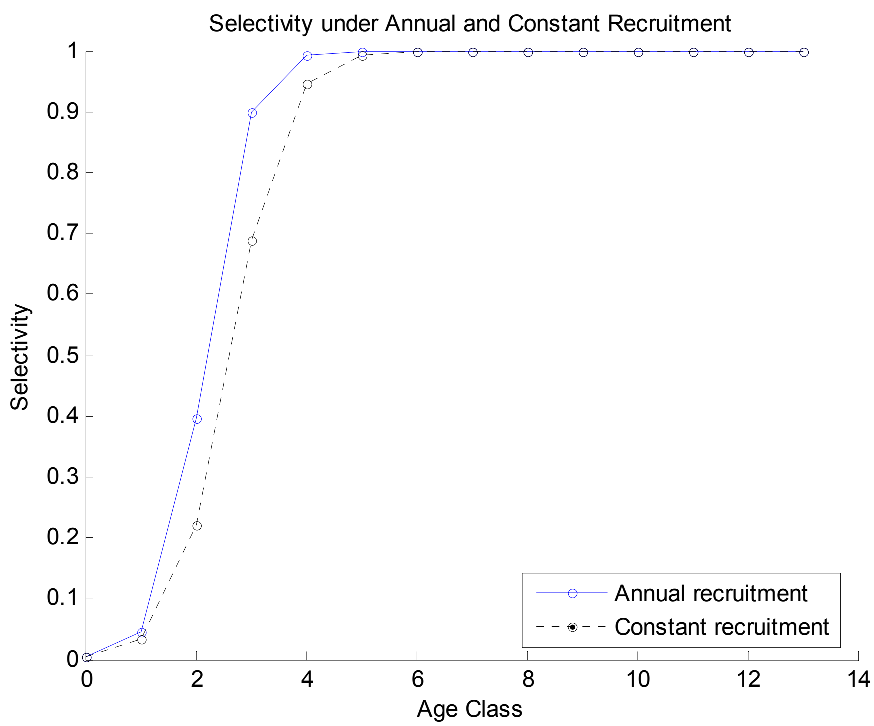


Figure 5.4 Estimated selectivity of each age class under the annual recruitment regime (solid line) and under the constant recruitment regime (dashed line).

5.1.4 ASSESSING THE GOODNESS-OF-FIT FOR THE ANNUAL RECRUITMENT ASSUMPTION

For this model, there was no evidence to suggest that the model was inadequate for the data or that **the** use of log-normal errors were inappropriate. Figure 5.5 shows that the model predicted the log of the observed catch-at-age quite well. The standardised residuals for this model fit (Figure 5.6) were all between –4 and 4, indicating that they were not extreme. The residuals for low catch values, which were dominated by the one and 8 ring-olds, tended to have higher standardised residuals, suggesting that the model did not fit quite as well for these age classes. These larger residuals were also reflected in the linear normality plot (Figure 5.7). The influence of these age classes (one and 8 ring-olds) had little effect upon the estimation of parameters. For example, removing their influence on the log-likelihood resulted in little change in the parameter estimates, suggesting the model was robust to these observations. The residual sum of squares from this model fit of annual recruitment was 19.345. No significant parameter correlations were apparent between recruitment and catchability (Figure 5.8).

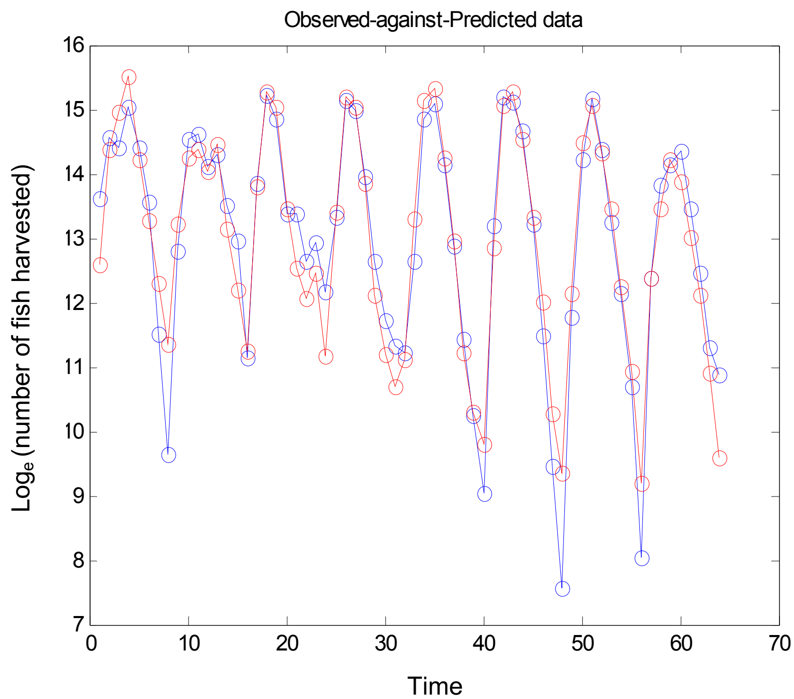


Figure 5.5 Observed-against-predicted catch (logarithms). The red line is the predicted logarithm of catch-at-age, and the blue line is the observed logarithm of catch-at-age. The peaks refer to 2, 3 and ring-old fish harvest in each year. There is one peak in each year (8 peaks from 1995 – 2003). The 8 circles each year correspond to the 8 age classes that are fitted in the model. Not shown is the gross catch in the 1997 estimate (residual 0.10157).

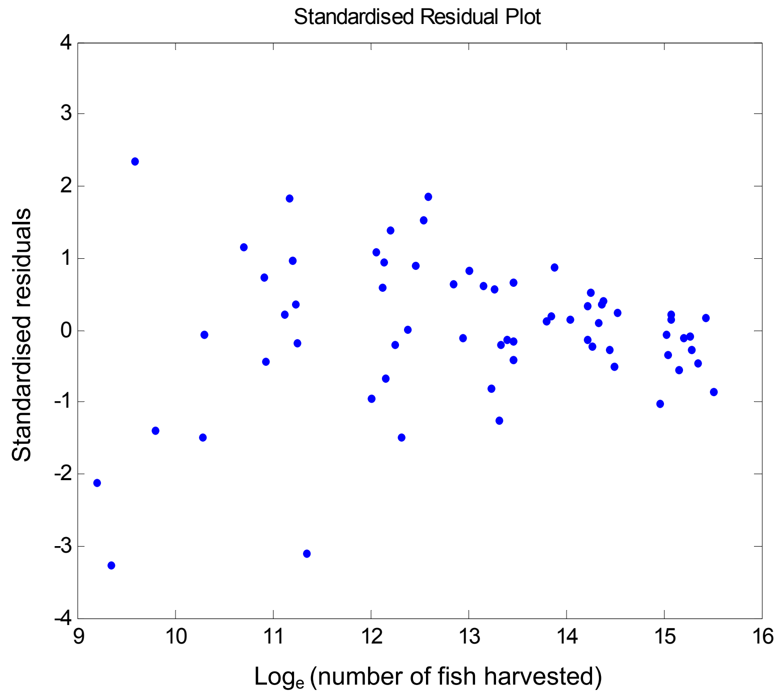


Figure 5.6 Standardised residuals (vertical axis) of the annual recruitment model fit. Note the 'splayed or fanning' effect for the lower catch values, which are predominately one and eight ring-old catches.

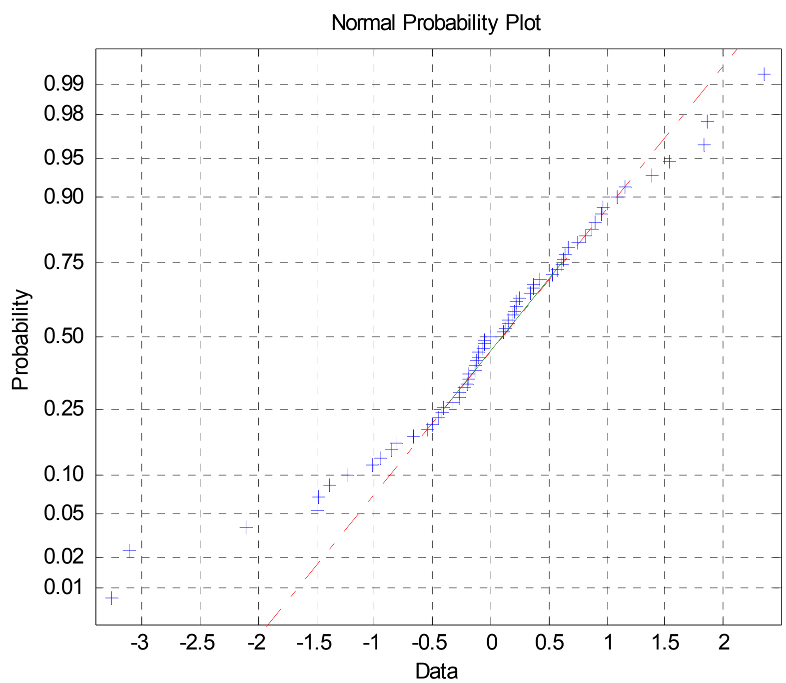


Figure 5.7 The linear normality of the residuals from the annual recruitment model.

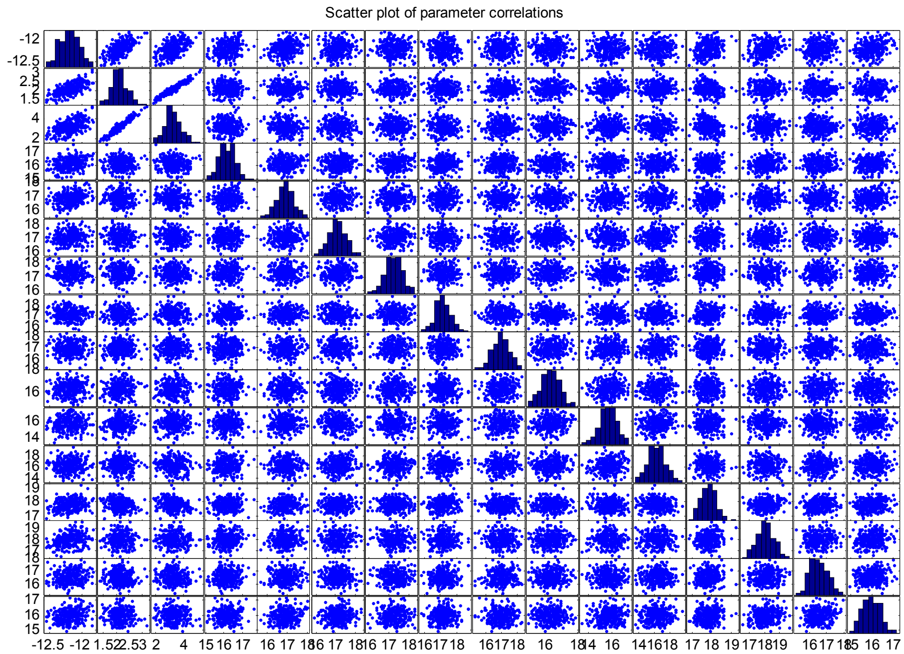


Figure 5.8 Scatter plot of 300 parameter correlations for annual recruitment. The first three rows (and columns) are *q*, *a50* and *a95* respectively. Notice the correlation between the selectivity parameters (row 2, column 3 and vice versa). The other rows and columns are log-recruitment estimates from 1991 to 2003, which appear to be uncorrelated.

5.1.5 ASSESSING THE GOODNESS-OF-FIT FOR THE CONSTANT RECRUITMENT ASSUMPTION

The goodness-of-fit for the model that assumed constant recruitment (Figure 5.9) was not as good as the model that assumed annual recruitment. For example, there were several cases where the predicted and observed catches were poorly matched (Figure 5.9). Fits for the low catches associated with the one and 8 ring-olds were generally poor (Figure 5.10). The residual sum of squares from the constant recruitment was 43.117, which indicates that the annual recruitment analysis resulted in a significantly better fit [df (12,56), F = 5.69, P < 0.001)]. The standardised residuals for the constant recruitment model are provided in Figure 5.10 and the linear normality plot is provided in Figure 5.7. No significant parameter correlations were apparent between recruitment and catchability (Figure 5.12).

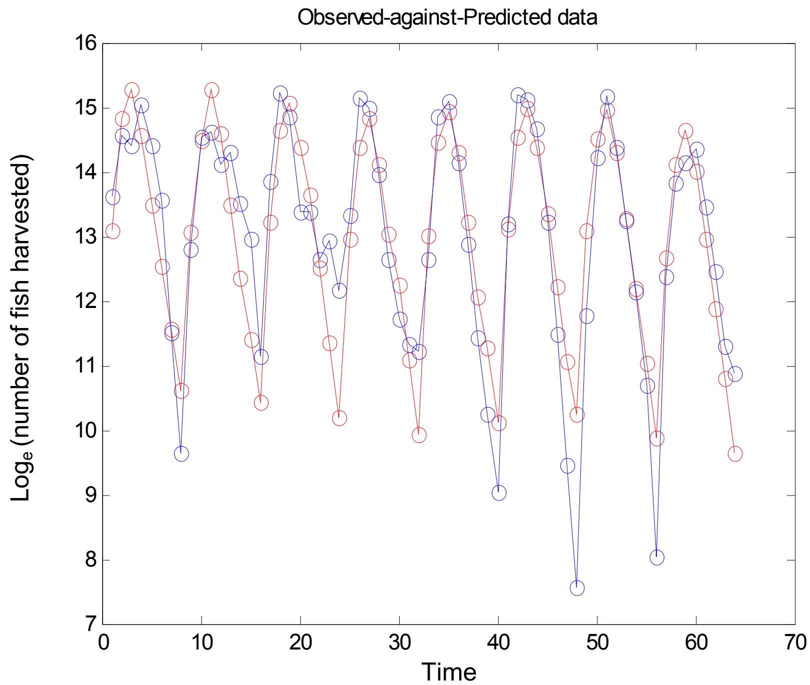


Figure 5.9 Observed-against-predicted catch (logarithms; vertical axis). Not shown is the gross catch in 1997 estimate (residual –0.11802). Each point represents a different age class and year.

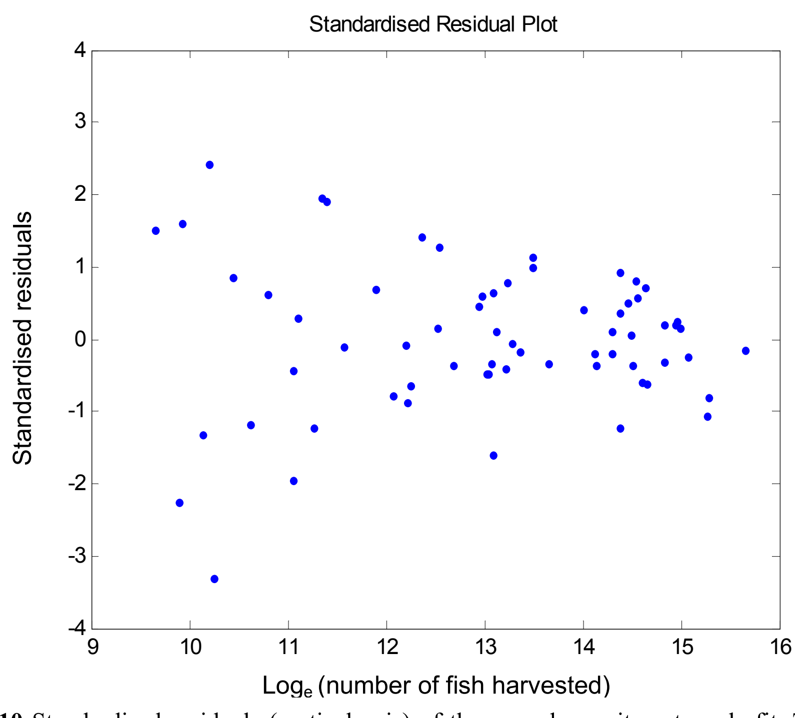


Figure 5.10 Standardised residuals (vertical axis) of the annual recruitment mode fit. The points are plotted against their actual values (logarithm of catch; horizontal axis).

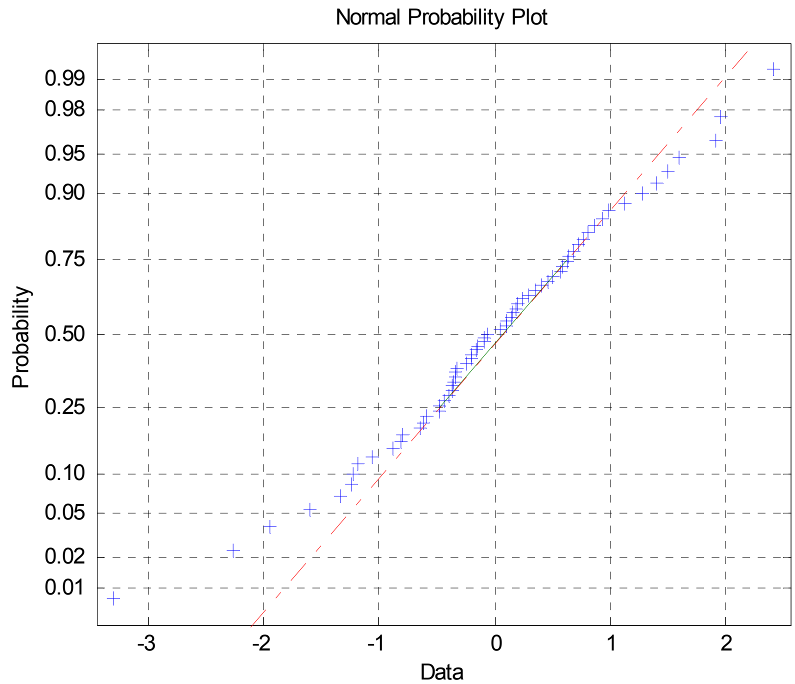


Figure 5.11 The normality of the residual distribution for the constant recruitment model.

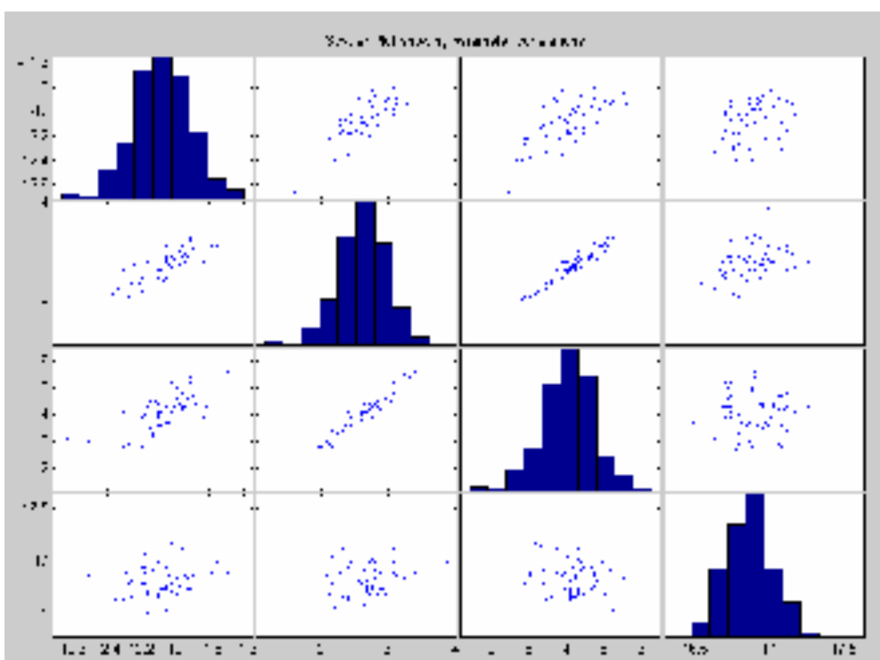


Figure 5.12 Scatter plot of 300 parameter correlations for constant recruitment. The first three rows (and columns) are *q*, *a50* and *a95* respectively. Notice the correlation between the selectivity parameters (row 2, column 3 and vice versa). The fourth row (and column) is the constant log-recruitment estimate for all years in the model.

5.1.6 EQUILIBRIUM BIOMASS CALCULATION

Using our approximate weight-at-age data (see section 4.2.9), equation 4.23, constant M at 0.33 and constant Z at 0.95 we arrive at

$$\frac{B_{Now}}{B_{Virgin}} = 0.59$$

which suggests that the stock could be around 59% of what it would be if the fishery didn't exist (under simple constant equilibrium conditions).

5.2 STATISTICAL CATCH-AT-AGE MODEL

The analysis showed big differences in population trend depending on which value of the natural mortality rate (M) was used. Fitted catch rates (which are assumed proportional to exploitable biomass) are shown in Figure 5.13–Figure 5.15. They show an increase for M = 0.33 year^{-1}, a slight decrease for M = 0.4 year^{-1}, and a dramatic decrease for M = 0.5 year^{-1}. The estimated levels of annual recruitment are plotted in Figure 5.16–Figure 5.18, and show no clear trend for M = 0.33 year^{-1}, a moderate downtrend for M = 0.4 year^{-1}, and a strong downtrend for M = 0.5 year^{-1}. Figure 5.19–Figure 5.21 show the harvest rate which has a slight downtrend for M = 0.33 year^{-1}, no clear trend for M = 0.4 year^{-1}, and an uptrend for M = 0.5 year^{-1}.

Hyperstability issues appear to prevent catch rates from indicating biomass trends. Estimated exploitable biomass (which is proportional to fitted catch rate) fell in the late 1990s, whichever value of M was used, and this fall is not reflected in observed catch rates (Figure 5.13–Figure 5.15). Therefore catch rate data were excluded from the analysis presented here.

Recruitment is evidently highly variable, with 1993 recruitment being much lower than 1992, and 2001 much lower than 2000. The results show either a partial or a full recovery (depending on the value of M) between 1993 and 2000 (Figure 5.16–Figure 5.18).

The results for M = 0.5 year^{-1} are alarming, with sharply falling stocks and recruitment (Figure 5.15 and Figure 5.18), but it is unknown whether M is really this high.

The fitted selectivity function is shown in Figure 5.22, from which it is clear that sea mullet are not fully recruited to the fishery until they are three or four years of age. Only the curve for the middle value M = 0.4 year^{-1} is shown; the others were very similar.

Observed and fitted age frequency distributions are shown in Figure 5.23, again for the middle value M = 0.4 year^{-1}. The ageing data appear very reliable in that both weak and strong year classes can be clearly tracked over several years. For example, the weakness of the 1993 year class relative to 1992 can be seen in the plots for 1995 (less three-year-old fish than four-year-old fish), 1996 (less four-year-old fish than five-year-old fish) and 1998 (less six-year-old fish than seven-year-old fish) in Figure 5.23.

The historical level of recruitment before 1990 is unknown. The model estimated values that were comparatively low, but the data are insufficient for there to be any certainty. The level of recruitment from 1990 to 1992 was high compared to later years, but whether 1990–92 was the historical norm or was exceptionally high is a matter for conjecture.

There is no clear relationship between recruitment and catch sizes (Figure 3.3 and Figure 5.16–Figure 5.18), so it is possible that the recruitment variation is caused by factors other than fishing.

Parameter estimates from the model are shown in Table 5.3.

Table 5.3 Parameter estimates from the age-structured model. The parameter N_0 represents historical recruitment, but the data are insufficient to precisely estimate it.

Parameter	M = 0.33 per year	M = 0.40 per year	M = 0.50 per year
Log-likelihood	39.2152	39.5031	39.2295
N_0 (millions of fish)	22.5678	27.3234	38.6348
a_{50} (year)	2.1273	2.1285	2.1110
a_{95} (year)	3.2997	3.3238	3.2813
$N_{0\ 1989}$ (millions)	53.0760	75.8739	120.1171
$N_{0\ 1990}$ (millions)	54.9221	77.0061	127.6502
$N_{0\ 1991}$ (millions)	51.8220	69.8176	112.1287
$N_{0\ 1992}$ (millions)	21.7373	27.9908	40.3807
$N_{0\ 1993}$ (millions)	21.2954	27.7414	40.9977
$N_{0\ 1994}$ (millions)	15.7261	18.8382	28.9261
$N_{0\ 1995}$ (millions)	21.0308	25.4754	36.8017
$N_{0\ 1996}$ (millions)	38.6732	43.4435	57.5167
$N_{0\ 1997}$ (millions)	48.0956	50.0711	62.5339
$N_{0\ 1998}$ (millions)	49.8249	46.3634	54.6266
$N_{0\ 1999}$ (millions)	79.5579	63.5790	63.6774
$N_{0\ 2000}$ (millions)	39.8413	25.5413	19.4538
$N_{0\ 2001}$ (millions)	41.8085	22.9931	14.4651

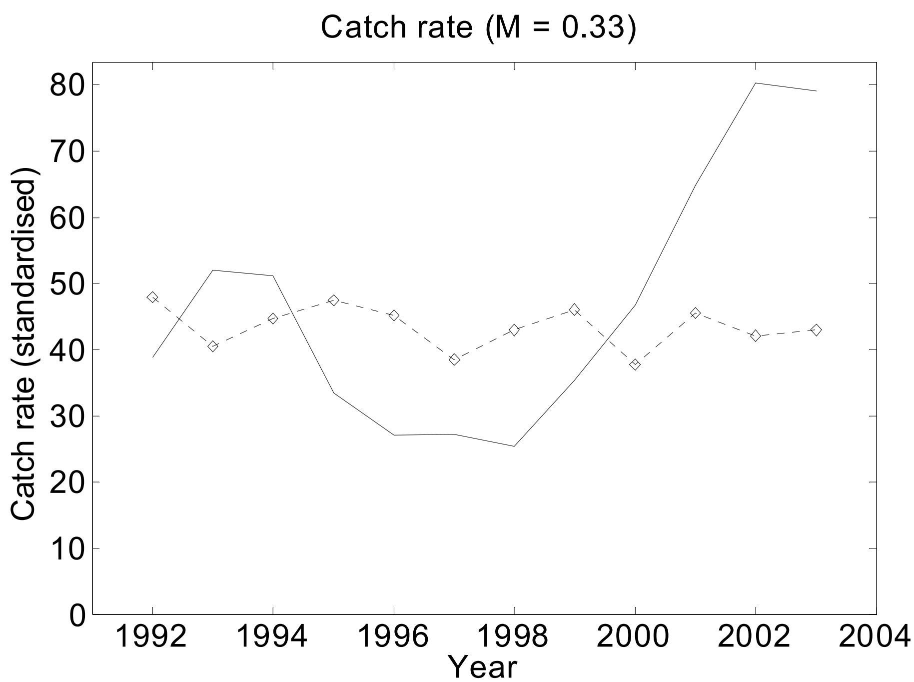


Figure 5.13 Catch rates (observed dashed line, predicted solid line) from the age-structured model for instantaneous natural mortality rate $M = 0.33$ per year.

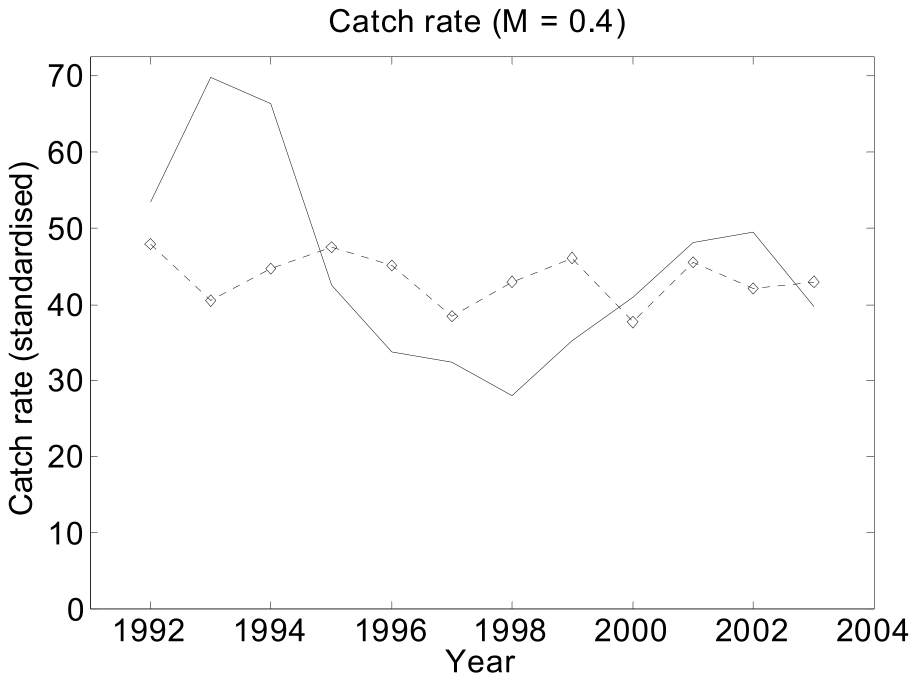


Figure 5.14 Catch rates (observed dashed line, predicted solid line) from the age-structured model for instantaneous natural mortality rate $M = 0.40$ per year.

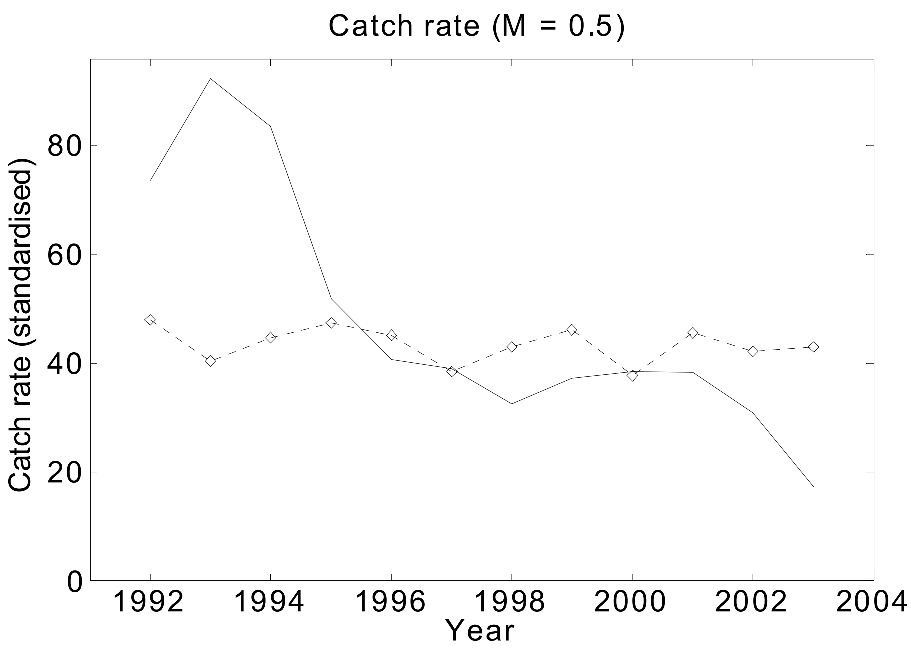


Figure 5.15 Catch rates (observed dashed line, predicted solid line) from the age-structured model for instantaneous natural mortality rate $M = 0.50$ per year.

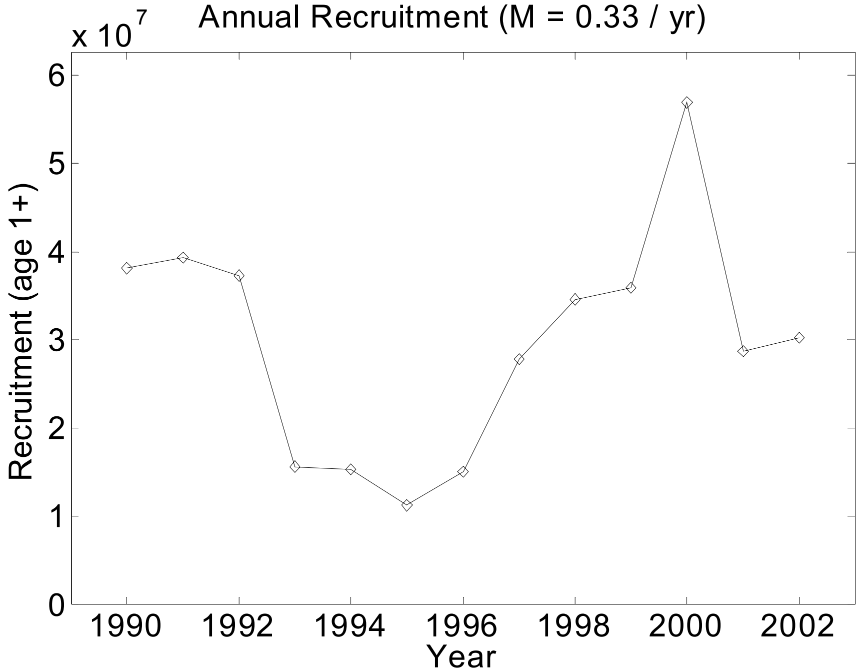


Figure 5.16 Estimated annual recruitment from the age-structured model for instantaneous natural mortality rate $M = 0.33$ per year.

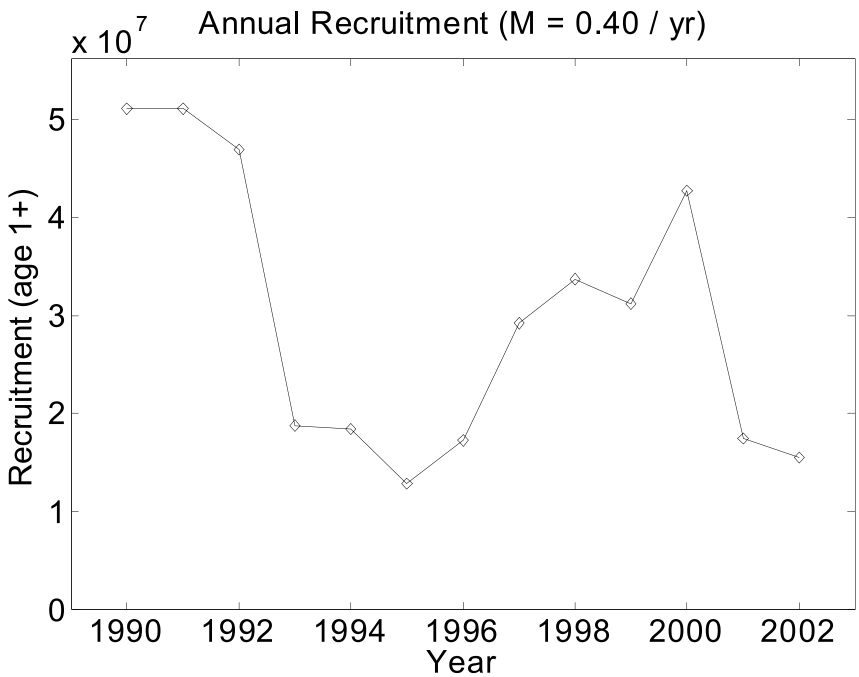
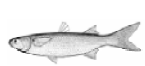


Figure 5.17 Estimated annual recruitment from the age-structured model for instantaneous natural mortality rate $M = 0.40$ per year.



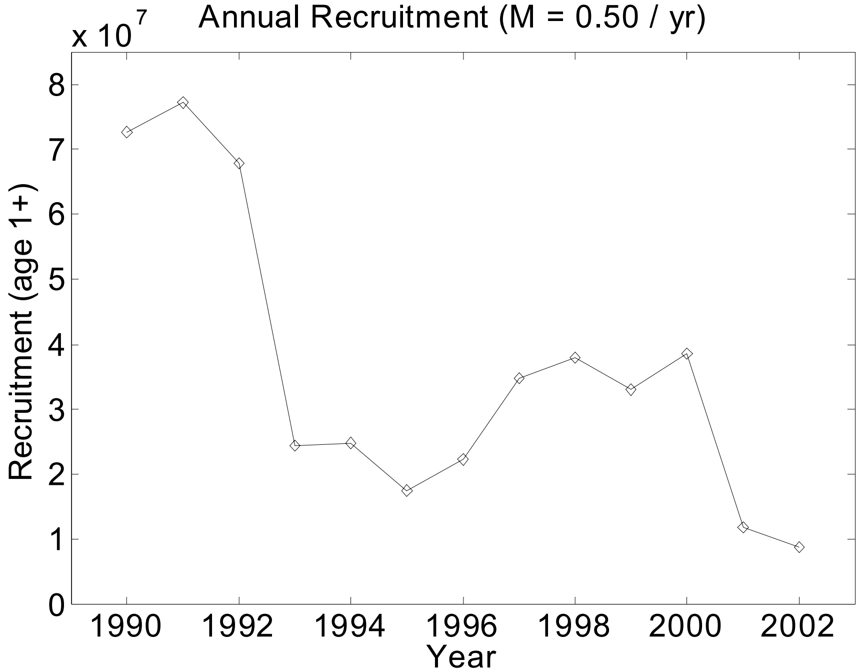


Figure 5.18 Estimated annual recruitment from the age-structured model for instantaneous natural mortality rate $M = 0.50$ per year.

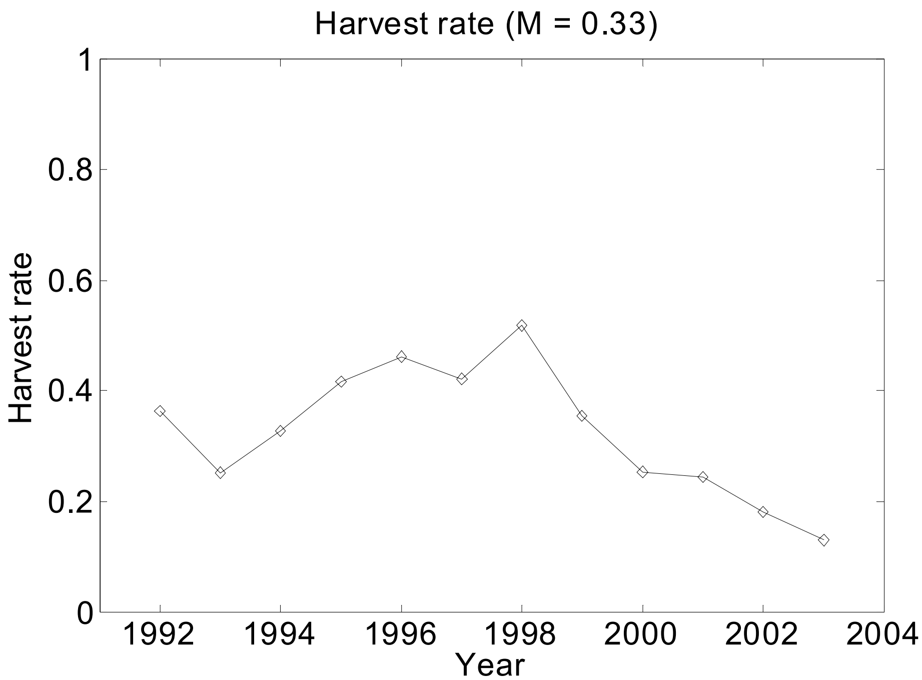


Figure 5.19 Estimated harvest rate (proportion of fish available to the fishery that are caught in a single year) from the age-structured model for instantaneous natural mortality rate $M = 0.33$ per year.

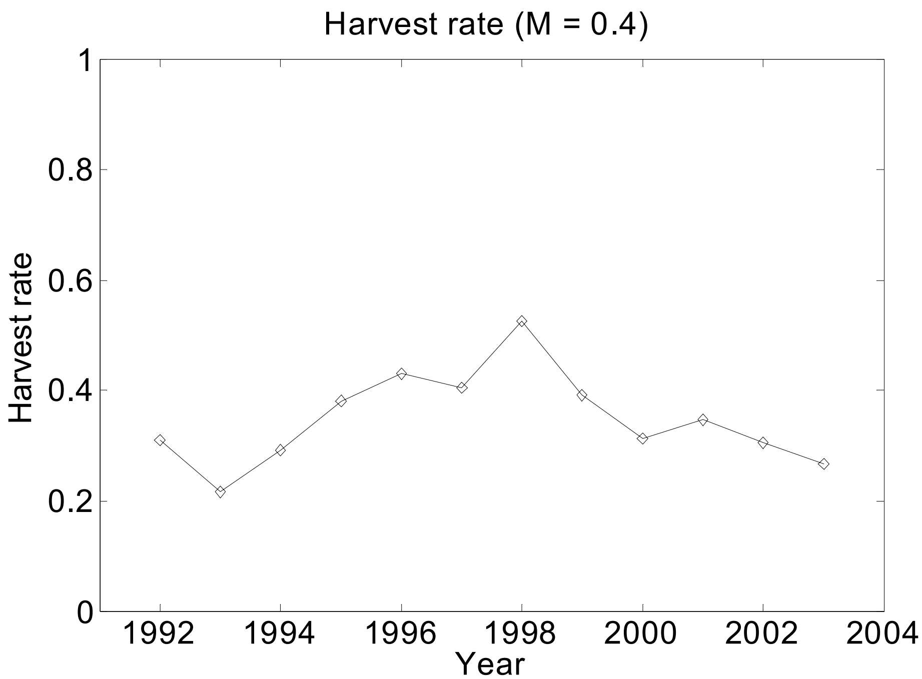


Figure 5.20 Estimated harvest rate (proportion of fish available to the fishery that are caught in a single year) from the age-structured model for instantaneous natural mortality rate $M = 0.40$ per year.

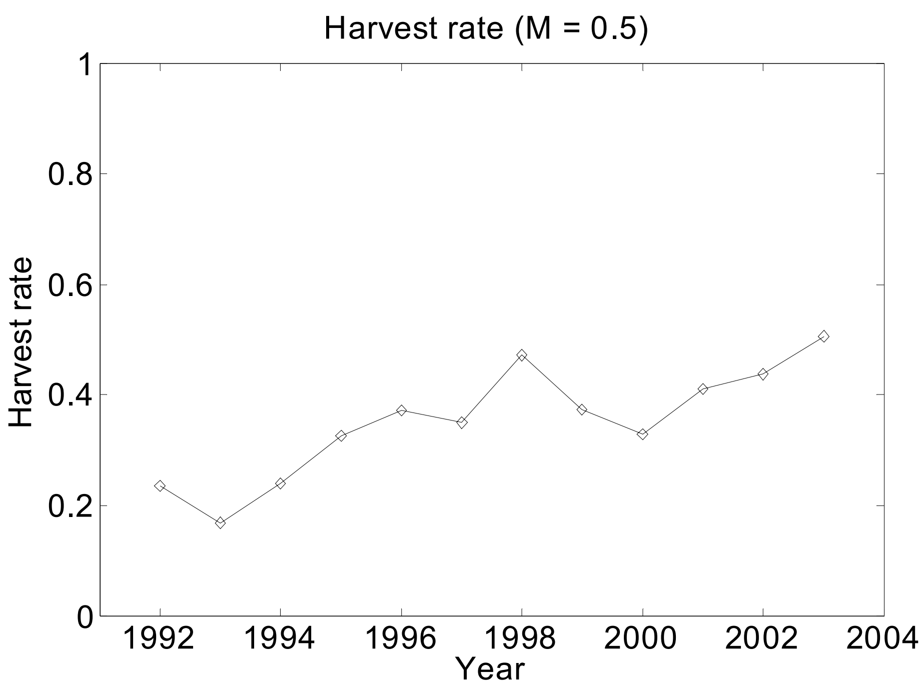


Figure 5.21 Estimated harvest rate (proportion of fish available to the fishery that are caught in a single year) from the age-structured model for instantaneous natural mortality rate $M = 0.50$ per year.

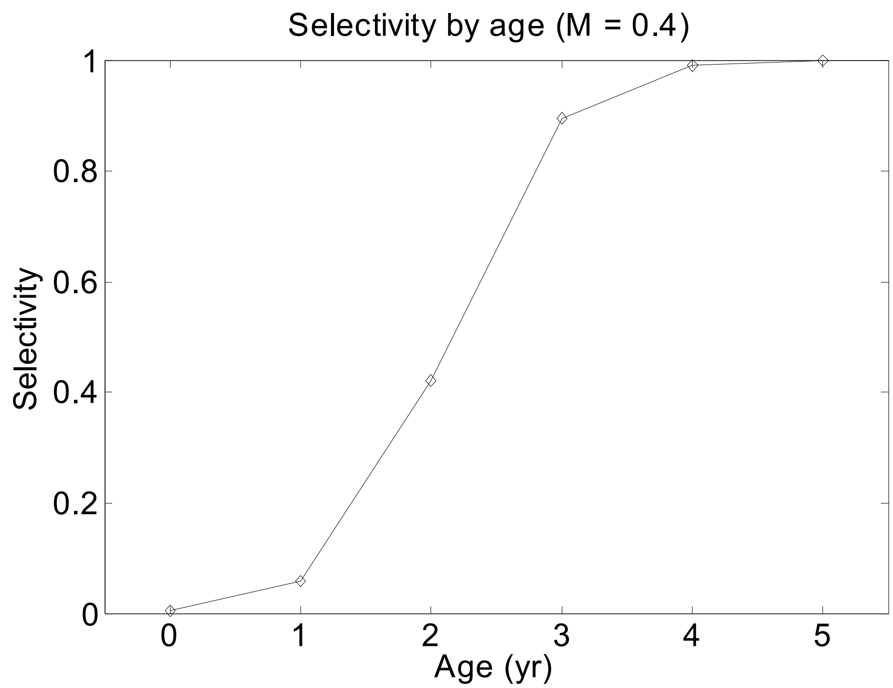


Figure 5.22 Estimated age selectivity of the fishery (proportion of fish of each age that are available to the fishery) from the age-structured model for instantaneous natural mortality rate $M = 0.40$ per year.

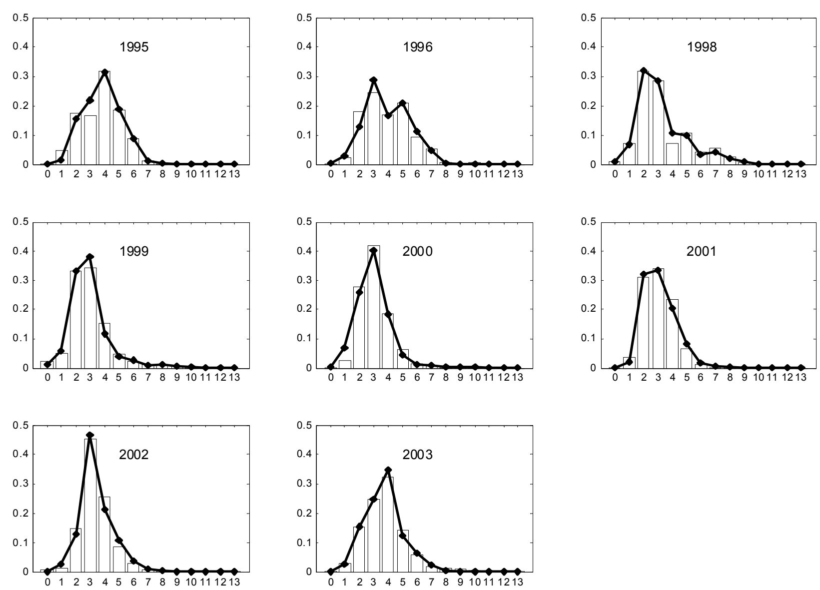


Figure 5.23 Observed (bars) and fitted (line) weight-based age frequency distributions from the age-structured model for instantaneous natural mortality rate $M = 0.40$ per year.

5.3 VIRTUAL POPULATION ANALYSIS

The VPA analysis used the age frequencies (Appendix 10.1) and the observed levels of standardised fishing effort (4.2.4). The results indicate that estimated annual levels of fishing mortality F from 1995 to 2002 varied widely (Table 5.4). Fishing mortality was estimated to be high on all fish aged four years or more (F exceeded natural mortality M = 0.33).

Generally, if fishing mortality was greater than natural mortality the fish stock could be viewed as heavily fished (Patterson 1992). Estimated recruitment numbers of fish indicated a decline in 2000 (Figure 5.24). It should be noted that the confidence intervals only relate to the years 1995 to 2000, and that the uncertainty is extremely large on the 2001 and 2002 recruitment estimates.

Table 5.4 Fishing mortality ($F_{y,a}$ – by year and age class) of sea mullet, derived from the base case (M = 0.33, age at maturity = 3) *ad-hoc* tuned VPA. The bold average annual F values indicate years when fishing mortality (F) exceeded natural mortality (M).

$F_{y,a}$	Ages									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1995	0.00165	0.08662	0.20655	0.32275	**0.52235**	**0.71690**	**0.74486**	**0.43809**	**0.09792**	**0.20712**
1996	0.00004	0.02812	0.37709	**0.40126**	**0.50191**	**0.61526**	**0.88730**	**1.66367**	**0.75493**	**1.12069**
1997	0.00005	0.00094	0.13886	**0.57286**	**0.99892**	**0.89832**	**0.60462**	**0.12017**	**0.18868**	**0.15058**
1998	0.00431	0.04723	0.35156	**0.68630**	**0.68649**	**1.32928**	**1.20329**	**1.41557**	**1.65120**	**1.52885**
1999	0.00697	0.03005	0.27263	**0.62145**	**0.80122**	**1.04908**	**1.34599**	**1.96717**	**1.50502**	**1.72065**
2000	0.00014	0.01297	0.21712	**0.53686**	**0.70166**	**0.88546**	**1.40238**	**2.27995**	**2.00000**	**2.13539**
2001	0.00296	0.05618	0.26403	**0.57641**	**1.01159**	**0.83502**	**0.67358**	**0.93765**	**1.78678**	**1.29436**
2002	0.00064	0.02192	0.25019	**0.51875**	**0.72527**	**0.88398**	**0.93638**	**0.91532**	**0.74542**	**0.82602**

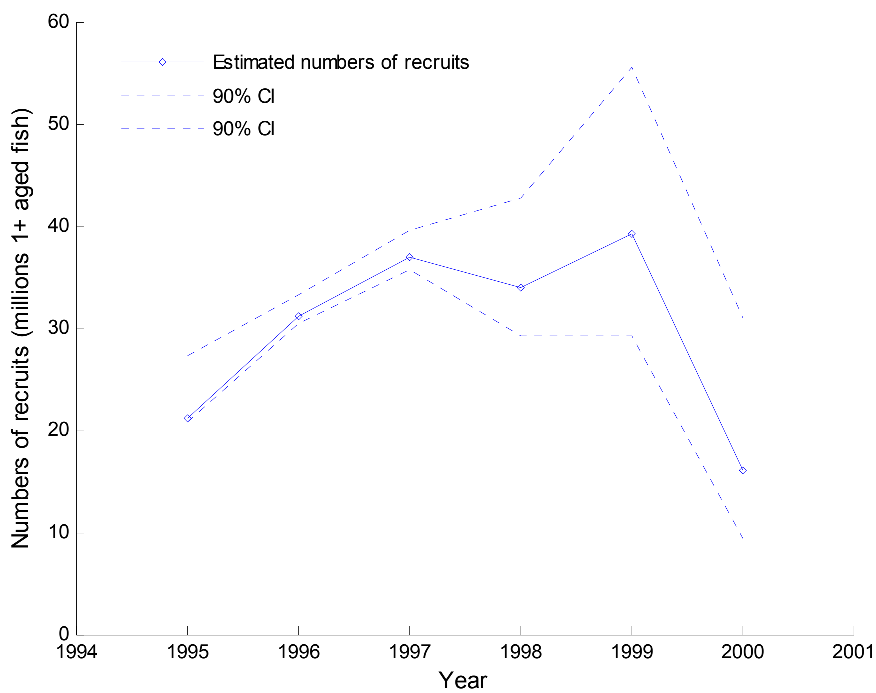


Figure 5.24 Estimated recruitment of sea mullet between 1995 and 2000, along with their upper 95% and lower 5% percentiles.

Table 5.5 contains the relevant management information. The B_{2002}/K^e is the ratio of the exploitable biomass in 2002 to the exploitable component of the carrying capacity (K^e). This ratio was estimated to be 0.22, indicating the resource is below the population size that supports maximum sustainable yield (≈ 0.38). $TAC_{0.1}$ or TAC_{sq} are the recommended catch strategies for allocating quota. $TAC_{0.1}$ is the quota if the $F_{0.1}$ policy is being used. The TAC_{sq} is the $F_{status\ quo}$ harvest strategy TAC that aims to keep the level of fishing mortality (effort) at the current levels. The upper 95% and lower 5%-iles are given in brackets. The TAC values are given in tonnes.

Table 5.5 Summary results from the VPA application using the base case natural mortality rate.

Parameter	M=0.33 per year Age at 50% mature = 3
B_{2002}/K^e	0.22 (0.05:1)
$TAC_{0.1}$	3620 (2232:71153)
TAC_{sq}	5046 (3060:105599)

5.4 FORECASTING WITH THE MODIFIED PALOHEIMO MODEL

Forecasting the behaviour of catch rate and exploitable biomass was accomplished by using the modified Paloheimo catch-at-age model from section 4.2. These were the steps used:

1. Generated 1000 sets of numbers-at-age in 2003 from the parameter estimates and distributions for recruitment, catchability and selectivity from the model output (annual recruitment version) using the Matlab function 'mvnrnd' on the covariance matrix from the Jacobian (obtained from the regression output).

2. Generated recruitment in the years 2003 onward by two regimes (section 5.4.1) based on the recruitment estimates from the model.

3. Simulate for each of the 1000 parameter-sets under each of three defined effort management scenarios (section 5.4.2). Each management scenario was tested under both recruitment regimes (section 5.4.1).

5.4.1 RECRUITMENT REGIMES

A considerable amount of effort went into to deriving a spawning stock-recruitment function under a Beverton-Holt or Ricker relationship (Haddon 2001). However, the relationship between spawning stock and recruitment was unclear, as shown in Figure 5.25.

Figure 5.25 Illustration of stock-recruitment irregularity. The points are taken from the estimates of recruitment and biomass, assuming that new recruits to the fishery were sired by the spawning biomass two years prior (recall that the first ring develops at the beginning of the third calendar year of life).

5.4.1.1 RECRUITMENT REGIME 1 (RR1)

Recruitment in each year from 2004 onwards is drawn from a log-normal distribution with the mean set at the constant recruitment regime derived from the modified Paloheimo catch-at-age model estimate, which was 20.956 million recruits per year. The variance of the distribution is taken from the variance of the annual recruitment predictions:

$$R_j = e^{\mathrm{N}(20.956,\,0.2598)} \tag{5.1}$$

It should be noted that recruitment regime 1 is optimistic in assuming that mean recruitment is at the value obtained from the constant recruitment model. Figure 5.1 clearly indicates that recruitment in recent years has been very poor so this assumption may not be well founded. In light of this, a second regime was constructed so the recruitments in 2004 through 2006 could be drawn from a more pessimistic distribution than the other years, in order to account for the recent decline in recruitment.

5.4.1.2 RECRUITMENT REGIME 2 (RR2)

This regime acts as per Regime 1, except that the mean of the distribution in 2004, 2005 and 2006 is set at the geometric mean of the annual recruitment regime catch-at-age model estimates for 2001, 2002 and 2003 (10.628 million recruits per year). The years following 2006 are the same as in Regime 1.

5.4.2 MANAGEMENT SCENARIO SIMULATIONS

It was originally intended to conduct several management scenario simulations to examine the dynamics of the fishery under as many circumstances as possible. In working on the forecasting segment of the project, it has been discovered that, given the rather disturbing nature of Figure 5.1, most of the management scenarios modelled yielded rather bleak predictions of catch, catch rate and biomass in the coming years. Rather than show the forecasts for all management scenarios tried, only the two most realistic and conservative scenarios, and a high effort scenario are discussed.

5.4.2.1 MANAGEMENT SCENARIO 1 (MS1)

In this scenario, effort is set at the arithmetic mean of the effort in the years 1999 through 2002 (recall that 2003 is a special case) for all years from 2004 onward. This corresponds to 135 420 standard units of effort.

Recruitment Regime 1 (RR1)
Under MS1 and RR1, Figure 5.26 suggests that catch rates are likely to decline in 2004 and gradually increase over the next 4–5 years.

Recruitment Regime 2 (RR2)
Under MS1 and RR2, Figure 5.27 suggests that catch rates are likely to decline heavily in 2004 and take several years to recover. This is largely due to the assumptions pertaining to future recruitment levels.

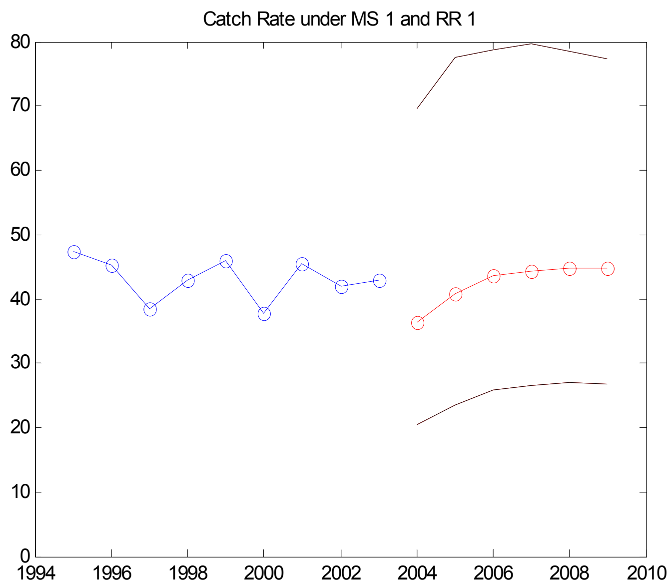


Figure 5.26 Catch rate predictions under MS 1, RR 1. Blue line is standardised catch rate. Red line is predicted catch rate. Black lines are 95% confidence intervals.

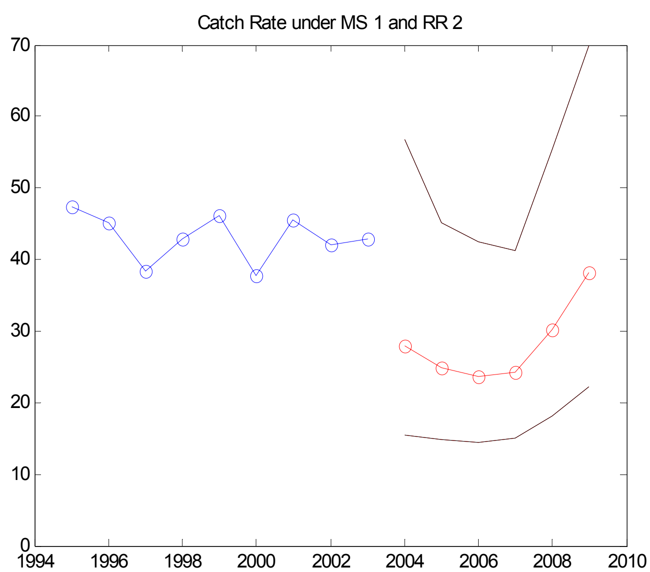


Figure 5.27 Catch Rate predictions under MS 1, RR 2. Blue line is standardised catch rate. Red line is predicted catch rate. Black lines are 95% confidence intervals.

5.4.2.2 MANAGEMENT SCENARIO 2 (MS2)

Effort is set as per scenario 1 for the years 2004 to 2005. Effort in 2006 onward is set to 2/3 the scenario 1 effort, 90 281 units.

Recruitment Regime 1 (RR1)
Under MS2 and RR1 catch rates were predicted to increase steadily from 2004 to 2009 (Figure 5.28)

Recruitment Regime 2 (RR2)
Under MS2 and RR2, catch rates were predicted to decline initially from 2004 to 2006 and then increase to 2009 (Figure 5.29).

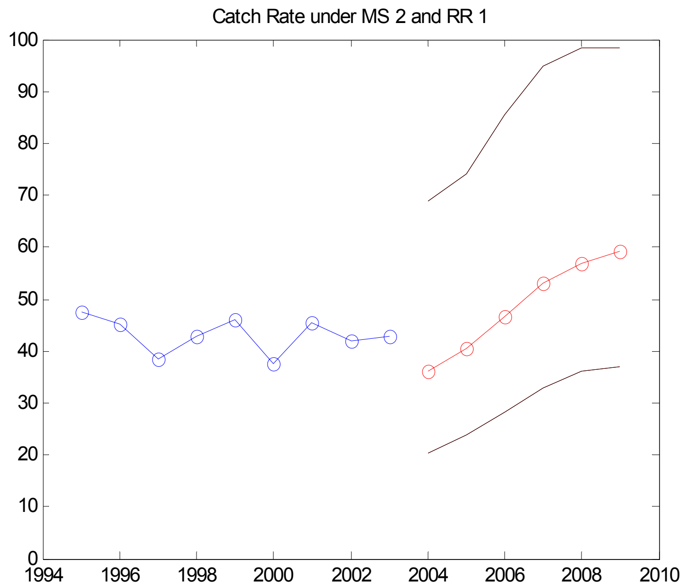


Figure 5.28 Catch Rate predictions under MS 2, RR 1. Blue line is standardised catch rate. Red line is predicted catch rate. Black lines are 95% confidence intervals.

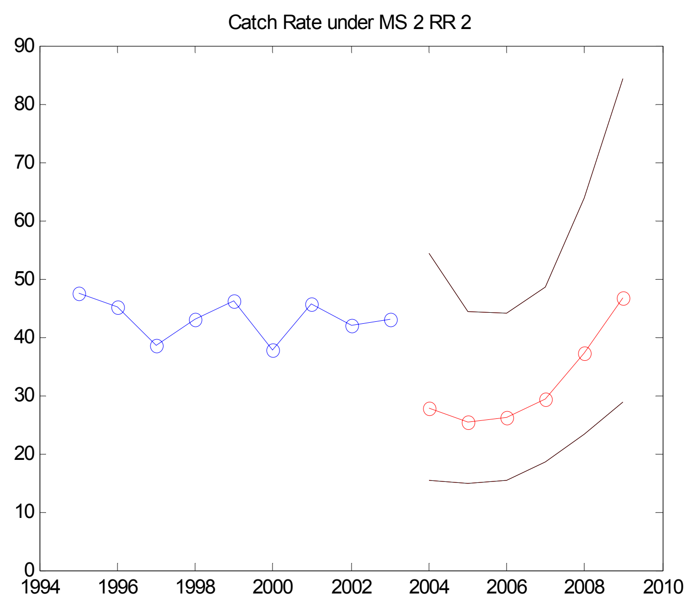
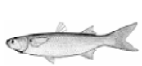


Figure 5.29 Catch Rate predictions under MS 2, RR 2. Blue line is standardised catch rate. Red line is predicted catch rate. Black lines are 95% confidence intervals.

5.4.2.3 MANAGEMENT SCENARIO 3 (MS3)

Effort is set as per scenario 1 for the years 2004 and 2005. Effort in 2006 onward is increased by a factor of 1.5 that of scenario 1 to a total of 203,130 units.



Recruitment Regime 1 (RR1)
Results for MS3 and RR1 suggest catch would generally decline through to 2009 (Figure 5.30)

Recruitment Regime 2 (RR2)
Under MS3 and RR2 catch rates would fall dramatically and although they would eventually begin to increase, they would remain below the long-term average of CPUE for many years (Figure 5.31).

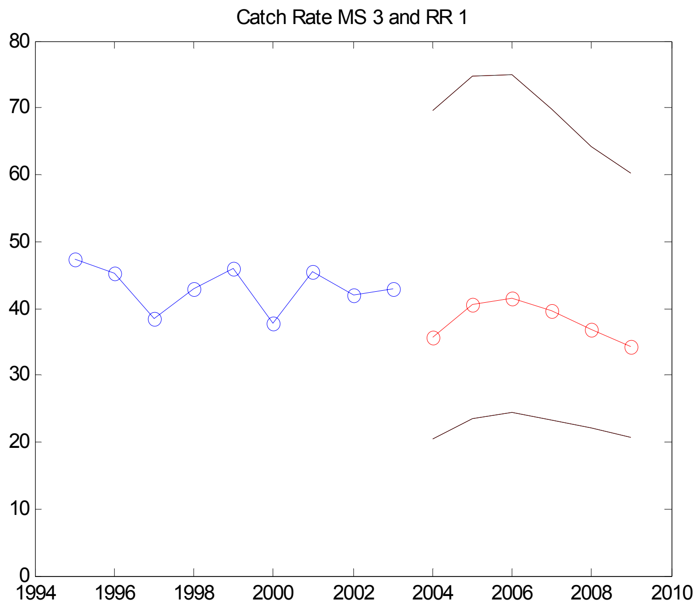


Figure 5.30 Catch Rate predictions under MS 3, RR 1. Blue line is standardised catch rate. Red line is predicted catch rate. Black lines are 95% confidence intervals.

Figure 5.31 Catch Rate predictions under MS 3, RR 2. Blue line is standardised catch rate. Red line is predicted catch rate. Black lines are 95% confidence intervals.

6 DISCUSSION

6.1 MODIFIED PALOHEIMO'S CATCH-AT-AGE MODEL

6.1.1 MODEL BEHAVIOUR

The catch rates in the years captured by the modified Paloheimo catch-at-age model (section 4.2) vary by only 11% on either side of the mean. This lack of contrast is deemed to cause the model behaviour to be heavily dictated by the dynamics of the age and length samples and not so much by the change in CPUE over time.

The low recruitment predictions in 2001 and 2002 (Figure 5.1) translate to predicted low catch rates in 2004 and 2005, which are supported in the simulations of section 5.4. All scenarios suggested the predicted catch rates for 2004 and 2005 would be lower than the observed catch rates from previous years (see Figure 5.26 through to Figure 5.31).

The model generally predicted the high catch numbers of the 2, 3 and 4 ring-old fish quite well (Figure 5.5). The numbers of 1 and 8 ring-old fish that were harvested were lower and the model fit for these age classes had slightly larger residuals. As shown in Figure 5.6, age classes with low catch rates (*i.e.* 1 and 8 ring-olds) have a higher spread of residuals than age classes with high catch rates (2, 3 and 4 ring-olds).

It should be noted that the model was originally constructed and fitted using only the criteria of 2 to 7 ring-olds. The additional points were included to increase the amount of data the model had to work with in order to counter over-fitting (the annual recruitment regime has a relatively high number of parameters).

6.1.2 RECRUITMENT AND MORTALITY

The assessment suggests that recruitment is a highly variable process. The catch curve analysis (section 4.2.6.1) shows clearly that fishing mortality plays a much more significant role in changing the population structure than natural mortality. Fishing mortality was estimated to be approximately twice that of natural mortality over the past 9 years:

$$\begin{aligned} F_{cc} &= Z_{cc} - M \\ &= 0.95 - 0.33 \\ &= 0.62 \end{aligned}$$

The large increase in the catch of ocean beach fish from 1992-1994 (Figure 3.5) may have contributed to the recruitment drop in 1994 and 1995 (Figure 5.1). Management changes brought into New South Wales in 1995, coupled with an overall decrease in oceanic landings in both States are thought to have assisted the partial recovery of recruitment during the late 1990's.

Changing environmental effects such as predation, transport and starvation of larvae are thought to impact recruitment levels and distinguishing these effects from exploitation is particularly difficult in fish populations (Wooster and Bailey 1989). The high estimated recruitment levels in 1991 and 1992 (Figure 5.1) may have been due to a 'one off'environmental effect. However, the relatively large number of fish in age classes six and older in 1995 and 1996 (Table 4.3) suggest that recruitment may have also been high in 1989 and 1990. Collectively, these results suggest that recruitment levels were significantly higher in the period 1989-1991, than they were from 1994-2002 and it is unknown whether this apparent change has been due to environmental effects or fishing effort.

The drop in recruitment in the last three years (Figure 5.1) is difficult to explain. Oceanic landings were relatively stable in Queensland (Figure 3.6) and dropped in New South Wales during the time that the spawners for recruitment in 2001 and 2002 would have been reproducing. Note that recruitment in 2003 is very uncertain as it is based on one data point only, namely the observations of fish in age class one in 2003. Given the very low selectivity of one ring-olds, model estimates of actual numbers of recruits in 2003 are tenuous at best.

6.1.3 FORECASTING

The simulations and forecasting (5.4) account for the recent slump in recruitment by selecting future recruitments from a distribution that is similar to that yielded by the model estimates. Obviously, if the biomass declines, recruitment will also decline, so the forecasts should be taken as realistic only in the short term (i.e. next two to three years). For the range of management scenarios and recruitment regimes that were considered, most of the forecasts (Figure 5.26 through to Figure 5.31) suggest that catch rates would eventually improve and increase above those for the period 1995–2003 over the long term (i.e. after about five years).

Comparison of the management scenarios indicates that the catch rate forecasts depend mainly on the recruitment regime of the simulation, and less upon the management strategy used. As expected, higher catch rates are observed under a scenario in which effort is reduced (Management Scenario 2) than under a scenario in which it is kept constant or increased (Management Scenarios 1 and 3).

It is important to note that regardless of which management scenario or recruitment regime is applied, the catch rate in the next two to three years is predicted as being low in comparison to observed rates over the last 20 years.

6.2 STATISTICAL CATCH-AT-AGE MODEL

This model considered a range for the possible values of natural mortality (M) equal to 0.33, 0.40 and 0.50 per year. Model results for all three cases indicated a) that recruitment varied greatly between years and b) that there was a significant decline in recruitment from 2000 to 2002. This decline in recruitment is consistent with the results from the modified Paloheimo catch-at-age model results (section 5.1). The overall trend in recruitment depended heavily on the value of M (Figure 5.16 to Figure 5.18). Because of the uncertainty over the true value of M, it is unknown whether the low recruitment in 2002 is a historically low level.

The ageing data were found to be very reliable. Strong year classes could be tracked from one year to the next. The CPUE data were not found to be useful for this modelling exercise because of hyperstability issues and because search time and technology used by fishing crews was not recorded. CPUE data were therefore omitted from the model.

Extra data on abundance would be required to identify the long-term trend in recruitment. Aerial surveys and fishery independent sampling could facilitate this (e.g. electrofishing and gillnetting). Abundance estimates that are based on fishing data could be improved by recording estimates of search time or search technology.

6.3 VIRTUAL POPULATION ANALYSIS

The VPA estimated that fishing mortality on fish aged four years and older was greater than the estimate of natural mortality ($M = 0.33$) and thus suggest relatively high exploitation rates. The VPA was based on a short time series of catch-at-age data from 1995 to 2002 and therefore the uncertainty on recent recruitment estimates was high. Again, there was no obvious relationship between spawning stock size and recruitment. However, if the geometric mean of the calculated annual recruitments is used (Figure 5.24), a possible total allowable catch (TAC) according to a $F_{0.1}$ fishing policy would be 3620 tonnes (Table 5.5). Again, uncertainty associated with this estimate is large.

6.4 THE STATE OF THE FISHERY

While the fishery has had a long and productive history in both States, both the modified Paloheimo catch-at-age model and the statistical catch-at-age model (section 5.2) suggest that recruitment is likely to have declined in 2001 and 2002. If this were a true reflection of reality, then biomass would be expected to decline in 2004 and remain low through to 2006.

The New South Wales licence restrictions introduced in the mid-nineties are likely to have prevented what could have been a serious long-term reduction in recruitment, allowing some recovery to take place between 1997 and 2000.

The biomass is forecast to be relatively low over the next few years. As discussed earlier, this is mainly because of what appears to be much lower recruitment in 2001 and 2002 (and possibly 2003 but analyses for this year are not complete).

The relatively constant catch rate is concerning in that the system may be more heavily susceptible to hyperstability than originally thought. If hyperstability is playing a significant role in preserving catch rates while the stock is declining then the projected catch rate trajectory may not indicate the true behaviour of the stock.

Mullet are known to develop in freshwater as well as estuarine environments. The lack of commercial fishing pressure in freshwater regions probably protects the stock to some extent, but the degree to which this issue may affect the assessment is unclear.

7 RECOMMENDATIONS

- Another stock assessment is conducted in about three years, if by this time more data are available for clarification of the recruitment dynamics.
- The Queensland Long Term Monitoring Program is extended to capture the age, length and sex structure of the estuarine component of the fishery.
- Annual otolith microchemistry is used to quantify the exploitable fraction of sea mullet (i.e. the proportion of sea mullet that move from fresh water to the fishery each year). This data may also help identify the important estuaries or catchments for recruitment.
- Historic tagging data be analysed to estimate selectivity.
- A fishery independent index of exploitation is developed.
- The commercial fishing logbooks should be improved to allow accurate reporting of target species, fishing search time, size of fishing operation, and zero catches.

7.1 MANAGEMENT

No major changes to the management of the sea mullet fishery are recommended at this time. It is recommended that management approaches to the fishery be revisited in three to five years, when more data will be available on catch rates and age structure, which can contribute to a revised stock assessment.

Relatively low biomass levels are to be expected over the next year or two. It is recommended that if catch rates turn out to be low and do not recover by around 2007 that, in the absence of further quantitative research, management action be taken to reduce effort across the entire fishery. Though the two States are responsible for their own fisheries, great care should be taken to ensure that management changes are made with a view to benefit both States. For example, halving ocean beach effort in Queensland would not be expected to improve sustainability of Queensland catch unless the New South Wales authorities also acted to reduce ocean beach activity. Given the high average exploitation rate, reduction in effort over a four to five year term may improve recruitment to pre-1993 levels, allowing a higher long-term sustainable catch rate.

7.2 MONITORING

Data related recommendations:

1. Queensland Long Term Monitoring

   The long term monitoring program should be brought in line with the New South Wales program to include:

   — Estuarine age and length sampling
   — Length frequencies containing sex at length information.

   In this assessment, estuarine sampling from New South Wales was drawn on exclusively when constructing the predicted catch-at-age of fish in Queensland estuaries. Samples taken from Queensland estuaries would thus be a valuable addition to the data set.

   Sex ratio is of special interest in the roe-driven sea-mullet fishery, and any extension of this work into more complex economic considerations would require detailed information on sex structure. Also, determining and recording sex in future length frequency samples would complement the New South Wales data.

2. Fishery-independent measures of abundance

   Given the uncertainty in definition of effort discussed in this report, an index of abundance that does not depend on fishing effort would be considered valuable. Aerial surveys, electrofishing and fishery-independent gillnetting are means by which this might be obtained. The cost-effectiveness of these monitoring methods should be investigated.

3. Fishery-dependent measures of abundance

   The commercial fishing logbooks should be improved to allow accurate reporting of target species, fishing method, fishing search time (and spotting), size of fishing operation, and zero catches. This information is currently incomplete or not available, but is essential to define accurate measures of fishing effort and to improve our understanding of the relation between catch-rates and abundance. These issues were detailed in the stock assessment review workshop in 1998 (Dichmont et al. 1999).

4. Collection of economic data

   Economic data such as historic records on the market price for mullet fillets and roe would provide a means of including economic force on the behaviour of fishermen, which is known to be substantial.

7.3 RESEARCH

7.3.1 BIOLOGY

The time between birth and the formation of the first otolith ring is uncertain. The algorithm applied in this assessment though logical may not completely account for variation between ring count and age class. It is recommended that biological research be invested into determining the expectancy and distribution of the time frame involved in this process, if possible.

7.3.2 QUANTITATIVE RESEARCH

The sex ratio of the population is not examined in this assessment, though it provides an excellent data set with which to link economic information into the modelling process due to the fact that the fishery is becoming increasingly roe-driven. Hwang et al. (1990) investigated the sex ratio behaviour in detail in their assessment of the Taiwanese sea mullet fishery.

The definition of fishing effort is the most significant limitation of the work herein. It is recommended that future quantitative research incorporate a comprehensive investigation into the appropriate definition of fishing effort such that catch-per-unit effort is, as far as possible, genuinely proportional to abundance as described by Hilborn and Mangel (1997).

Modelling the impact of market forces on the behaviour of the fishing fleet would be a valuable extension to this work, but could not be accomplished without first re-examining the definition of effort.

Given the uncertainty of the reconstituted biomass estimates, reference point analysis is not presented in this report. Reference point and robust biomass definition are shorter-term goals that could be achieved relatively easily based on the materials and methods employed in this assessment.

8 ACKNOWLEDGEMENTS

Professor Hugh Possingham, University of Queensland provided advice and academic guidance to Paul Bell, who based his Master's degree thesis project on the assessment. Professor John Hoenig, Virginia Institute of Marine Science (Virginia, USA), reviewed the assessment and put forward suggestions for improving the analyses and quantifying key population parameters.

We are very grateful for the encouragement, advice and patience dealing with our data requests provided by Dr. James Scandol and Mr. David Makin of New South Wales Fisheries. Without this level of cooperation between the States (Queensland and New South Wales), assessment of such shared stocks would not be possible.

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10 APPENDICES

10.1 AGE FREQUENCIES

In the figures below, age class (ring count) is shown on the x-axis, with the corresponding proportion of the age class in the sample shown on the y-axis.

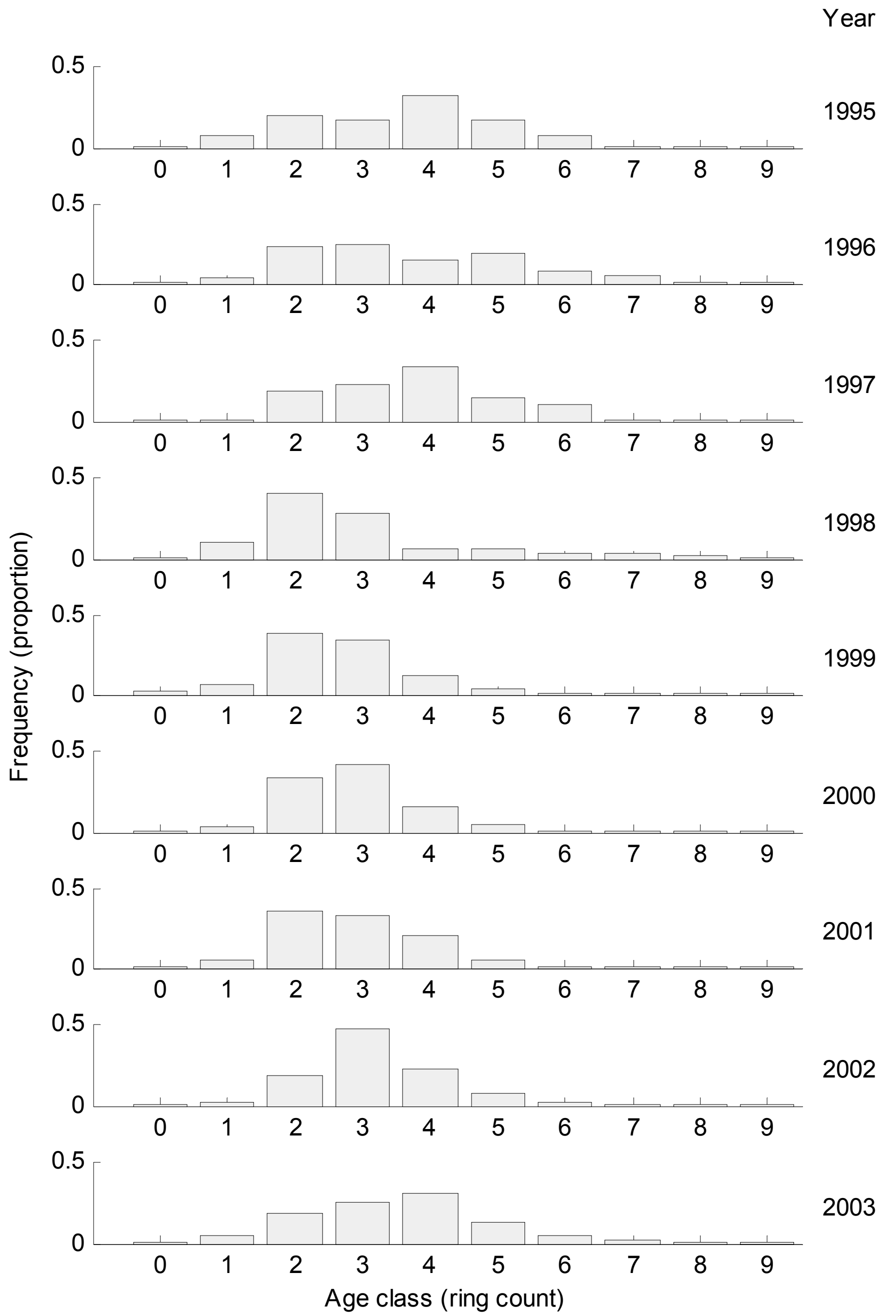

Figure 10.1 The frequency of each age class in each year.

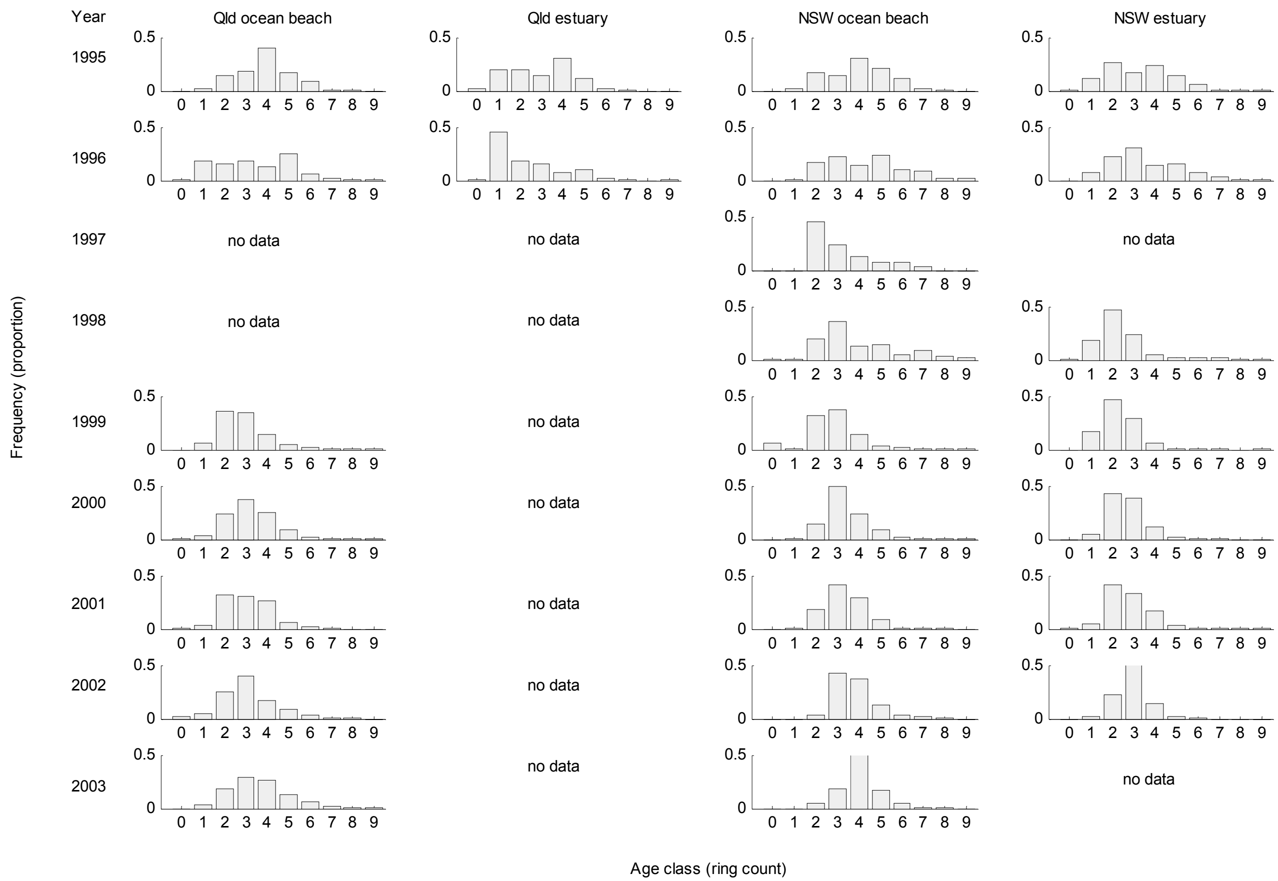

Figure 10.2 The frequency of each age class in each year split into State and sector groups.

10.2 LENGTH FREQUENCIES

In the figures below, fork length is shown on the x-axis, with the corresponding proportion of each length in the sample shown on the y-axis. Note that the data in the Queensland figures below are presented at rounded 1 cm resolution.

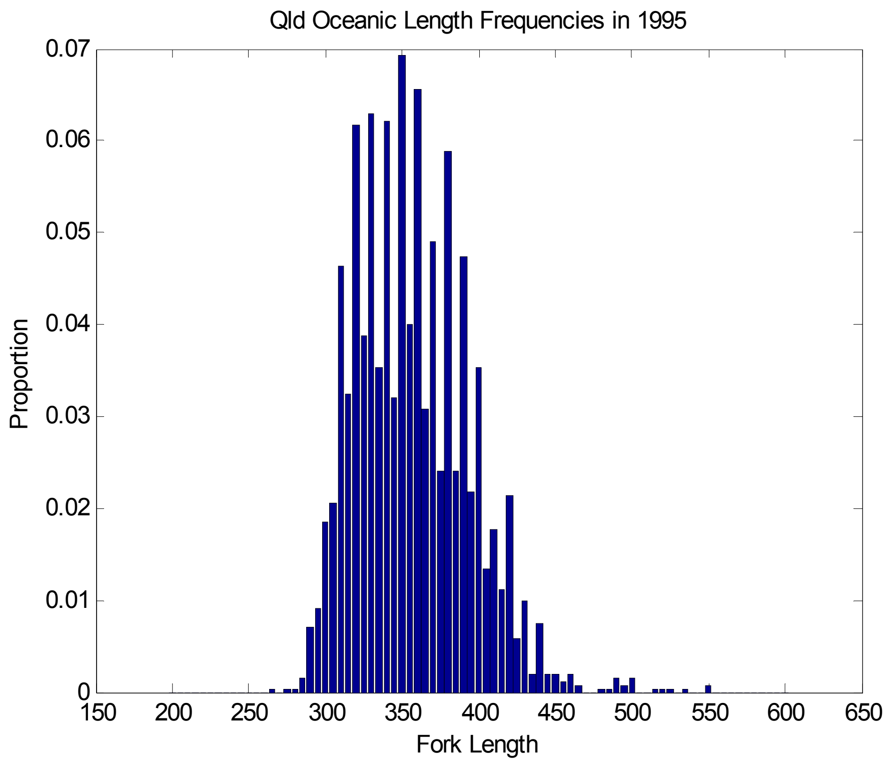

Figure 10.3 The Queensland oceanic length frequencies for 1995. The spikes coincide with whole centimetre measurements, indicating that some of the sampling in Queensland was likely to have been carried out at 1 cm resolution.

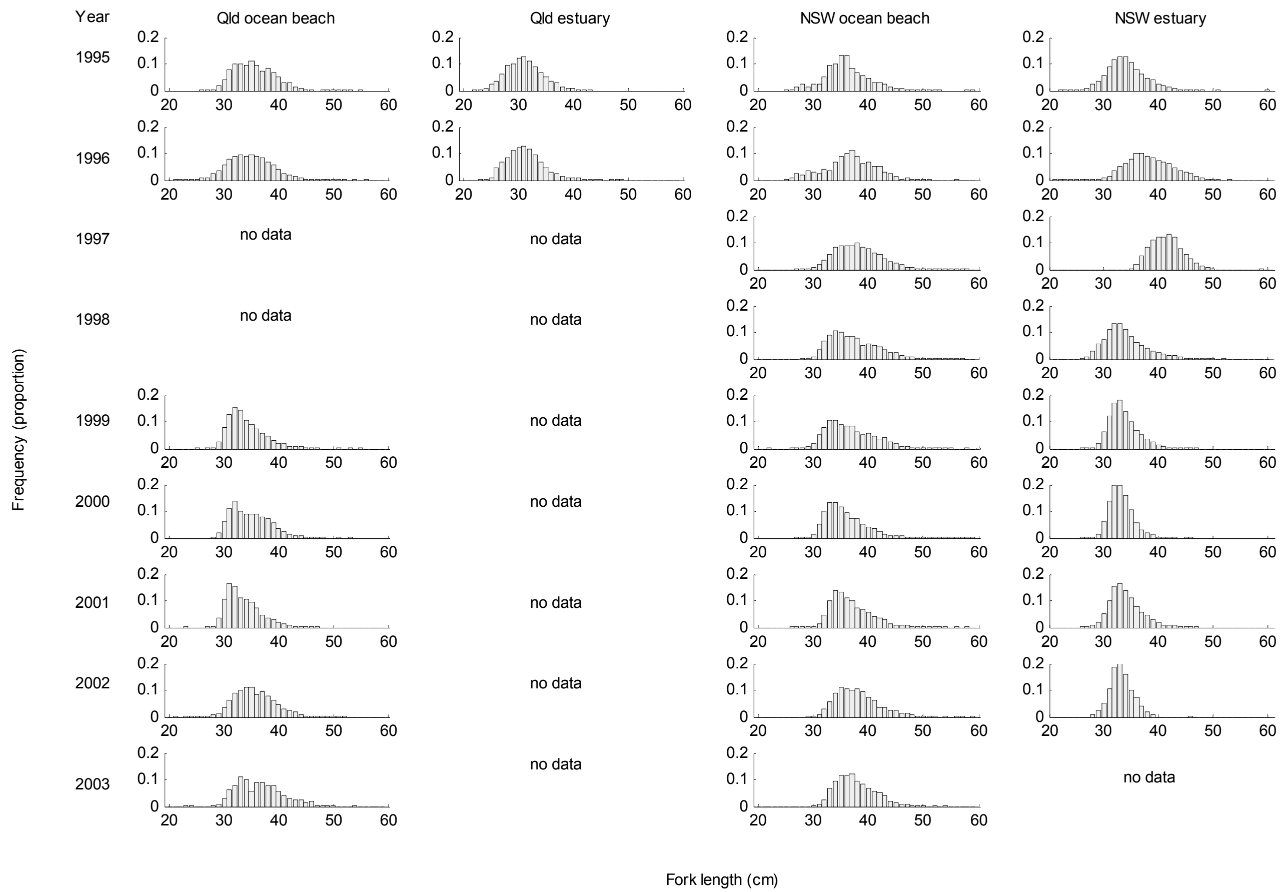

Figure 10.4 The length frequencies for each year split into State and sector groups.

10.3 VON BERTALANFFY GROWTH

The von Bertalanffy growth equation (von Bertalanffy 1957) provides a mechanism through which length can be quantified as a function of age. It takes the form:

$$L_t = L_\infty\left[1 - e^{-K(t-t_0)}\right] \qquad (10.1)$$

where L is the length, t is the age (time since birth), K and t_0 are constants, and L_∞ is the asymptotic average-length obtained at time infinity (von Bertalanffy 1957).

The von Bertalanffy growth equation is of limited use in this assessment because our sampling data is very fishery dependent. Fishery dependent samples can result in significantly different estimates of growth rate than from estimates obtained from fishery-independent sampling (Smith and Deguara 2002). This problem is demonstrated by examining the von Bertalanffy growth curve, which has been fitted to the age samples shown in **Figure 10.5**. In **Figure 10.5**, age in years has been obtained by application of the algorithm described in section 3.2.2. The line of best fit was obtained by use of the Matlab function 'nlinfit', which is capable of fitting a non-linear function by least squares. The parameter estimates for the regression are given in Table 10.1.

Table 10.1 Parameter estimates and 95% confidence limits for the von Bertalanffy parameters.

Parameter	Lower Confidence	Estimate	Upper Confidence
L_∞	411.68	419.91	428.14
t_0	–6.9515	–6.3956	–5.8398
K	0.18559	0.23647	0.21103

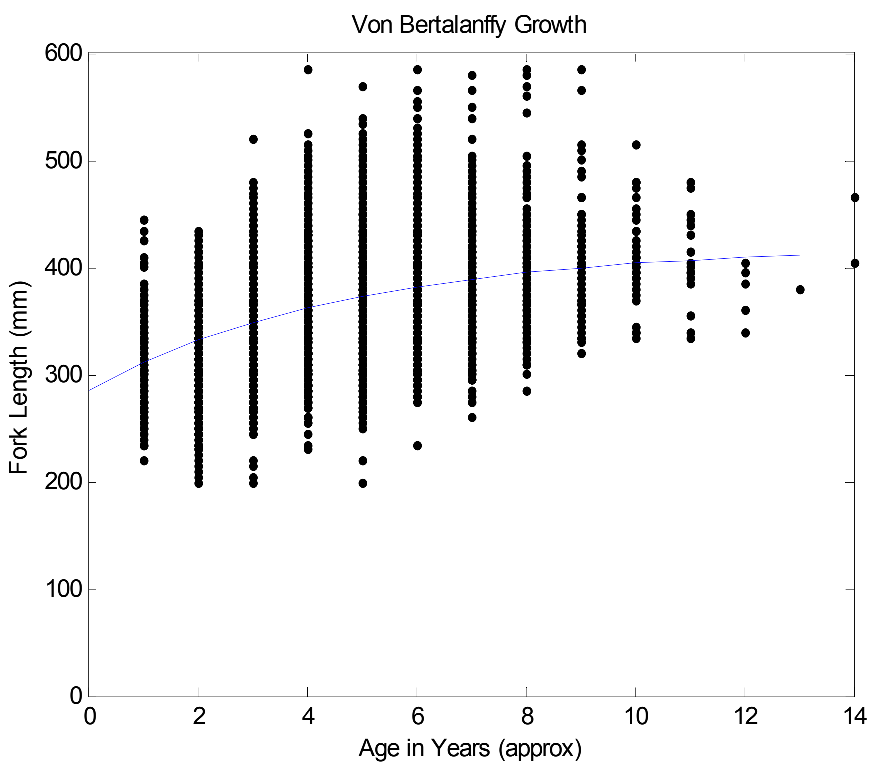

Figure 10.5 von Bertalanffy growth curve fitted by least-squares regression.

Notice the lack of fish at smaller lengths in **Figure 10.5**. Intuitively, there must exist many individuals much smaller than 200 mm in the population. The shape of the fitted curve results from the fact that the minimum legal length prevents samples of very small fish; an independent study would provide data points for the lower left hand corner of the scatter and perhaps make von Bertalanffy growth fitting more appropriate.

Note that there are a handful of genuinely juvenile fish in the 1995 and 1996 samples (around 8 cm in length) that have not been included in the regression (or indeed any of the analyses), which are presumed to have been obtained independently. If the von Bertalanffy approach were being used in the analysis in any real sense, these juveniles would help to anchor the curve near the origin (one would expect a newly hatched larvae to be close to 1 cm).

10.4 MODIFIED PALOHEIMO APPROXIMATION

In the interest of linearising the catch-at-age equation, Paloheimo (1980) and Hilborn and Walters (1992) used the following approximation:

$$\log_e\left(\frac{1-e^{-Z}}{Z}\right) \approx -\frac{Z}{2} \tag{10.2}$$

$-Z/2$ gives a reasonable approximation for the left hand side of this equation when Z is low, as illustrated in Figure 10.6.

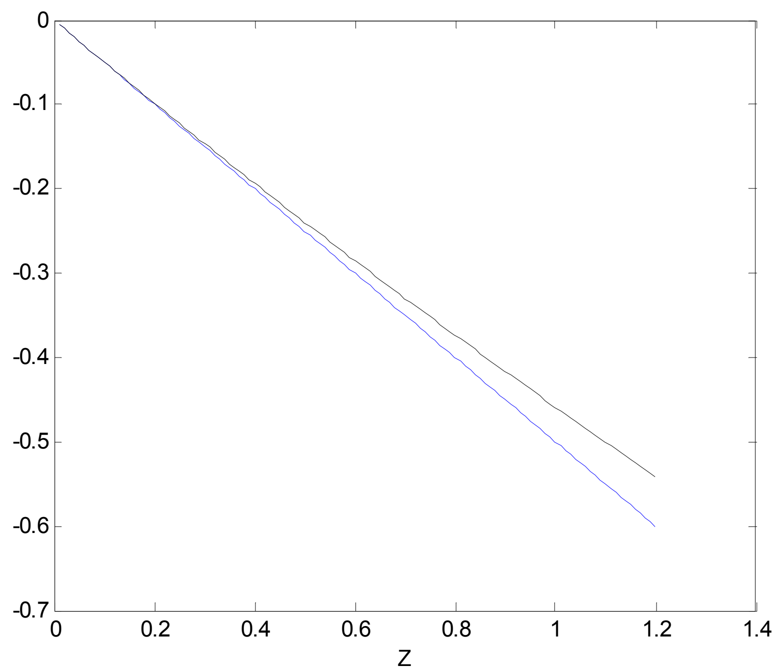

Figure 10.6 The function $\log_e((1\text{-}\exp(-Z))/Z)$ is in black, Paloheimo's approximation is in blue. Note the deficiency as Z becomes large.

It was found that dividing Z by a number slightly higher than 2 gave a better approximation, as shown in Figure 10.7.

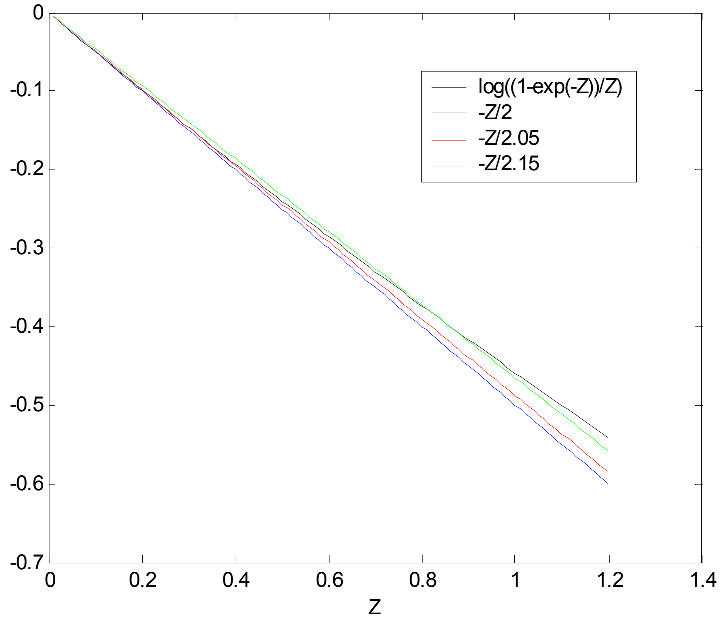

Figure 10.7 Approximations to $\log_e((1-\exp(-Z))/Z)$.

It is clear that by increasing the divisor in the approximation one can better approach the actual curve. Note that after a point the approximation begins to over-estimate the function for small values (green line), which is undesirable since it is preferred to err on the side of high mortality. The advantage of dividing by 2, as Paloheimo did, is that *Z*/2 intuitively means 'half the total mortality' for the current year in the equation. Not wanting to buck the trend, but since it is more accurate, this assessment made use of a modified Paloheimo approximation:

$$\log_e\left(\frac{1-e^{-Z}}{Z}\right) \approx -\frac{Z}{2.05} \tag{10.3}$$

10.5 REGRESSION OUTPUT FOR STANDARDISATION OF CATCH-RATES

Table 10.2 Estimates of parameters for standisation of catch rates.

Parameter	Estimate	S.E.	t(233991)	pr.
Constant	3.7199	0.0488	76.21	<.001
logeffort	0.56372	0.00723	77.93	<.001
year 1985	0.1335	0.0404	3.31	<.001
year 1986	0.2208	0.0396	5.58	<.001
year 1987	0.2308	0.0395	5.84	<.001
year 1988	0.2714	0.0359	7.56	<.001
year 1989	0.2334	0.036	6.48	<.001
year 1990	0.1665	0.0361	4.61	<.001
year 1991	0.1412	0.0362	3.9	<.001
year 1992	0.3185	0.0364	8.75	<.001
year 1993	0.1633	0.0363	4.49	<.001
year 1994	0.2574	0.0363	7.08	<.001
year 1995	0.3132	0.0364	8.61	<.001
year 1996	0.2494	0.0364	6.85	<.001
year 1997	0.0436	0.0364	1.2	0.23
year 1998	0.195	0.0379	5.15	<.001
year 1999	0.2599	0.038	6.83	<.001
year 2000	0.0653	0.038	1.72	0.086
year 2001	0.2542	0.0378	6.73	<.001
year 2002	0.1676	0.038	4.41	<.001
year 2003	0.1864	0.0379	4.92	<.001
month 2	0.1061	0.0168	6.33	<.001
month 3	0.2186	0.0163	13.44	<.001
month 4	0.39	0.0163	23.97	<.001
month 5	0.3833	0.0158	24.2	<.001
month 6	0.5709	0.0154	37.07	<.001
month 7	0.3061	0.0159	19.28	<.001
month 8	–0.2064	0.0169	–12.19	<.001
month 9	–0.4159	0.0175	–23.77	<.001
month 10	–0.3836	0.0172	–22.29	<.001
month 11	–0.2944	0.0173	–17	<.001
month 12	–0.1838	0.018	–10.23	<.001
method haul	0.6011	0.0147	40.77	<.001
method line	0.2692	0.0442	6.09	<.001
method ringnet	0.3953	0.0172	22.98	<.001
method seine	–0.5	0.145	–3.45	<.001
method trap	–0.732	0.0817	–8.96	<.001
method trawl	–1.8868	0.0468	–40.32	<.001
method tunnel	0.9911	0.0271	36.57	<.001
location Estuary	0.1077	0.0193	5.57	<.001
location Ocean	0.0295	0.0128	2.31	0.021
grid 29	–0.4004	0.027	–14.83	<.001
grid 30	–0.555	0.0328	–16.9	<.001
grid 31	–0.3067	0.0284	–10.78	<.001
grid 32	–0.4975	0.0252	–19.71	<.001
grid 33	–0.6814	0.0259	–26.33	<.001
grid 34	–1.0868	0.0291	–37.32	<.001
grid 35	–0.9969	0.034	–29.34	<.001

Parameter	Estimate	S.E.	t(233991)	pr.
grid 36	–0.8902	0.0358	–24.85	<.001
grid 37	0.376	0.115	3.28	0.001
grid 38	–2.79	1.09	–2.56	0.011
grid unknown	–0.1867	0.0824	–2.27	0.024
grid q21	–1.8651	0.0351	–53.08	<.001
grid q22	–1.5191	0.043	–35.32	<.001
grid q23	–1.8223	0.0471	–38.66	<.001
grid q24	–2.0574	0.0426	–48.26	<.001
grid q25	–1.5593	0.0406	–38.37	<.001
grid q26	–1.8354	0.0585	–31.36	<.001
grid q27	–1.9695	0.055	–35.79	<.001
grid q28	–1.5511	0.0459	–33.77	<.001
grid q29	–1.6616	0.0399	–41.66	<.001
grid q30	–1.4504	0.0348	–41.62	<.001
grid q31	–0.788	0.0394	–19.99	<.001
grid q32	–0.594	0.0318	–18.67	<.001
grid q33	–0.89	0.0326	–27.3	<.001
grid q34	–0.5996	0.0322	–18.6	<.001
grid q35	0.0034	0.0321	0.1	0.917
grid q36	–0.4718	0.0317	–14.87	<.001
grid q37	–0.4097	0.0318	–12.88	<.001
grid q38	–0.8312	0.0319	–26.02	<.001
grid q39	0.4812	0.041	11.73	<.001
grid q88	–0.5365	0.0319	–16.83	<.001

Parameters for factors are differences compared with the reference level:
Factor Reference level:

year 1984
month 1
method gillnet
location Both
grid 28

Table 10.3 Accumulated analysis of variance for standisation of catch rates.

Source	d.f.	s.s.	m.s.	v.r.	F pr.
logeffort	1	89849.325	89849.325	37694.24	<.000
year	19	2891.059	152.161	63.84	<.001
month	11	26193.553	2381.232	998.99	<.001
method_new	7	17599.547	2514.221	1054.78	<.001
location	2	3886.68	1943.34	815.28	<.001
final_grid	31	47818.783	1542.541	647.14	<.001
Residual	233991	557749.193	2.384		
Total	234062	745988.139	3.187		

10.6 CATCH-CURVE REGRESSIONS

10.6.1 LONGITUDINAL CATCH CURVE MODEL 1

Table 10.4 Summary of analysis for longitudinal catch curve model 1.

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	12	106.610	8.8842	51.54	< .001
Residual	43	7.413	0.1724		
Total	55	114.023	2.0731		

Table 10.5 Estimates of parameters for longitudinal catch curve model 1.

Parameter	Estimate	s.e.	t(43)	t pr
cohort 1988	5.705	0.51	11.19	<.001
cohort 1989	7.105	0.447	15.89	<.001
cohort 1990	6.863	0.398	17.24	<.001
cohort 1991	6.803	0.363	18.73	<.001
cohort 1992	5.666	0.413	13.71	<.001
cohort 1993	5.255	0.413	12.71	<.001
cohort 1994	4.899	0.375	13.07	<.001
cohort 1995	5.469	0.359	15.23	<.001
cohort 1996	5.977	0.359	16.65	<.001
cohort 1997	6.326	0.343	18.46	<.001
cohort 1998	6.391	0.339	18.85	<.001
cohort 1999	6.623	0.378	17.52	<.001
age	–0.9567	0.0596	–16.06	<.001

10.6.2 LONGITUDINAL CATCH CURVE MODEL 2

Table 10.6 Summary of analysis for longitudinal catch curve model 2.

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	21	109.540	5.2162	39.56	<.001
Residual	34	4.483	0.1318		
Total	55	114.023	2.0731		

Ta**ble 10.7** Estimates of parameters for longitudinal catch curve model 2.

Parameter	estimate	s.e.	t(34)	t pr.
cohort 1988	–0.992	0.257	–3.860	<.001
cohort 1989	2.700	2.820	0.960	0.346
cohort 1990	5.190	2.380	2.180	0.036
cohort 1991	5.454	0.763	7.150	<.001
cohort 1992	6.108	0.908	6.730	<.001
cohort 1993	7.860	1.360	5.800	<.001
cohort 1994	6.740	0.774	8.710	<.001
cohort 1995	6.059	0.644	9.400	<.001
cohort 1996	5.185	0.644	8.050	<.001
cohort 1997	5.357	0.920	5.820	<.001
cohort 1998	3.780	1.640	2.300	0.028
cohort 1999	2.796	0.257	10.890	<.001
age.cohort 1988	0.000	*	*	*
age.cohort 1989	–0.261	0.445	–0.590	0.561
age.cohort 1990	–0.643	0.445	–1.450	0.157
age.cohort 1991	–0.687	0.148	–4.630	<.001
age.cohort 1992	–1.030	0.148	–6.950	<.001
age.cohort 1993	–1.377	0.217	–6.340	<.001
age.cohort 1994	–1.279	0.133	–9.600	<.001
age.cohort 1995	–1.064	0.115	–9.270	<.001
age.cohort 1996	–0.813	0.115	–7.080	<.001
age.cohort 1997	–0.763	0.182	–4.200	<.001
age.cohort 1998	–0.378	0.363	–1.040	0.306
age.cohort 1999	0.000	*	*	*

10.6.3 CROSS-SECTIONAL CATCH CURVE MODEL

Table 10.8 Summary of analysis for cross-sectional catch curve model.

	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	15	107.882	7.1921	55.56	<.001
Residual	40	5.178	0.1294		
Total	55	113.060	2.0556		

Table 10.9 Estimates of parameters for cross-sectional catch curve model.

Parameter	estimate	s.e.	t(40)	t pr.
year 1995	3.828	0.639	5.990	<.001
year 1996	–0.207	0.903	–0.230	0.820
year 1998	–1.832	0.903	–2.030	0.049
year 1999	1.831	0.639	2.870	0.007
year 2000	3.621	0.639	5.670	<.001
year 2001	5.234	0.639	8.200	<.001
year 2002	3.375	0.639	5.280	<.001
year 2003	3.392	0.639	5.310	<.001
age.year 1995	–1.184	0.114	–10.400	<.001
age.year 1996	–0.376	0.161	–2.340	0.025
age.year 1998	–0.217	0.161	–1.350	0.185
age.year 1999	–0.996	0.114	–8.750	<.001
age.year 2000	–1.295	0.114	–11.380	<.001
age.year 2001	–1.634	0.114	–14.360	<.001
age.year 2002	–1.175	0.114	–10.330	<.001
age.year 2003	–1.067	0.114	–9.370	<.001

10.7 MATLAB CODE FOR CATCH-AT-AGE ANALYSIS

```
%-----------------------|
% Catch-at-age Analysis |
%-----------------------|

function output = caacode(Beta,x),

% 'output' is a column vector containing the logarithm of catch-at-age of
% 1 through 8-ring olds, starting in 1995. There are 64 such points (8 age
% classes in each of 1995 through 2003 except 1997). The first 8 points are
% ages 1 to 8 (in order) in 1995. The 9th through 16th points are ages 1 to 8 in 1996 etc.
% The logarithm of the gross catch in kilograms in 1997 is the 65th element of this vector.

% x is a dummy 'independent' variable of the same size as output. It is
% only required when using Matlab's regression tool.
% Beta is a column vector containing in this order:
% q, a50, a95, R95 to R03, R91 to R94 or in the case of constant
% recruitment q, a50, a95, R.

% Individual recruitment regime.
% Parameters for Individual Recruitment Regime - note the EXPONENT
% (lognormal errors)
q = exp(Beta(1));
a50 = Beta(2);
a95 = Beta(3);
R = exp(Beta(4:12)); %R95 to R03
Rprior = [exp(Beta(13:16))]; % R91 to R94

% Constant recruitment regime
%R(1:9) = exp(Beta(4));
%Rprior(1:4) = exp(Beta(4));

% Absolute untinkered average weight at age for 0 to 11 year olds:
avwa = [389.15 471.65 552.98 660.14 744.97 861.35 895.78 973.53 1052.8 971.52 1244.6];

% Adjusted avwa:
avwa = [389.15 471.65 552.98 660.14 744.97 861.35 895.78 973.53 1052.8 (1052.8+1244.6)/2 1244.6 1260 1260 1260];

% Adjusted weight at age each year
```

```
wa = horzcat([308.12  406.61  550.86  616.48  631.19  690.73;
  198.24  433.35  569.21  711.67  800.52  834.66;
  646.26  646.46  585.97  878.91  913.74  970.66;
  508.2  491.33  550.95  713.98  764.6  1190.5;
  627.17  490.91  557.69  656.08   823  900.99;
  461.63  469.88  512.79  620.71  719.71  831.18;
  285.84  440.11   551  642.77  710.61  828.15;
  421.41  573.37  555.32  657.16  801.93  839.02;
  302.61  467.65  576.04  662.29  708.21  775.55;],...
  [757.63  899.85  1037.1  1020.4  avwa(11)  avwa(12);
  833.91  844.35  768.58  800.89  961.58  avwa(12);
  1037.5  1202.4  1042.1  1639.5  1364.1  avwa(12);
  1012.6  985.17  951.82  904.5  1285.6  avwa(12);
  1145.8  934.04  975.65   1073  1639.5  avwa(12);
  864.57  1108.9  844.84  884.09  1172.5  avwa(12);
  845.17  1140.8  avwa(9)  1214.5  avwa(11)  avwa(12);
  844.77  1004.7  1194.6  avwa(10) avwa(11)  avwa(12);
  861.88  870.46  822.85  903.21  1163.9  avwa(12);],...
  [avwa(13)  avwa(14);
  avwa(13)  avwa(14);
  avwa(13)  avwa(14);
  avwa(13)  avwa(14);
  avwa(13)  avwa(14);
  avwa(13)  avwa(14);
  avwa(13) avwa(14);
  avwa(13) avwa(14);
  avwa(13) avwa(14);]);

% Selectivity curve - from Haddon
ages = [1:1:13];
S = 1./(1+(1/19).^((ages-a50)/(a95-a50)));

% Natural mortality (annual)
M = 0.33; % Taiwan paper and Hoenig estimate

% Total annual mortality estimate from longitudinal catch curve analysis -
% used below for K estimate only
ccZ = 0.9567;
F = ccZ - M;
```

```
% Standardised effort from 1988 to 2003
E = [127096.7329 129531.0791 129706.2219 145824.9679 148354.2244 136557.7601 161051.7862 141545.7688 138427.5466 144577.9001
163503.7033 122960.6237 132386.8416 144970.3019 141369.7498 93795.11338];

% Compute N95
N95 = [0;0;0;0;0];
for pp = 1:4,
   PastEff = 0;
   for k = pp:4,
    PastEff = PastEff + E(k+3)*S(k-pp+1);
   end

   nM = 4-pp+1; % natural mortality suffered


   N95(4-pp+2) = Rprior(pp)*exp(-q*PastEff - M*(nM - 1));
end

% Fill out the other ages in 95:
for i = 6:13,
 N95(i) = N95(i-1)*exp(-ccZ);
end

%----------------------------------------------------
% Given the parameters and hardcoded constants above, how many 'a' ring olds
% would we expect to catch in year 'j'?

catchatage = []; % 64 elements
C97 = []; % catch in 97
numsatage = zeros(13,8); % 13 ages in 1996 to 2003
B95to03 = zeros(1,9); % Biomass in each year

for j = 1:9, % 95 onward
 for a=1:13,
  % Figure out Cja and attach it to catchatage

  % set up Past Eff and 'R'initial - fish born in the 80s/early 90s were
  % 'recruited' as mature fish in 95
  if (j-a)>=0, % Recruited in 1995 or later
```

```
   Rin=R(j-a+1);
   PastEff = 0;
   for k = (j-a+1):(j-1),
    PastEff = PastEff + E(k+7)*S(a-j+k);
   end

   nM = a; % years of exposure to natural mortality since recruitment (including this year)

  else % Recruited in 1994 or earlier - needs Nxx variables

   Rin = N95(a-j+1);
   PastEff = 0;
   % k = no. of years since 1995 up to last year
   for k = 1:(j-1),
    PastEff = PastEff + E(k+7)*S(a-j+k); % 1 yo can't get to this line
   end

   nM = j; % natural mortality suffered since 95 (including this year)

  end

  logC = log(Rin*q*S(a)*E(7+j)) - q*(PastEff + (S(a)*E(7+j)/2.05)) - M*(nM - 1.05/2.05);

  if (j~=3),
   if (a<=8), % Older fish number estimates excluded from fitting.
    catchatage = [catchatage;logC];
   end
  else
   C97 = [C97;logC];
  end

  % Numbers at age
  if j>=2,
   numsatage(a,j-1) = Rin*exp(-q*PastEff - M*(nM - 1));
  end
 end

 % Biomass and Recruitment calculations to be done once all the ages for
 % year j are worked out
  if j>=2,
```

```
   B95to03(j) = sum((wa(j,2:14)/1000).*S(:)'.*numsatage(:,j-1)');
  else
   B95to03(j) = sum((wa(j,2:14)/1000).*S(:)'.*N95(:)')+R(4).*S(1)*wa(j,2)/1000;
  end

end

GC97 = log(sum(exp(C97).*(avwa(2:14)'/1000)));
output = [catchatage; GC97];% GC97
%output = [numsatage];
```

10.8 John Hoenig's review

Review of Stock Assessment for Sea Mullet (*Mugil cephalus*) in Queensland

Report completed under contract to the Queensland Department of Primary Industries and Fisheries by John M. Hoenig, Ph.D. (contractee), Virginia Institute of Marine Science, Gloucester Point, Virginia, USA

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Available data for sea mullet in New South Wales and Queensland were reviewed and then the assessment model was examined. The model is in its infancy but the general structure is appropriate. In an effort to get the model running in time for the review, some shortcuts were taken. Thus, an "average" age-length key (i.e., one in which data were averaged over time) and a constant length frequency distribution (i.e., that did not change over time) were used for illustrative purposes. The result was to produce model output in which all years looked similar. Results will undoubtedly look more realistic when the actual data are run through the model.

Data for 1997 and 1998 may be problematic due to limited sampling. I recommend that, if these data prove problematic and it is desired to use estimates for these years as substitutes for the data, then the population should be projected forward from 1996 rather than using an "average" age-length key to estimate the age composition. The former procedure will preserve year class strength whereas the latter will perpetuate the abundance at a given age over time.

Selectivity is estimated in the model. However, some historic tagging data exist and these could be analyzed to try to estimate selectivity. That would reduce model uncertainty. The data should also be examined to see if total mortality can be estimated for the period around 1995.

Age composition, catch and effort data are available from 1995 through 2003 (with possible problems arising for the years 1997 and 1998). These data could be used for cross-sectional or longitudinal catch curve analysis, or both. This would provide estimates of total mortality that could then be apportioned among natural and fishing mortality. This would be useful for model verification and possibly serve to anchor model outputs.

The value of natural mortality used in the assessment model appears reasonable. However, some "rules of thumb" for estimating natural mortality should be examined, notably the ones by Pauly, Watanabe-Chen, and Petersen-Wroblewski.

The assessment model estimates recruitment for every year. This is appropriate. However, it is also a good idea I think to try to fit a model with constant recruitment (for 1995-2003) to gain an impression of average stock size in recent history. A model with one recruitment instead of 16 recruitments might be significantly more stable. Ultimately, a stock-recruitment relationship will be needed in the model.

The time series available for analysis is rather short. Therefore it is of interest to try to incorporate data from earlier years. There are three phases to the available data. In the early years there was just catch data. From 1988 to 1994 there were catch and effort data. After that, there were catch, effort, and age composition data. It would be worthwhile to try to fit a production model to all of the data and, also, to try to fit a model that involved a production model from 1988 to 1994, and that became an age-structured model starting in 1995. A production model would involve estimating the virgin biomass and the biomass at the start of the period where catch and effort statistics started being collected. Virgin biomass is difficult to estimate if all observations are at a stock size far from the virgin level. I think the ratio of virgin biomass to biomass at a reference point in time where total mortality rate is known can be approximated by summing the weights at age when $Z = M$ and dividing by the sum of the weights when Z equals a known value (e.g., as determined from a catch curve).

It does not appear to me that the time series of catches from the early period will be very helpful because there is a gap in the time series just before the beginning of the period where catch and effort started being collected.

At this point, I do not have a good feel for the status of the sea mullet resource. I'd have a much better idea if I saw the results of the catch curve analyses. Should the mortality rate appear high, then it would be appropriate to look at current status in relation to benchmarks such as ratio of current biomass to virgin biomass or current egg production to virgin egg production.

Longer term research recommendations include conducting a tagging study and conducting aerial surveys. Mullet could be tagged in the estuaries and recaptured off the beaches. This could provide information on selectivity, total mortality, and possibly components of mortality (fishing and natural mortality). An aerial survey of mullet in the estuaries could provide a fishery-independent index of abundance. (This is contingent on preliminary studies showing mullet are visible in aerial surveys). It would also help quantify the importance of various estuaries and estuarine habitat, and it would help to weight estimates of exploitation from the tagging study by the importance of the estuary.