Sustainability Assessment of the Torres Strait Rock Lobster Fishery

CRC-TS Project Task Number: 1.3

National Library of Australia Cataloguing-in-Publication data:
Sustainability assessment of the Torres fishery: Torres Strait CRC task number: 1.3.
Bibliography.
ISBN 1 921232 07 2 (online).
ISBN 1 921232 06 4 (pbk).
1. Lobster fisheries - Torres Strait.
2. Fishery resources - Research - Torres Strait.
3. Fish stock assessment - Torres Strait.
I Ye, Y. (Yimin)
338.37253840916476

Published: July 2006  by CSIRO Marine and Atmospheric Research

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Sustainability Assessment of the Torres Strait Rock Lobster Fishery

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CSIRO Marine and Atmospheric Research
Cleveland, Australia

ISBN 1 921232 07 2 (online).
ISBN 1 921232 06 4 (pbk).

CRC Torres Strait Research Task Final Report
ACKNOWLEDGEMENTS

The project was funded by the Cooperative Research Centre for Torres Strait. The authors wish to sincerely thank the master Mr Donald Battersby and crew of the M. V. James Kirby for excellent assistance in all aspects of the field research in Torres Strait, and in logistic support prior to and after the field surveys. A special thanks to the master and crew for independently conducting underwater video tows to supplement the habitat distribution data from dive surveys during the surveys. Jim Prescott was the task associate of this project and provided valuable support, cooperation and inspiring discussion throughout the project. Finally, we also thank Shane Griffiths and Wayne Rochester for reviewing this report critically and constructively.
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NON-TECHNICAL SUMMARY

PROJECT:
CRC-TS Task Number 1.3. Sustainability Assessment of the Torres Strait Rock Lobster Fishery

PRINCIPAL INVESTIGATOR:
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OBJECTIVES:

1. Conduct the May/June annual survey of the relative abundance of the recruiting age 1+ and fished age 2+ groups and the size frequency distribution of the Torres Strait lobster population;
2. Collect information on benthic habitats at the survey sites;
3. Analyse the annual survey data, the size-frequency and catch effort data to be collected from processors in certain months each year by AFMA TI staff or Processor staff, and annually available industry data such as AFMA total catch and logbook data, PNG-NFA catch and logbook data, processor size-grade records;
4. Monitor recruitment fluctuations and changes in age composition of the lobster population and assess stock response to recently introduced regulatory measures;
5. Annually update the stock assessment model to include the newly available information and provide evaluation of the stock status and advice on management of the fishery;
6. Conduct the November 2005 pre-season survey of the abundance of the recruiting (1+) year-class and the size-frequency distribution of the population;
7. Provide a recommendation on the 2006 total allowable catch for the Torres Strait lobster fishery.

NON-TECHNICAL SUMMARY:

Three surveys of the Torres Strait ornate rock lobster *Panulirus ornatus* population were conducted in April/May in 2004 and 2005 and November 2005, respectively. The catch rates of recruiting (1+) and fished (2+) lobsters from the surveys were standardized to measured belt transect (500 × 4 m) counts to improve the accuracy and precision of the abundance indices estimated over the last 17 years (1989-2005). A catch-age model was developed and fitted to the commercial catch and fishery-independent survey index data. The model outputs were used to construct a stock-recruitment relationship and to estimate the maximum productivity of the fishery and its corresponding fishing intensity. A number of models were developed to estimate total allowable catch (TAC) for the lobster fishery and their forecasting skills were evaluated using various methods including cross validation. Finally, an investigation was completed to examine the influence of seabed habitat, temperature, wind strength and larval advection on lobster distribution.

*Lobster population surveys*

Three surveys of the lobster population were undertaken as part of CRC-TS Task 1.3. The first survey was completed during April/May in 2004 and the second during April/May 2005 by four CSIRO staff, using the research vessel M.V. James Kirby. A total of 117 sites were surveyed by divers in April/May 2004, including 29 in the PNG stratum. A total of 86 sites, from those allocated in 2004, were
surveyed in April/May 2005. Each site was re-located accurately using portable GPS. As in the 1989 survey, measured belt transects (500 m by 4 m) were employed as the primary sampling unit, as they were found to give the greatest precision (p=SE/Mean) of lobster abundance. Transect distance was measured, to the nearest metre, using a Chainman® device. At the completion of each transect a diver recorded; the number of lobsters caught, the number and age-class of those missed, depth, visibility, distance swum, numbers of pearlshell (*Pinctada maxima*) and holothurian species observed, and percent covers of standard substratum and biota (including seagrass and algae species) categories. The duration of each transect and the number of lobsters sighted outside the transect were also recorded to provide data to allow conversion of historical (pre-1996) timed swim (20 minutes) counts to measured transect (500 m by 4 m) counts.

The third survey was completed during November 2005 and differed in design from the 2004 and 2005 annual surveys. This pre-season survey aimed to provide an estimate of the age 2+ lobster population before the 2006 fishing season started so that a sustainable TAC for that year could be determined. A total of 154 sites were sampled during the pre-season survey, including 86 sites sampled during the annual (mid-year) surveys in 2002 and 2005, 27 new reef-edge sites and 10 new sites in the Warraber_bridge stratum. The new sites were allocated to address the concerns of commercial fishers and managers that previous surveys may not have adequately sampled the north-east quadrant of the fishery, including Warrior Reef. A data collection protocol similar to that used for the annual (mid-year) surveys was adopted. Lobster density was estimated based on stratified random sampling theory.

**Evaluation of data compatibility**

Commercial catch statistics and annual (mid-year) and pre-season surveys are the primary sources of data available for assessment of the Torres Strait lobster fishery. Before being used for stock assessment and other analyses, these data were technically examined for their validity and consistency over time as the methods used to collect these data had changed over time. The most notable change was the introduction of the new docket book system in 2003 to collect catch data from the Torres Strait Island Boat sector. Before 2000, the old system gathered lobster landings from shipping records of commercial trading companies. No data were collected in 2001 and 2002 but during 2003-2004 AFMA spent considerable effort to retrieve the data from these two years. To examine how comprehensive the recovered data was and the consistency of the two data collection systems, a comparison of the annual catches of 8 selected vessels, that had comprehensive logbook records and the annual catch of the whole lobster fishery was undertaken. The comparison showed that the two time series of catches were almost identical during 2001 to 2005, and similar during 1997 to 2000. This suggests that the 2001 and 2002 catch data retrieved by AFMA were comprehensive and the estimates of annual catches from the historical shipping records are comparable with those from the new system.

The annual (mid-year) population surveys have been carried out since 1989 and their design and implementation have been modified during that time to accommodate financial constraints and logistical difficulties. The survey catch rate data were successfully standardized as measured belt transect (500 × 4 m) counts in this study. The trends of relative abundance for age 2+ lobsters were similar to those of CPUE for the 8 selected vessels over the period in which logbook data were available. Although this comparison is not conclusive, it does suggest that the abundance indices estimated from the annual surveys are representative of the actual abundance of the lobster population.

Some recent revisions were made to the design of the annual surveys including; an extension of the survey to included more sampling strata to increase spatial coverage, an increase in the number of sample sites within each stratum, and a change from 2 transects per location to 1 transect per location. The analysis of the resulting survey data demonstrates that the first two measures resulted in a better spatial coverage and a consequent reduction of the potential bias to the estimates of abundance indices that would be caused by any temporal variation in lobster distribution. The third measure appeared to have lead to slightly larger standard errors, but this was inevitable in achieving the first two without increasing funding.

The pre-season population survey carried out in November 2005 adopted a fixed station sample design, which was not ideal but an expedient measure. The catch rate estimates from sites repeated during the pre-season survey and the 2002 Benchmark Lobster Survey were used as comparative
relative abundance indices. The size of the 2005 pre-season lobster population was then calculated, using the population estimate from the Benchmark Lobster Survey. It should be noted that the ability of this survey design to produce reliable estimates of population size depends on the assumption that the spatial distribution of the lobster population was consistent between June and November. A simple comparison of the two surveys showed that the distribution of age 1+ lobsters was consistent during this period, but the distribution of age 2+ lobsters changed significantly. Since a TAC can be feasibly set using only the population size of age 1+ lobsters, it could be concluded that the pre-season survey is suitable for this purpose. However, to provide a reliable recruiting (1+) population estimate there must be no significant change in the distribution of lobsters between the two surveys. There are also many issues that will demand further study in the future, particularly if a benchmark pre-season survey is not completed.

**Stock assessment**

A catch-age model was developed and fitted to the commercial catch statistics and fishery-independent survey abundance estimates from 1989-2005 using a maximum likelihood method. Based on the catch-age model estimates of recruitment and spawning stock, a stock-recruitment model was then established. Combining individual growth information with the stock recruitment relationship and natural mortality estimate, the maximum sustainable yield of the Torres Strait lobster fishery (Australia+PNG) was estimated at 640 tonnes total weight with a fishing mortality $F=0.5$ year$^{-1}$. To achieve this MSY, the fishery has to allow $120 \times 10^4$ lobsters to escape to breed, on average, by the end of each fishing season. However, even with this level of escapement, recruitment is highly variable in this fishery, and this spawning stock has only a 45% probability of producing a recruiting year-class larger than that required to achieve MSY. To increase the probability to 70%, the spawning stock has to increase by 1.5 times this level ($180 \times 10^4$ lobsters). The spawning stocks were $170 \times 10^4$ and $130 \times 10^4$ lobsters in 2004 and 2005, respectively. As the current spawning stocks are similar to SMSY, this fishery may be regarded as fully exploited at present.

**Development of TAC estimation methods**

Three kinds of models were developed and tested for estimating TACs of the Torres Strait lobster fishery. The first was a spawning stock–based model. This model forecasted catch from spawning stock using a stock-recruitment relationship and a recruit-catch production function. The second model was a population-based model, which estimated catch from the age 2+ population size based on a population-catch production function. The third models were based on empirical relationships and did not use production functions derived from population dynamics. Uncertainty in the model parameters and input variables, such as spawning stock and the population estimate of age 2+ lobsters, were incorporated through Monte Carlo techniques. Therefore, these catch forecasts were probabilistic forecasts that allow estimation of the distribution of possible catches instead of point estimates as in deterministic analysis.

The spawning stock-based model forecasted the 2006 catch to be from 296 to 1028 tonnes (total weight) with a most likely (mode) value of 535 t. In contrast, the population-based model forecasted catch to be from 360 to 673 t with a modal value at 515 t. The empirical models produced similar modal catch forecasts of 499 to 523 tonnes.

The forecasting skills of the models were evaluated using cross-validation techniques for the empirical models and using standardized forecast errors for the other models. The population-based model and the Beverton-Holt empirical model outperformed the others in estimating the TAC. Therefore, it is recommended that these two models should be used to estimate TACs for the lobster fishery.

The combination of highly variable recruitment and catch comprised of a single cohort makes the estimation of TAC for the lobster fishery extremely difficult. It is crucial for scientists, managers and the industry to be aware of this challenge. Although some methods have been developed in this study, they should be regarded as preliminary and require refinement and further development. To ensure the success of the quota management system, management procedures must be developed and implemented.
Relationship between lobster distribution and habitat

This study investigated the possible influence of seabed habitats on the lobster population within the Torres Strait. The habitat data comprised estimates of percent cover of standard substratum categories including: mud, sand, rubble, consolidated rubble, pavement and live coral. In addition, the percent cover of seagrass and counts of pearlshell (*Pinctada maxima*) were recorded during the annual (mid-year) and pre-season surveys from 1989-2005. The 1989, 2002 and 2005 pre-season surveys were the most extensive population surveys, and our analysis was restricted to these years. The habitat data collected during the population surveys was mapped to highlight the distributions across the area of the fishery. This information has been used previously to improve the designs of the lobster population survey, through the allocation of sampling strata. Overall the comparisons of habitat variables and recruiting (1+) and fished (2+) lobster abundance were generally insignificant ($R^2=0.003 – 0.367$), although this result is likely due to the spatial scale of the sampling. The correlation was most precise for percent rock and soft sediment and lobster abundance, and this relationship was obvious from the mapped distributions. The relationship between seagrass cover and lobster abundance suggested that seagrass beds in the northwest quadrant of the fishery influence the population dynamics of the lobster population in that region. It should be stressed that these analyses were univariate and should be regarded as preliminary investigations.

Relationship between lobster recruitment and environmental correlates

The abundance of the ornate rock lobster *Panulirus ornatus* population in Torres Strait is likely to be heavily influenced by environmental conditions including; water temperature, wind strength and direction and oceanographic conditions. This study investigated the potential influence of these environmental correlates on lobster recruitment strength. Sea water temperature data from Torres Strait were collected by CSIRO (1992 – 1997), AIMS (1998 – 2003) and NOAA TIROS Satellite images (1993-2005). Wind speed and direction data were recorded by the Bureau of Meteorology from 1988-2005. Indices of lobster settlement, driven by larval advection in the Coral Sea Gyre, were extracted from an oceanographic circulation model developed by CSIRO Hobart (Pitcher et al., 2005). The influence of wind and temperature on recruitment did not appear to be significant. However, there appears to be a significant relationship between the modelled larval settlement indices and recruitment of lobsters to Torres Strait estimated by the annual population surveys. This area of research warrants further study. It should be stressed that as for the analyses of the relationship between habitat and lobster distribution, the analyses of the relationship between the environmental correlates and recruitment used simple univariate methods, and more powerful methods such multiple regression could be pursued in the future.

The results have been presented and discussed at a number of key meetings including the Lobster Working Group meeting and the lobster Resource Assessment Group meeting and published in 7 journal papers and reports.

RECOMMENDATIONS

The pre-season survey conducted in November 2005 adopted a fixed station design as a compromise between the funds available and determining an accurate and precise estimate of the size of the lobster population before the season starts. It is recommended that the absolute population estimate from the pre-season survey be used with caution and that annual (mid-year) and pre-season surveys should be done in parallel for at least 3-4 years so that the distributional consistency can be further monitored and a more reliable relationship between estimates from the annual (mid-year) and pre-season surveys can be established.

Escapement and subsequent spawning stock left at the end of each fishing season should be the management target for the lobster fishery. The spawning stock required to achieve the maximum sustainable yield, $S_{\text{MSY}}$, could be used as a limit reference point. As recruitment to the lobster fishery is highly variable, it is recommended that spawning stock should be larger than $S_{\text{MSY}}$ for precautionary reasons.

The estimation of TACs is obviously a crucial aspect of TAC management. This project developed a number of models for estimating TAC of the lobster fishery. Based on the evaluation of forecasting skill, the population-based and the Beverton-Holt empirical models are preferable and should be used.
in future although all the developed models are preliminary and should be tested further. The combination of highly variable recruitment and single cohort fished makes the estimation of TAC for the lobster fishery extremely difficult. It is crucial for scientists, managers and the industry to be aware of this challenge. To ensure the success of the quota management system, management procedures must be developed and implemented.

Outcomes Achieved
Three surveys of the Torres Strait lobster population were completed during this project. The two annual (mid-year) surveys in April/May 2004 and 2005 provided relative abundance indices for stock assessment of the Torres Strait lobster fishery, and the pre-season survey in November 2005 provided a population estimate for setting a TAC for the fishery. These survey data together with the commercial catch statistics are the primary data for studies on population dynamics and the long-term sustainable productivity of the lobster fishery. The extension of the survey data series has improved the data quality and made possible the updated stock assessment of the lobster fishery.

A catch-age model was developed for the Torres Strait lobster fishery. The model was used to estimate natural and fishing mortality as well as spawning stock and recruitment. The maximum sustainable yield was estimated to be 640 tonnes total weight. To achieve the maximum sustainable yield, spawning stock should be kept above 120x10^4 lobsters by the end of each fishing season. The estimated spawning stock in 2005 was similar to the level that would produce the recruitment associated with maximum sustainable yield. Therefore, the lobster fishery is considered to be fully exploited. These parameters have provided clear indicators about the current stock status, long-term productivity and the relationship between catch and fishing intensity. This information has helped set appropriate management objectives and keep the effort reduction of the industrial sector and a cap on the number of licences in the islander sector over the last two years for the long-term sustainability of the fishery and benefits of various stakeholders.

As a result of the decision by the PZJA to adopt a quota management system for the Torres Strait lobster fishery a number of methods were developed to estimate a TAC for the lobster fishery. The development of TAC estimation methods paved the way for the implementation of TAC management and will subsequently facilitate the execution of the 50-50 resource allocation between the industrial and islander sectors.

The results of this project have been presented at a number of key meetings including the Lobster Working Group meeting and the lobster Resource Assessment Group meeting and these results have influenced the industry, managers and stakeholders to adopt more effective and precautionary measures in managing the lobster fishery, for example, setting the target reference point of spawning stock and taking into account uncertainties in setting a TAC.

KEYWORDS: Torres Strait, Rock Lobster Fishery, Stock Assessment, Total Allowable Catch
1. INTRODUCTION

1.1. BACKGROUND

The Torres Strait rock lobster (TRL) fishery is the most important commercial fishery to Torres Strait Islanders and provides significant financial independence for island communities in the region. In addition, the fishery provides income for non-indigenous fishers living in Torres Strait. The fishery is managed by the Protected Zone Joint Authority (PZJA) comprising representatives from the Australian and Queensland governments. The fishery is managed under Article 22 of the Torres Strait Treaty (February 1985) between Australia and Papua New Guinea. The treaty established the Torres Strait Protected Zone (TSPZ, Figure 1-1), maritime boundaries between the two countries and protection of the way of life and livelihood of traditional inhabitants and conservation of the marine environment. Members of the PZJA also participate in bilateral (Australia/PNG) meetings on issues of fisheries management common to both countries.

The Torres Strait lobster fishery began in 1969 when the first seafood processing factory opened on Thursday Island, providing facilities that stimulated commercial fishing by local divers (Channels, 1986). Reliable commercial catch data became available in 1978 and during the 1980s catches increased steadily with peaks in 1982 and 1986 (Figure 1-2). Although trawling for lobsters began in PNG in the early 1970s, targeted trawling only began in Australian waters in 1981, and peaked at ~170 t (live weight) in 1982. Trawling was subsequently banned in 1984 between 6 August and 15 October to conserve the migratory breeding populations; a total ban on taking lobsters by trawling was later implemented.

As the commercial catch increased during the 1980s there was concern raised about the long-term sustainability of the fishery, and managers sought data and a method to estimate potential yield. An analysis of trends in catch and effort data was precluded as only a small part of the fishery was monitored and there were no logbook programs for the islander or non-islander sectors. An alternative to the use of commercial catch data for stock assessment was to estimate potential yield from absolute stock abundance. As the area of the Torres Strait fishery is rarely greater than 25 m deep it was feasible to estimate stock abundance using visual censuses of the seabed by research divers. CSIRO and PNG NFA initiated the fishery-independent survey of the lobster population in Torres Strait in 1989, to estimate stock abundance and establish a baseline with which to compare future fishery-independent surveys.

The abundance of the Torres Strait lobster stock was estimated in May-June 1989, by visual census of 542 sites distributed over the ~25,000 km² area of the fishery (Pitcher et al., 1992). The sites were paired and at each site two divers surveyed a 500×4 m belt transect, recording the number of lobsters and pearlshell and qualitatively describing seabed habitat. The estimate of lobster abundance in 1989 was ~14 million (95% CI ± 21%). A professional diver sampled lobsters concurrently to provide information on the size/age composition of the population. The size distribution of the sampled population showed that legal-size lobsters (>100 mm tail length in 1989) comprised 57% of the population and their average tail weight was 346 g. Hence, of the total lobster population about 8 million were legal size, and the estimated stock size was 5200 to 8000 t whole weight, which was about ten-fold greater than the annual catch of ~600 t. Preliminary estimates of maximum sustainable yield (MSY) using a range of natural mortality estimates (0.4 to 0.9) and a rule-of-thumb model for data poor cases (Gulland, 1983) ranged from 740 to 2800 t whole weight. Hence, the fishery was deemed under-exploited and would support additional effort.

Following the success of the 1989 stock survey managers and researchers suggested that abbreviated fishery-independent population surveys could be conducted annually to determine the relative abundance of recruiting (1+) and fished (2+) lobsters. Further, if the surveys were conducted at a sub-set of the 1989 sites the indices of relative abundance could provide relatively precise inter-annual comparisons. Annual monitoring of the lobster population began in 1990 and involved a sub-set of 100 of the original 542 sites sampled in 1989. These sites were again paired. In 1996, due to funding constraints the number of monitoring sites was reduced to 82 by retaining 78 paired sites and 4 additional sites from the original pairs. The 4 sites from the original pairs were excluded on the basis
that the surveys had shown the habitat at each site was unsuitable for lobsters. In 2002 a benchmark stock abundance survey was undertaken, involving 375 sites and including the 82 repeats, to provide an updated estimate of stock abundance and to determine if the distribution of lobsters had changed since 1989.

Figure 1-1. Map of northern Queensland and southern Papua New Guinea showing the EEZ boundary, boundaries of the lobster fisheries in both countries, the Torres Strait Protected Zone and the 200 m and 1000 m isobaths.

Further modifications to the sample design were made during the TS CRC research in 2004 due to the imposition of conservative new dive regulations under the Australian Standard for Scientific Diving AS2299.2. The new regulations would have effectively doubled sampling time due to the depths at some of the sites. To meet the new dive regulations and to retain the link with the original surveys a total of 42 sites were retained from the 100, and additional shallower sites were added from the benchmark survey to increase the spatial distribution of sampling. The annual fishery-independent surveys were always conducted during May/June each year.
The original absolute stock survey in 1989 involved surveys of measured (500 × 4 m) transects along a line laid and retrieved from the seabed. This method was time consuming and subsequent annual fishery-independent surveys involved divers counting and collecting lobsters during timed (20 minute) swims at each site located throughout central and western Torres Strait. The introduction of reliable GPS coverage in 1992 allowed the first recording of distance swum to compare with the timed swim data. GPS distance has been recorded for all years since 1992. Subsequent availability of the Chainman® device in 1996, which allows recording of distance swum underwater, allowed a precise record of the transect length for subsequent years. These distance records in combination with time and distance data recorded during the Benchmark Survey in 2002 have allowed conversion of the abundance data from timed swim (20 minute) to measured transect (500 m by 4 m) records for all years.

The abundance and size distribution data from the annual surveys were used to calculate fishery independent indices of the relative abundance of the recruiting (1+) and fished (2+) year-classes. In previous stock assessments abundance data recorded in 1989 were adjusted to account for the different survey method (measured 500 × 4 m transects versus timed 20 minute swims). The abundance indices were compared with, and corroborated by CPUE information recorded during concurrent monitoring of the island-based catch and effort by CSIRO during 1989 to 2001. The relative abundance indices were compared with indices from previous years and provided information on the relative strength of both year-classes and forewarning of trends in future stock size.

A simple cohort dynamics model of the fishery was developed by CSIRO with inputs from the annual fishery-independent surveys and commercial catch monitoring. The model estimated percentage escapement and the corresponding fishing mortality, natural mortality and potential yield one year in advance. The model outputs provided valuable information to the AFMA managers about the status of the stock and exploitation levels, particularly as there were no comprehensive records of commercial catch and effort. The target reference point for the fishery was set at 75% escapement of each year class, which corresponded to $F=0.4$. This conservative level of escapement ensured the sustainability of each breeding year-class. Potential yield was estimated for each year, given the target $F=0.4$, and the estimates varied from year to year dependent on recruitment strength. The model was also used to evaluate yield per recruit (YPR) under different management scenarios. The model showed that up until the mid-1990s the minimum size limit and seasonal hookah ban did not significantly increase YPR or escapement.

There was a downward trend in stock abundance through the 1990s and in 1999 the abundance of fished (2+) lobsters fell to the lowest ever recorded. This very low stock abundance prompted a workshop on Torres Strait lobster fishery assessment, which was convened in March 2000 and attended by CSIRO researchers, AFMA managers and stock assessment experts. The Torres Strait Tropical Rock Lobster Fishery Assessment Group (TSTRLFAG) Workshop concluded that the very low 1999 stock raised serious concerns about the long-term sustainability, particularly given the likelihood of a record low recruitment in 2001, which was later confirmed by the annual survey data. The workshop also concluded that the fishery had likely fallen below the biological reference point at which the spawner biomass will produce half the recruitment strength of that in an un-fished state ($B_{50}$), and that the fishery model should be revised to assess the long-term risks.

During 2000-2001 research confirmed that the stock was likely biologically over-exploited during the 1990s, particularly given the 1999 spawning stock was the lowest recorded. Consequently, the 1999 egg-production was likely to be low, leading to a pessimistic outlook for subsequent recruitment in 2001, which was later confirmed. Further concern was raised when the natural mortality of lobsters during 1999/2000 was found to be unusually high (only ~25% survival, cf. average=40%). This was thought to be due to an extensive sea-grass die-back in northwest Torres Strait. As a result, the 2000 lobster stock was also very low leading to a pessimistic outlook for subsequent recruitment in 2002. During 1999-2001 both stock and recruitment levels fell to record lows raising further concern about the long-term sustainability of the fishery.

Given the pessimistic long-term outlook for the fishery, a management strategy was devised to allow the stock to recover using outputs from the fishery model. The fishery model showed that if the minimum size was increased from 100 to 115 mm tail length and the seasonal ban was extended from October-November to October-January, fishing mortality would be reduced. Consequently, the fishery would recover to a level above the target biological reference point $B_{50}$. The recovery strategy was
also contingent on capping effort in the fishery at the 1990s level. This new management was introduced in 2002 and the stocks have recovered since, possibly due to the new management but likely also to habitat recovery and improved lobster survival.

The Torres Strait CRC research Task 1.3 continued the lobster stock assessment program initiated in 1989. The 2003 lobster population survey and stock assessment research was funded separately by AFMA within the TS CRC triennium. The 2004 and 2005 population surveys and stock assessment were funded under the TS CRC and the outcomes of this research are reported here. In addition, due to the decision by the PZJA in July 2005 to move to a quota management system (QMS) for the Torres Strait lobster fishery, a pre-season lobster population survey was funded by AFMA and conducted in November 2005 by CMAR through the existing TS CRC Task 1.3.

This report summarizes the results of the TS CRC Task 1.3 and the key outcome of this task, stock status assessment, includes analysis of results of all previous fishery-independent surveys funded by AFMA since 1989.

**Figure 1-2.** Commercial lobster catch (tones live weight) taken by the Australian, PNG and QLD fisheries between 1973 and 2005. The Australian and PNG totals include trawled catches prior to the ban in 1984.

### 1.2. NEED

Research conducted in the TS CRC Task 1.3 continued the assessment of Torres Strait rock lobster (TRL) fishery, initiated in 1989, and provided managers with key information on the status of the lobster stock. The TRL fishery is the most important commercial fishery to Torres Strait Islanders and provides significant income to the local economy. The fishery is also important directly and indirectly to many non-islanders living in Torres Strait. The long-term sustainability of the fishery is the main objective of the Torres Strait Treaty (1985), particularly to ensure the protection of the life and livelihood of the traditional inhabitants. The fishery-independent population surveys provide critical information on the status of the recruiting (1+) and fished (2+) year-classes, particularly as there has been no comprehensive monitoring of commercial catch and effort data until recently.

The need to continue assessment of the TRL fishery under the TS CRC was emphasized by the significant decline in the stock and recruit abundance during 1999-2001, which lead to the lowest recorded catch in 2001 (Figure 1-2). Fishery modeling suggested that the fishery was biologically over-exploited and a new management strategy was conceived to allow the stock to recover. The recovery strategy included three new regulatory measures: a commercial fishing closure between October and November each year, a prohibition on the use of hookah gear between October and January, and an increase in the minimum size limit for commercial and recreational fishing. This new management was introduced in 2002, contingent on effort capped at the 1990s level. As the stock
recovered effort in the fishery increased and in 2003 effort in the commercial sector was reduced by 30%.

The stock assessment undertaken in Task 1.3 allowed an analysis of whether the lobster population is recovering under the recently implemented management regulations. This information is critical to effective management of the fishery and ensuring the fishery is sustainable.

The reliability of stock assessment and the specific questions it can answer greatly depend on availability and quality of the data on which stock assessment is based. A basic dynamic stock assessment demands at least two sets of time series data, annual catch and effort. Unfortunately, although historical catch data is available for the TRL fishery, there is no total fishing effort data available. Hence, to permit an assessment of the lobster stock, the time series of stock abundance indices was constructed from the annual population survey data. This is why the fishery-independent surveys are crucial for effective management of the lobster fishery. In addition, the surveys provide other important information such as recruitment fluctuation, size/age distribution, spatial distribution, and temporal variation in abundance. The importance of continued monitoring of the lobster population by fishery-independent surveys was emphasized at the recent Torres Strait Tropical Rock Lobster Working Group (TSTRLWG) Workshop held in March 2003. The TSTRLWG considered ongoing fishery independent surveys necessary to properly assess the sustainability of the fishery and evaluate strategies to bring the fishery to a sustainable level of exploitation.

Annual updates of stock assessment provide; the opportunity to incorporate the most recent data, timely evaluation of the effectiveness of new regulations, and prompt advice to management. These measures will reduce the risk of over-fishing and ensure the fishery is biologically sustainable despite the great uncertainties of the marine environment. The annual population surveys and stock assessment provide the only population abundance indices and advice for the conservation, management and optimum utilization of the Torres Strait rock lobster fishery, as required under the Treaty.

In July 2005 the PZJA decided to implement a quota management system for the Torres Strait lobster fishery. This system was meant to be operational in 2006 but was deferred to 2007 due to time and logistical constraints. The quota management system will control the total allowable catch (TAC) of the fishery based on forecasts of catch. Therefore, there was a critical need to develop techniques to forecast catch of the coming season. The accuracy of this forecast depends on the historical variability of the catch. The Torres Strait lobster fishery targets mainly a single cohort in each fishing season and recruitment is variable. Consequently, annual lobster catches are highly variable and are difficult to predict. Given this variability and to reduce forecast uncertainties, the need to conduct a pre-season population survey each year was identified. Therefore, there was an urgent need for research on techniques to estimate TACs and for a pre-season survey in November 2005 so that a trial TAC could be set for 2006 before the commencement of the TAC system in 2007.

1.3. OBJECTIVES

1. Conduct the May/June annual survey of the relative abundance of the recruiting age 1+ and fished age 2+ groups and the size frequency distribution of the Torres Strait lobster population;
2. Collect information on benthic habitats at the survey sites;
3. Analyse the annual survey data, the size-frequency and catch effort data to be collected from processors in certain months each year by AFMA TI staff or Processor staff, and annually available industry data such as AFMA total catch and logbook data, PNG-NFA catch and logbook data, processor size-grade records;
4. Monitor recruitment fluctuations and changes in age composition of the lobster population and assess stock response to recently introduced regulatory measures;
5. Annually update the stock assessment model to include the newly available information and provide evaluation of the stock status and advice on management of the fishery.
6. Conduct the November 2005 pre-season survey of the abundance of the recruiting (1+) year-class and the size-frequency distribution of the population.
7. Provide a recommendation on the 2006 total allowable catch for the Torres Strait lobster fishery.
1.4. PUBLICATIONS (2003 - 2006)


2. ANNUAL POPULATION SURVEYS

2.1. INTRODUCTION

Annual fishery-independent monitoring of the Torres Strait ornate rock lobster *Panulirus ornatus* population has been carried out during 1990 to 2005. These surveys, conducted mid-year, provided the only information on the relative abundance of recruiting (1+) and fished (2+) lobsters, since there has been no comprehensive monitoring of commercial catch and effort. The relative abundance indices and age composition data are used in the age-structured fishery model for assessments of the status of the stock, and to set and evaluate new management regulations.

During 1990-1995 the annual population surveys involved a sub-set of 100 paired sites from the original 542 paired sites sampled in 1989. Since then there have been several modifications to the sample design used for the annual population surveys to address; funding constraints, imposition of conservative new dive regulations under the Australian Standard for Scientific Diving AS2299.2 and spatial distribution of sampling sites. A sub-set of 42 sites from the original survey in 1989 were retained in all years providing a reference for inter-annual comparisons. The relative merits of random versus fixed site population monitoring are discussed in Chapter 4.

As for sample design, there have been several modifications of the sampling method used during the annual population surveys. Although the original absolute stock survey in 1989 involved surveys of measured (500 × 4 m) transects along a line laid on the seabed, this method was considered overly time consuming and subsequent annual surveys involved divers counting and collecting lobsters during timed (20 minute) swims. The introduction of reliable GPS coverage in 1992 allowed the first recording of distance swum to compare with the timed swim data. Subsequent availability of the Chainman ® device in 1996, which allows recording of distance swum underwater, allowed a precise record of the transect length for the latter years. These distance records in combination with duration, current and visibility data have allowed standardization of the abundance data from timed swim (20 minute) counts to measured transect (500 m by 4 m) counts for all years (see Chapter 4 for details).

During 1989 to 2001 the relative abundance indices from the annual population surveys were corroborated by CPUE data recorded during concurrent monitoring of the island-based catch and effort. The subsequent introduction of compulsory logbooks for the non-islander sector of the fishery provided CPUE data that could be compared with the fishery-independent survey data. The validated abundance indices provided information on the relative strength of the recruiting (1+) and fished (2+) year-classes and forewarning of trends in future stock size. This data was also used to calculate the stock-recruitment relationship.

The fifteenth and sixteenth annual population surveys were conducted in 2004 and 2005 as key objectives of CRC-TS Task 1.3 “Sustainability assessment of the Torres Strait lobster fishery”.

2.2. METHODS

2.2.1. Survey Design

As in previous years the study area included all seabed habitats bounded by 142⁰E in the west, Warrior Reef and 142.9⁰E in the east, the southern PNG coastline in the north and 10.8⁰S in the south (Figure 1-1). This area encompasses the main fishing grounds in both Australia and PNG, and nearly all of the commercial catch is taken within this area. The study area covers about 19000 km² and depth is generally less than 25 m throughout. The seabed habitat in the study area is heterogeneous, ranging from bare mud and sand to complex coral reefs and seagrass meadows. The distribution of seabed habitats was determined during several historical research surveys conducted by CMAR, including the 1989 lobster population survey. This information, with seabed bottom stress, was collated in 2002 to allow optimisation of the Benchmark Lobster Survey and allocation of sampling strata, containing more homogenous seabed habitats (Figure 2-1).
The study area is characterized by predominantly turbid waters, due to terrestrial inputs from southern PNG and high tidal current flow which re-suspends sediments. Unlike eastern Torres Strait, live coral cover is low in the area of the fishery and reefs are characteristically mud or sand banks with a small fringing reef. The Warrior Reef complex, which delineates the eastern margin of the lobster fishery has a large reef flat containing dense seagrass meadows and the perimeter of the reef is colonized by macro-algae (*Sargassum* spp., *Turbinaria ornata*, *Padina* spp.).

The climate in Torres Strait is monsoonal, with strong persistent south-east trade winds dominating in winter (May-September) and sporadic north-west winds in the summer months. Current flow is strong (up to 8 knots) during spring tides, particularly in the networks of inter-reefal channels throughout the fishery. For this reason, and as water clarity is generally higher then, most lobster fishing is restricted to neap tides.

**Figure 2-1.** Map of Torres Strait and southern PNG showing the distribution of seabed substrates determined during research by CMAR between 1989 and 2001, bottom stress contours and lobster density observed during the 1989 lobster population survey.
The sample design employed during the annual population surveys in 2004 and 2005 was similar to that used in previous surveys (1990-2003) funded by AFMA (Pitcher et al. 1997). However, the design had to be modified to incorporate the restrictions imposed by the new conservative procedures in the Australian Standard for Scientific Divers (AS2299.2). To retain a link to previous years one of each of the 100 paired transects sampled prior to 1996 was retained and additional sites surveyed during the 2002 Benchmark Lobster Survey were allocated to increase the spatial distribution of sampling. Further, the selection of only one transect from each pairs increased the spread of transects in the study area.

The sampling strata used in 2004 and 2005 were modified slightly from the design used in the 2002 Benchmark Lobster Survey (Figure 2-2), to incorporate the updated seabed habitat information. Of the thirteen sampling strata (Table 2-1), nine were sampled in 2004 (including PNG) and eight were sampled in 2005. The PNG stratum was not sampled in 2005 because CMAR was not able to obtain an exemption from customs clearance for the research vessel.

Table 2-1. List of sampling strata, and those sampled in the 2004 and 2005 annual lobster population survey designs and area of each stratum.

<table>
<thead>
<tr>
<th>Sampling Strata</th>
<th>sampled</th>
<th>AREA_KM²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buru</td>
<td>YES</td>
<td>1688.93</td>
</tr>
<tr>
<td>Kircaldie_rubble</td>
<td>YES</td>
<td>960.59</td>
</tr>
<tr>
<td>Mabuiag</td>
<td>YES</td>
<td>1393.71</td>
</tr>
<tr>
<td>No_sample</td>
<td>YES</td>
<td>2085.54</td>
</tr>
<tr>
<td>PNG_sample</td>
<td>YES</td>
<td>528.76</td>
</tr>
<tr>
<td>SE_omit</td>
<td></td>
<td>514.47</td>
</tr>
<tr>
<td>Sand_omit</td>
<td></td>
<td>6301.02</td>
</tr>
<tr>
<td>Sand_sample</td>
<td></td>
<td>561.08</td>
</tr>
<tr>
<td>South-east</td>
<td>YES</td>
<td>893.05</td>
</tr>
<tr>
<td>TI_bridge</td>
<td>YES</td>
<td>2924.48</td>
</tr>
<tr>
<td>Warraber_bridge</td>
<td>YES</td>
<td>744.48</td>
</tr>
<tr>
<td>Warrior_back</td>
<td>YES</td>
<td>231.37</td>
</tr>
<tr>
<td>Reef-edge</td>
<td>YES</td>
<td>92.52</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>18920.00</strong></td>
</tr>
</tbody>
</table>

### 2.2.2. Field Surveys

The fifteenth and sixteenth annual surveys of the Torres Strait lobster population were conducted during April/May in 2004 and 2005 by four CSIRO staff, using the research vessel M.V. *James Kirby*. A total of 117 sites were surveyed by divers in April/May 2004, including 29 in the PNG stratum. A total of 86 sites, from those allocated in 2004, were surveyed in April/May 2005. Each site was re-located accurately using portable GPS.
Figure 2-2. Map of western Torres Strait showing distribution of the sampling strata used in the 2004 and 2005 annual lobster population surveys, and ornate rock lobster *Panulirus ornatus* abundance recorded during the 2002 Benchmark Lobster Survey.

As in the 1989 survey, measured belt transects (500 m by 4 m) were employed as the primary sampling unit, as they were found to give the greatest precision (p=SE/Mean) of lobster abundance. The full 500 m was not surveyed at 30 deeper sites due to a lack of tidal current, and as the duration to complete the dive would have breached the conservative limits set by the Australian scientific diving code (AS2299.2). Transect distance was measured, to the nearest metre, using a Chainman® device.

At the completion of each transect a diver recorded; the number of lobsters caught, the number and age-class of those missed, depth, visibility, distance swum, numbers of pearlshell (*Pinctada maxima*) and holothurian species observed, and percent covers of standard substratum and biota (including seagrass and algae species) categories. The duration of each transect and the number of lobsters sighted outside the transect were also recorded to provide data to allow conversion of historical (pre-1996) timed swim (20 minutes) counts to measured transect (500 m by 4 m) counts.
2.2.3. **Size and Age Distribution**

The sampled lobsters were measured (tail width in mm), sexed and moult staged to provide size-frequency data. The year-class components in the size frequency distribution of sampled lobsters were determined using modal analysis (Mix; Macdonald and Pitcher, 1979). The resulting proportions of recruiting (1+) and fished (2+) year-classes were combined with the counts of missed 1+ and 2+ lobsters to estimate the age composition of the lobster population.

2.3. **RESULTS**

2.3.1. **Field Surveys**

The annual lobster population surveys were successfully completed in 2004 and 2005, continuing the long-term monitoring of the Torres Strait stock initiated in 1989. The 2004 annual survey began eventfully with several items of CMAR sampling equipment stolen from the M. V. James Kirby, whilst at anchor in Thursday Island harbour. During the survey two CMAR current moorings, previously deployed by CRC staff undertaking Task 2.2, were retrieved and stored onboard for transfer to Thursday Island. Diving fieldwork at the survey sites in Australian waters was completed without incident. Subsequent fieldwork at the allocated survey sites in PNG waters was hampered by a new requirement for the M. V. James Kirby to clear customs in both countries, even though an exemption had been granted. This requirement added two redundant days to the fieldwork. Due to the delay, which forced sampling into the time of the spring tides, several allocated sites could not be completed because of high current and poor visibility. Nevertheless, a total of 29 sites were completed in PNG waters in 2004. One CMAR researcher stayed on Thursday Island following the fieldwork to attend a TRL working group meeting convened by AFMA.

The 2005 annual survey was again conducted from the M. V. James Kirby. Diving fieldwork was completed without incident. In addition to the diver surveys, broodstock sandfish *Holothuria scabra* were collected by CMAR staff at Warrior Reef and stored onboard for a DPI&F aquaculture research program. The additional charter cost for this fieldwork was funded by DPI&F.

2.3.2. **Lobster Density**

The highest mean density of recruiting (1+) lobsters was recorded in the south-east stratum (see Figure 2-2 for stratum locations), followed by the reef-edge, kircaldie_rubble and mabuiag strata in 2004 (Figure 2-3). The precisions of the estimates were high in most strata except the reef-edge stratum, but additional sample sites are not warranted due to the small area of the this stratum (Table 2-1). The highest density of fished (2+) lobsters was recorded in the kircaldie stratum in 2004, and as a result most commercial non-islander fishers spent a considerable amount of effort diving at sites in this stratum in 2004. Densities of fished lobsters were also higher in the small reef-edge, south-east and warraber-bridge strata.

The mean density of recruiting (1+) lobsters was two to five-fold lower in all sampling strata in 2005 compared to 2004 (Figure 2-4). The highest mean density was again recorded in the south-east stratum in 2005, but densities were very low in all other strata. Given these consistent low densities, the forecast densities of fished 2+ lobsters, and subsequent catch rates, in 2006 were also low. In contrast, the mean densities of fished (2+) lobsters were higher in most strata in 2005, except the kircaldie_rubble and buru strata.
Figure 2-3. Mean number (± SE) of recruiting (1+) and fished (2+) ornate rock lobsters *Panulirus ornatus* recorded per 2000 m$^2$ belt transect during the 2004 annual lobster population survey.

Figure 2-4. Mean number (± SE) of recruiting (1+) and fished (2+) ornate rock lobsters *Panulirus ornatus* recorded per 2000 m$^2$ belt transect during the 2005 annual lobster population survey.
2.3.3. Inter-annual Lobster Abundance

Figure 2-5 shows the temporal variation in recruiting (1+) and fished (2+) lobster abundance recorded between 1989 and 2005. The trends of abundance were consistent for the timed (20 minute swim) count data and the measured belt transect (500 × 4 m) data, particularly for 2+ lobsters for years post 1990. The widest margin between the two measures of abundance was the estimated 2+ abundance in 1989. This was likely due to re-scaling of the measured belt transect counts in 1989 to timed swim counts, as recorded in subsequent years. The standardized measured belt transect data is more precise and this data was used in the age-structured fishery model for assessment of the status of the stock. The 2005 2+ year-class was the highest recorded since 1992, just greater than the 1998 level (Figure 2-5). This above average 2+ year-class continued the recovery since the record low in 2001 and suggests that the high survival and reduced fishing mortality (F) recorded in recent years, likely due to the new management measures introduced in 2002 and restoration of seabed habitat, has continued. The fishery catch is comprised almost totally of 2+ lobsters, due to the current minimum size limit (115 mm tail length ≈ 60 mm tail width). This is shown in the size-frequency distributions of lobsters sampled voluntarily by fishers from commercial catches between February and August (Figure 2-6), that are composed almost entirely of the 2+ year-class. As a result, the sizes of commercial catches are dependent largely on the abundance of the 2+ year-class, and as a result the increased commercial catches since 2001(Figure 1-2) have coincided with increased stock abundance.

**Figure 2-5.** Relative abundance (red=scaled to 20 minute swim counts; blue=scaled to 500 m by 4 m transect counts) of recruiting (1+) and fished (2+) ornate rock lobsters *Panulirus ornatus* recorded during annual surveys of the Torres Strait lobster population between 1989 and 2005. Error bars represent standard errors.
Figure 2-6. Size-frequency of commercial lobster *Panulirus ornatus* catches (blue bars) sampled voluntarily by Torres Strait fishers between February and August 2006 and the size-frequency of the population sampled during the annual population survey in 2005 (red bars).
To determine the spatial trends in lobster abundance the mean abundances in 3 quadrants of the fishery were estimated (Figure 2-7). The NE quadrant, which includes Warrior Reef was excluded due to insufficient number of sites sampled there each year. The overall trend of increasing 2+ abundance since 2001 was recorded in the SW and NW quadrants, although the precision of these estimates was low due to the patchiness of lobsters. However, the 2+ lobster abundance in the SE quadrant fell just below the long-term average in 2005. This data highlights the spatial and temporal variability in 2+ lobster abundance, and the need to sample all strata in the fishery during population surveys to ensure the resulting population estimates are representative.

In contrast to the increasing trend for 2+ year-class, the abundance of the 1+ year-class declined during 2004 and 2005 to the second lowest level recorded, just greater than the record low 2001 level (Figure 2-5). The abundance of 1+ lobsters was also well below the long-term average in all quadrants of the fishery (Figure 2-7), particularly the NW quadrant, which includes important fishing grounds for island-based fishers of the central islands. The low abundance of 1+ lobsters recorded in 2005 suggested that even if the recent high survival rate persisted it was likely the 2006 2+ year-class would be well below the recent high levels. Anecdotal reports of low catch rates from fishers operating during 2006 to date have corroborated this forecast.

The 2005 recruiting (1+) and fished (2+) lobster abundance indices, standardized to measured belt transect (500 × 4m) counts, have been incorporated into the age-structured fishery model to allow assessment of the status of the stock

![Figure 2-7. Mean numbers (± SE) of recruiting (1+) and fished (2+) ornate rock lobsters Panulirus ornatus per site in 3 quadrants of the Torres Strait lobster fishery and all quadrants combined between 1990 and 2005, showing spatial and temporal differences in abundance of the two year-classes. Dashed lines represent the sixteen year averages.](image)

### 2.3.4. PNG Inter-annual Lobster Abundance

Fishery-independent surveys of the lobster population in PNG waters of Torres Strait have been conducted in 1989, 1998, 2002, 2003 and 2004. The sample design employed during the 1998 population survey, funded by ACIAR, was based on seabed habitat data recorded during the 1989
The absolute stock abundance and biomass of lobsters was estimated during the 1998 survey and subsequently during the 2003 survey (see Ye et al, 2004 for details). The abundance of lobsters was estimated at ~460000 ± 50% (95%CI) in 1998 cf. ~1062000 ± 42% in 2003 (Table 2-2). The stock biomass estimated in 2003, ~150 t tail weight, was approximately 15% of the entire Torres Strait stock.

Figure 2-8. Map of PNG waters of Torres Strait showing locations of sampling strata and densities of ornate rock lobsters *Panulirus ornatus* at sites sampled during fishery-independent surveys in 1989, 1998, 2002 and 2003.
Table 2-2. Estimates of ornate rock lobster *Panulirus ornatus* abundance and biomass in PNG waters of Torres Strait from fishery-independent surveys conducted in 1998 and 2003.

<table>
<thead>
<tr>
<th>Year</th>
<th>Count</th>
<th>Population estimate</th>
<th>95% CI</th>
<th>%1+</th>
<th>1+ Stock</th>
<th>2+ Stock</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>133</td>
<td>459991</td>
<td>50</td>
<td>56</td>
<td>257595</td>
<td>202396</td>
<td>136617</td>
</tr>
<tr>
<td>2003</td>
<td>69</td>
<td>1061836</td>
<td>42</td>
<td>48</td>
<td>509681</td>
<td>552154</td>
<td>149641</td>
</tr>
</tbody>
</table>

Using the same sample design as that employed in 1998 and 2003, the estimated abundance of lobsters in PNG waters of Torres Strait in 2004 was ~690000 ± 43% (Table 2-3). However, this estimate was based on lobster counts from only 29 transects, and the precision of this estimate is obviously very low. Given that recruiting (1+) lobsters comprised 68% of those sampled, the 1+ population was estimated at ~469000 lobsters, whilst the 2+ population was estimated at ~221000 lobsters.

Table 2-3. Stratified estimate of ornate rock lobster *Panulirus ornatus* abundance in PNG waters of Torres Strait from diver survey counts recorded in May 2004.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Area km²</th>
<th>Wb</th>
<th>Variance</th>
<th>Mean</th>
<th>Weighted Mean</th>
<th>Count</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daru mud</td>
<td>94.26</td>
<td>0.040</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gimini hard</td>
<td>287.56</td>
<td>0.122</td>
<td>5.773</td>
<td>1.340</td>
<td>0.164</td>
<td>12</td>
<td>192658</td>
</tr>
<tr>
<td>Kokope Reef</td>
<td>56.12</td>
<td>0.024</td>
<td>0.826</td>
<td>0.930</td>
<td>0.022</td>
<td>3</td>
<td>26087</td>
</tr>
<tr>
<td>North Awamaza</td>
<td>6.49</td>
<td>0.003</td>
<td>8.546</td>
<td>3.360</td>
<td>0.009</td>
<td>2</td>
<td>10903</td>
</tr>
<tr>
<td>Northeast channel</td>
<td>501.34</td>
<td>0.213</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Southwest Daru</td>
<td>176.93</td>
<td>0.075</td>
<td>0.000</td>
<td>1.820</td>
<td>0.137</td>
<td>2</td>
<td>160998</td>
</tr>
<tr>
<td>Wapa back reef</td>
<td>28.64</td>
<td>0.012</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Warrior near front</td>
<td>134.94</td>
<td>0.057</td>
<td>21.346</td>
<td>4.438</td>
<td>0.255</td>
<td>8</td>
<td>299447</td>
</tr>
<tr>
<td>West Awamaza</td>
<td>176.09</td>
<td>0.075</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>West Warrior</td>
<td>890.50</td>
<td>0.378</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2353</td>
<td>1.0</td>
<td>0.587</td>
<td>29</td>
<td>690093</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3.5. Lobster Distribution

The general distribution of ornate rock lobsters *Panulirus ornatus* recorded during 2005 was similar to 2004, although recruiting (1+) lobsters were significantly less abundant at sites in the south-east quadrant of the fishery (Figure 2-9). There has been no sampling conducted throughout most of the northern mid-section of the fishery since 1989, as this area is predominantly sand and mud and unsuitable habitat for lobsters (see Chapter 7 for more detail). The overall distribution of recruiting lobsters was uniformly low in 2005 compared to 2004. In 2005 2+ lobsters were recorded at 51% of sites surveyed cf. 41% in 2004, while 1+ lobsters were recorded at 53% of sites surveyed in 2005 cf. 66% in 2004 (Figure 2-9).

The spatial distribution of lobsters throughout western Torres Strait has not changed significantly since the initial population survey in 1989, as shown during the Benchmark Lobster Survey in 2002 and subsequent annual population surveys. This is likely due to the consistency in the distribution of seabed habitats, particularly hard substrates that are preferred by lobsters. This temporal consistency of lobster distribution is important as the annual population surveys are conducted at repeated sites each year, and the lobster populations at these sites are presumed to be representative of the whole area.
2.3.6. Size and Age Distribution

The size-frequency distributions of ornate rock lobsters *Panulirus ornatus* sampled during annual population surveys between 1989 and 2005 are comprised of two modes, representing the recruiting (1+) and fished (2+) year-classes (Figure 2-10). The recruiting year-class has been significantly more abundant in most years, except 1989 and 1998 when the proportions were almost equal. In some years the population is also comprised of a small percentage of 3+ lobsters, predominantly males that had not migrated during the previous year. In contrast, the size-frequency distributions of lobsters sampled from the island-based commercial catches prior to 2002 are comprised mainly of 2+ lobsters (Figure 2-10). Nearly all of the 1+ lobsters in these commercial catches were smaller than the recently implemented minimum size limit (115 mm tail length ≈ 60 mm tail width), and current commercial catches taken at the time of the mid-year surveys are composed almost entirely of 2+ lobsters (Figure 2-6).

**Figure 2-9.** Maps of western Torres Strait showing geographic distribution of recruiting (1+) and fished (2+) lobsters *Panulirus ornatus* recorded during annual lobster population surveys in Torres Strait in April/May 2004 and April/May 2005.
Figure 2-10. Size-frequency distributions of the ornate rock lobster (*Panulirus ornatus*) catch landed at Mabuiag/Badu Islands in June/July 1989-2001 contrasted with the size-frequency distributions of the Torres Strait lobster population surveyed by research divers in May/June 1989-2005. The graphs are scaled by CPUE of the fishery and survey respectively to indicate inter-annual differences in relative abundance.
The mean size of 2+ lobsters sampled during the annual population surveys has been relatively consistent (Figure 2-11), around the long-term average of 97 mm carapace length (≈ 67 mm tail width). However, the mean size of 1+ lobsters varied widely between years (Figure 2-11), around the long-term average of 59 mm carapace length (≈ 40 mm tail width). It is difficult to determine the cause of this inter-annual variation, initially because the timing of larval delivery to Torres Strait has not been determined each year. Back calculation of early growth of juvenile lobsters indicated that settlement peaked in Torres Strait in June 1992 (Dennis et al. 1997), but subsequent studies have not been done to determine the consistency of this timing. Subsequent larval transport modeling indicated that settlement into Torres Strait occurred between May and August for the years 1995 to 2000 (Pitcher et al. 2005).

**Figure 2-11.** Mean carapace lengths of recruiting (1+) and fished (2+) lobsters *Panulirus ornatus* sampled during annual surveys of the Torres Strait population between 1990 and 2005. Vertical bars represent standard errors. Dashed horizontal lines represent the 16 year averages.

Assuming the timing of settlement is relatively consistent between years the above average size of both recruiting and fished lobsters in 2005 suggests that conditions for growth have been favourable recently, and this is supported by the observed recovery in seabed habitats since 2001. Many factors are known to influence growth of lobsters including; temperature, density dependence and diet, and these factors will all influence the sizes of the stocks. Fishers regularly report finding aggregations of lobsters in areas with dense coverage of small mussels and pearl shells (termed bastard shell), particularly in deeper water. These aggregations are rarely seen during annual population surveys, likely due to their patchiness, but their abundance may be tied to an environmental variable that could be monitored (e.g. primary productivity or SST). Possible influences of environmental variables on
lobster recruitment are reported in Chapter 8. A greater understanding of the environmental influences may provide greater accuracy of future stock forecasts.

Importantly, the temporal differences in lobster growth influence the timing of recruitment of 1+ lobsters to the fishery and hence, selectivity of the fishery. It is hoped that the timing of fishery recruitment can be more accurately determined through the recently implemented commercial catch size monitoring program, and this information will be incorporated into future stock assessments.

The size-frequency distributions of ornate rock lobsters *Panulirus ornatus* sampled during the annual population surveys in 2004 and 2005 were comprised of almost equal proportions of males and females, of consistent size (Figure 2-12). This consistency is due to the timing of the annual population surveys, chosen deliberately to fall just prior to the emigration of lobsters in spring. The annual migrations cause changes to the size structure and sex ratio of the Torres Strait lobster population as all 2+ females and a large proportion of 2+ males emigrate to breed (Skewes et al. 1994).

![Size-frequency distributions of female (red bars) and male (blue bars) ornate rock lobsters (*Panulirus ornatus*) sampled during the annual population surveys in Torres Strait in 2004 and 2005.](image)

**Figure 2-12.** Size-frequency distributions of female (red bars) and male (blue bars) ornate rock lobsters (*Panulirus ornatus*) sampled during the annual population surveys in Torres Strait in 2004 and 2005.
2.4. DISCUSSION

The annual population surveys provided key data for assessment of the status of the Torres Strait lobster stock including; relative abundance of recruiting (1+) and fished (2+) lobsters and age composition of the population. The relative abundance data was used to construct a stock-recruitment relationship and in combination with commercial catch this information, allows modeling of the fishery. Hence, the fishery-independent data collected during the annual population surveys are critical for effective management of the fishery.

The annual population surveys were initially undertaken to provide lobster abundance data since there was no comprehensive monitoring of commercial catch and effort. The catch and effort of the island-based sector was monitored during 1989-2001, and this data corroborated the trends in abundance estimated from the population surveys. The introduction of the docket book system by AFMA in 2003, in combination with the compulsory logbook program should ensure all catch and effort from the fishery is recorded in the future. This data will allow a more robust comparison of CPUE and fishery-independent data as proxies for abundance.

The trends of abundance for recruiting (1+) and fished (2+) lobsters were consistent for the timed (20 minute swim) count data and the standardized measured belt transect (500 × 4 m) data, particularly for 2+ lobsters for years post 1990. This consistency was not unexpected given that previous studies showed that divers swim ~500 m in about 20 minutes and transect width is obviously controlled by visibility, the factor used to scale to measured belt transects. The 20 minute swims were adopted in 1990 due to the inefficiency of laying and retrieving a transect line from the seabed (as done in 1989) but this inefficiency for measured transects no longer exists with the advent of the Chainman® device. In any case, the 20 minute count data was less precise for both age-classes and all future surveys should adopt measured belt transects to improve the precision of the inter-annual comparisons. Importantly, the consistency of the timed count and measured transect count data indicates that previous stock assessments made using the timed count data were consistent with the up-to-date stock assessment.

Although the abundance of fished (2+) lobsters in 2005 was near the highest level recorded the abundance of recruiting (1+) lobsters in that year was amongst the lowest recorded. Hence, although recent survival rates have been high the 2006 stock forecast was pessimistic. This highlights the high year to year variability in stock levels for this fishery and explains why historic catches have been variable; particularly given that the catch is derived almost entirely of a single cohort. This variability also emphasizes the need for precautionary management of this fishery since over-exploitation in year X directly impacts the catch in year X+3.
3. PRE-SEASON POPULATION SURVEY

3.1. INTRODUCTION

In July 2005 the Torres Strait Protected Zone Joint Authority (PZJA) made the decision to change management of the Tropical Rock Lobster (TRL) fishery from effort restricted to a quota management system through modification of the input controls. The new management system included moving to a 50/50 share of Australian commercial entitlements between Torres Strait islanders and non-islanders. The decision brought about an urgent need to develop a method to set a sustainable total allowable catch (TAC) in 2006 and to prioritize research needed to obtain the necessary lobster stock and fishery data to estimate the TAC. The new quota management system was subsequently delayed to 2007, but research was funded to ensure an operational TAC could be set for the 2007 fishing season.

The main research priority identified, to support the new TAC, was a pre-season population survey of recruiting (1+) lobster abundance. The first pre-season survey was conducted in November 2005 to provide managers with information on the abundance and biomass of fishery recruits and the likely stock biomass available to be fished in the 2006 fishing season. This information was subsequently used by the TRL research assessment group (RAG), in March 2006, to help formulate a method to set a sustainable TAC for the 2006 fishing season.

The success of the new quota management system also relies on an accurate estimate of commercial catch. The recent implementation of the docket book system, to cover commercial lobster catches of island-based fishers, in combination with the compulsory logbook system for freezer vessels will ensure there is comprehensive monitoring of the TRL catch. The reliability of this data is discussed in Chapter 4.

As is the case for the annual mid-year population surveys (1989-2005) the pre-season survey provides the only fishery-independent indices of lobster abundance throughout the Torres Strait fishery. The combination of long-term stock assessment, based on the age-structured fishery model and current estimates of stock abundance is critical in ensuring the TAC is set at a sustainable level. This information is essential for the conservation, management and optimum use of the Torres Strait lobster fishery, as required under the treaty.

3.2. METHODS

3.2.1. Sample Design

The sampling strata used in the 2005 pre-season survey sample design were the same as those used for the annual population surveys (Figure 2-2). The number of sites allocated was constrained by logistics of the field survey and it was anticipated that around 160 sites could be sampled over 20 days, assuming a maximum of 8 transects surveyed per day. Given these logistical constraints, a stratified random sample design was not considered due to the likely high proportion of zero counts, and the resultant low population estimate precision. For example, lobsters were recorded at only 40% of the 375 sites sampled during the Benchmark Lobster Survey in 2002, and this was after stratification of the survey area to exclude unsuitable lobster habitat. For this reason the 2005 pre-season survey was designed to estimate relative abundance with high precision.

The 86 sites allocated in the sample design of the 2005 annual population survey were again chosen for the 2005 pre-season sampling to ensure continuity between the annual surveys (1989-2005) and the pre-season survey. Additional sites were chosen based mainly on the distribution and variance in abundance of recruiting (1+) lobsters recorded during the 2002 Benchmark Lobster Survey, because of the wide geographic extent of this survey. Results of the 2005 annual population survey were also included to provide current information on the distribution and abundance of recruiting (1+) lobsters.

A total of 175 possible sites were allocated for the pre-season survey, including 27 new reef-edge sites and 10 new sites in the Warraber_bridge stratum. The new sites were allocated to address the concerns of commercial fishers and managers that previous surveys may not have adequately sampled the north-east quadrant of the fishery, including Warrior Reef.
3.2.2. Field Survey

The field survey was planned for November 2005, just prior to the opening of the 2006 fishing season in December (only free-diving is permitted in December/January). The sampling protocol was consistent with the previous annual population surveys (1989-2005), again to ensure consistency between the surveys. Lobsters were surveyed using measured belt transects (500 × 4 m) at each site throughout the fishery and the sites were re-located accurately using portable GPS.

In addition to recruiting (1+) and fished (2+) lobsters, recently-settled lobsters (0+) were also recorded to provide current information on the spatial distribution of settlement. It is highly likely that recently-settled lobsters were under-sampled due to their size and cryptic behavior but the counts may serve as relative indices of settlement strength for future surveys. As in all previous annual population surveys lobsters were sampled by divers, where possible, during each transect. At the completion of each transect a diver recorded; the number of lobsters caught, the number and age-class of those missed, depth, visibility, distance swum, numbers of pearlshell (*Pinctada maxima*) and holothurian species observed, and percent covers of standard substratum and biota (including seagrass and algae species) categories.

3.2.3. Size and Age Distribution

The sampled lobsters were measured (tail width in millimeters), sexed and moult staged to provide size-frequency data. The year-class components in the size frequency distribution of sampled lobsters were determined using modal analysis and the resulting proportions of recently-settled (0+), recruiting (1+) and fished (2+) year-classes were combined with the counts of missed 0+, 1+ and 2+ lobsters to estimate the age composition of the lobster population. The resulting proportions were combined with the lobster density data to determine the abundance of 0+, 1+ and 2+ lobsters.

3.2.4. Lobster Density

The stratified mean density of the Torres Strait lobster population, and precision of this estimate, was calculated using lobster count data from each sampling stratum. The density estimates could not be used alone to estimate absolute abundance, since the survey sites were not chosen strictly at random. The absolute abundance of recruiting (1+) and fished (2+) lobsters in November 2005 was estimated by scaling the 2002 Benchmark Lobster Survey abundance estimate using the stratified mean densities in both years (see Chapter 5 for details). The abundance of recruiting (1+) lobsters in combination with estimates of sustainable catch from the fishery model were used to calculate a recommended (theoretical) TAC for 2006.

The absolute abundance of recently-settled (0+) lobsters was estimated using the diver counts from each sampling stratum as there is no benchmark estimate to compare 2005 densities against. This abundance estimate may be biased given that sites were not chosen strictly at random, and it is likely this year-class was under-sampled. Nevertheless, the 2005 pre-season survey provided the first opportunity to estimate relative settlement strength, and provided future pre-season surveys follow a similar protocol the 0+ abundance estimate provides a comparative benchmark.

3.3. RESULTS

3.3.1. Field Survey

The 2005 pre-season lobster population survey was conducted during 15 November to 4 December by six CMAR staff using the research vessel M. V. James Kirby. As our application for customs clearance exemption was again unsuccessful, no sampling was conducted in PNG waters. The prevailing weather conditions during the pre-season survey (light winds and smooth seas) were more suitable to diving than the predominant rough seas encountered during the annual surveys. As a result, a total of 154 sites were sampled in each of the 8 sampling strata (Figure 3-1).
Figure 3-1. Map of western Torres Strait showing distribution of the sampling strata and sample sites used in the pre-season lobster (*Panulirus ornatus*) population survey in November 2005.

3.3.2. Lobster Distribution

The distribution of recruiting (1+) lobsters recorded during the 2005 pre-season survey was consistent with that of the 2005 annual survey, with low and uniform densities at most sites and slightly higher densities in the south-east of the fishery (Figure 3-2). In contrast, the distribution of fished (2+) lobsters was different from that observed in all previous annual surveys, due to the absence of fished lobsters at most sites.
3.3.3. Recruiting (1+) and Fished Lobster (2+) Density

The highest mean densities of recruiting (1+) lobsters were recorded in the south-east and Warrior_back strata (Figure 3-3), but only 2 sites were sampled in the latter stratum. The south-east stratum also housed the highest, and similar, density of recruiting lobsters in April/May (Figure 2-4). Recruiting lobsters were also abundant in the kircaldie_rubble stratum, even though recruits are normally sparse in this stratum during mid-year. The absence of fished lobsters in November, and hence more available shelter for smaller lobsters, may account for this. The precisions of the estimates were high in most strata except the warraber_bridge, south-east and kircaldie_rubble strata, and additional sample sites in these strata may be warranted for future surveys. The precision of the reef-edge stratum was very high due to the over-allocation of sites to address the concerns of fishers and managers about adequate sampling of the Warrior Reef area.

The highest density of fished (2+) lobsters was recorded in the warrior_back stratum but again this result is unreliable due to only 2 sites being sampled there (Figure 3-3). The next highest density was recorded in the reef-edge stratum.

Figure 3-2. Maps of western Torres Strait showing geographic distribution of recruiting (1+) and fished (2+) lobsters (*Panulirus ornatus*) recorded during the pre-season lobster population survey in Torres Strait in November 2005.
3.3.4. Recently-settled (0+) Lobster Density and Abundance

Recently-settled (0+) lobsters were observed at 41% (63/154) of the sites sampled during the 2005 pre-season survey. Of these sites, 57% (36/63) also housed recruiting (1+) lobsters. The highest mean density of recently-settled (0+) lobsters was recorded in the Mabuiag stratum, followed by the TI_bridge stratum (Figure 3-4). The precisions of the density estimates were low in most strata due to the over-dispersed distribution of recently-settled lobsters, and particularly due to the high proportion (59%) of zero occurrences.

The population estimate of recently-settled (0+) lobsters was ~8.5 million ± 42% (95% CI; Table 3-1). The majority of the population was recorded in the mabuiag and ti_bridge strata, and these strata combined account for ~50% of the total study area. The reef-edge housed the least recently-settled lobsters due to the low density there and the small area of this stratum. Although this estimate is preliminary, and likely biased, as discussed above, the differences in distribution and abundance of 0+ and 1+ lobsters highlights the need for different sample designs to adequately estimate the abundance of these year-classes.

Although there were slightly more lobsters recorded at shallow (<10 m) depths, there was no significant relationship between the number of lobsters and depth for non-zero occurrences throughout the study area (Figure 3-5).
Figure 3-4. Mean number (± SE) of recently-settled (0+) ornate rock lobsters (*Panulirus ornatus*) recorded during the pre-season survey of the Torres Strait population in November 2005.

Figure 3-5. Number of recently-settled (0+) ornate rock lobsters (*Panulirus ornatus*) against depth (m) recorded during the 2005 pre-season population survey. The line represents the least-squares fit to the data.
Table 3-1. Stratified estimate of recently-settled (0+) lobster (*Panulirus ornatus*) abundance in November 2005.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Area km²</th>
<th>Wb</th>
<th>Variance</th>
<th>Mean</th>
<th>Count</th>
<th>Population</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buru</td>
<td>1689</td>
<td>0.189</td>
<td>1.455</td>
<td>0.636</td>
<td>11</td>
<td>537388</td>
<td>6.30</td>
</tr>
<tr>
<td>Kircaldie_rubble</td>
<td>961</td>
<td>0.108</td>
<td>0.492</td>
<td>0.444</td>
<td>12</td>
<td>213465</td>
<td>2.50</td>
</tr>
<tr>
<td>Mabuiag</td>
<td>1394</td>
<td>0.156</td>
<td>12.996</td>
<td>3.938</td>
<td>16</td>
<td>2743875</td>
<td>32.19</td>
</tr>
<tr>
<td>Reef-edge</td>
<td>93</td>
<td>0.010</td>
<td>7.772</td>
<td>0.820</td>
<td>36</td>
<td>37946</td>
<td>0.45</td>
</tr>
<tr>
<td>South-east</td>
<td>893</td>
<td>0.100</td>
<td>4.485</td>
<td>1.474</td>
<td>19</td>
<td>658042</td>
<td>7.72</td>
</tr>
<tr>
<td>TI_bridge</td>
<td>2924</td>
<td>0.328</td>
<td>59.564</td>
<td>2.854</td>
<td>44</td>
<td>4173488</td>
<td>48.96</td>
</tr>
<tr>
<td>Warraber_bridge</td>
<td>744</td>
<td>0.083</td>
<td>0.571</td>
<td>0.429</td>
<td>14</td>
<td>159533</td>
<td>1.87</td>
</tr>
<tr>
<td>Warrior_back</td>
<td>231</td>
<td>0.026</td>
<td>0.000</td>
<td>0.000</td>
<td>2</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8929</strong></td>
<td><strong>1.0</strong></td>
<td><strong>154</strong></td>
<td></td>
<td></td>
<td><strong>8523736</strong></td>
<td><strong>100.00</strong></td>
</tr>
</tbody>
</table>

3.3.5. Size and Age Distribution

The size-frequency distribution of 302 lobsters sampled during the 2005 pre-season lobster population survey was comprised of three components representing recently-settled (0+), recruiting (1+) and fished (2+) lobsters (Figure 3-6). Fished lobsters, predominantly males, comprised only a small proportion (3%) of the population as the majority of fished lobsters would have emigrated to breed during the previous months. The progression of the modes of the 2+ and 1+ year-classes is shown in Figure 3-7.

Recruiting (1+) lobsters, with equal contributions of males and females, comprised most (67%) of the population and less than half were larger than the minimum legal size (115 mm tail length \(\approx 60 \text{ mm tail width}\)). This highlights why the commercial catch is comprised of such a low proportion of 1+ lobsters. Recently-settled (0+) lobsters, also equally comprised of males and females, comprised 30% of the population and averaged \(\approx 25 \text{ mm tail width}\).

![Figure 3-6. Size-frequency distribution of female (red bars) and male (blue bars) ornate rock lobsters (*Panulirus ornatus*) sampled during the pre-season population survey in Torres Strait in November 2005. The recently-settled (0+), recruiting (1+) and fished (2+) modes are shown.](image-url)
Figure 3-7. Comparative size-frequency distributions of ornate rock lobsters (*Panulirus ornatus*) sampled during the annual (May) and pre-season (November) population surveys in Torres Strait in 2005. The recently-settled (0+), recruiting (1+) and fished (2+) modes are shown.

3.4. DISCUSSION

The sample design used for the 2005 pre-season survey was a compromise between funds available and precision of the relative abundance estimate. In addition, the sample design could only be determined using information from the annual (mid-year) surveys since this was the first occasion a pre-season survey had been conducted. Nevertheless, the precisions of density estimates for recruiting (1+) lobsters were high in most sampling strata. The reef-edge stratum was over-sampled and sites in this stratum should be re-allocated in future pre-season surveys.

The 2005 pre-season lobster population survey provided the first opportunity to document the distribution and abundance of recently-settled (0+) lobsters throughout the Torres Strait fishery. Recently-settled lobsters are rarely recorded during annual (mid-year) surveys because of their small size and cryptic behaviour at that time of year. Further most settlement likely occurs later than the time of mid-year surveys. The recently-settled lobsters were recorded throughout the fishery and independent of depth, but their distribution was over-dispersed. Targeted sampling of the 0+ year-class at a limited number of sites during future pre-season surveys could provide useful forecasts of recruiting (1+) and fished (2+) lobster abundance.
4. TECHNICAL ANALYSIS OF THE DATA COLLECTION METHODS

4.1. INTRODUCTION

Catch landings and survey abundance indices are the two fundamental data sources available for assessment of the Torres Strait lobster fishery. Stock assessment and studies on fishery sustainability and management strategies are based on these two data sources as fishing effort data is only available for the freezer boat (non-islander) sector, due to the introduction of compulsory log-books for this sector in 1997. Some data was also collected by a voluntary log-book program for the same sector during 1994 to 1996. In any case, there have been many variations in the way the catch landings and survey abundance indices data were collected over time. It is important to evaluate the potential impact of these variations on the data and to make necessary revisions if significant differences between the sources can be identified and quantified. This chapter describes the preparation of a time series of landed catches and survey abundance indices for subsequent analysis.

4.2. COLLECTION OF COMMERCIAL CATCH DATA

Commercial catches of the lobster fishery were originally obtained from shipping records of commercial companies that were involved in lobster trading. This practice was considered fairly reliable because the local trading companies bought frozen lobster tails in Torres Strait, shipped them to Cairns and then sold them overseas. However, in the late 1990s some product was marketed live and several new trading companies began transporting lobsters by air. Hence, commercial catch could no longer be estimated from shipping records and the data collection system stopped in 2001. A new system to determine the commercial catch was introduced in 2003, which involved collecting data from the freezer boat sector through the compulsory log-book system and from the Torres Strait Island Boat (TIB) sector through a new docket book system. The logbook system is a condition of the primary vessel license and records of daily catch, rough fishing location, time spent fishing etc. are mandatory. In contrast, the docket book system records the catch and fishing location when island-based fishers sell their catch to shore-based trading companies. The new system is believed to be reliable at least in gathering catch data.

Unfortunately, there was a gap between the old and new systems and no catch data was collected in 2001-2002. The obvious importance of catch data for stock assessment meant that the missing data had disastrous consequences on the effectiveness of lobster research and advice to managers. In 2004 AFMA made a concerted effort to rescue the 2001-2002 data and personnel were dispatched to all trading companies to retrieve old catch records these companies had archived. The annual landed catches for 2001-2002 were calculated from these rescued trading records. When the catch data from the different systems were plotted together, the catches from the last five years appeared much more variable than the catches from the early years (Figure 4-1). The 2001-02 catches were the lowest and the 2004-05 catches the highest. It should be noted that the 2005 data was not complete at the time of preparing this report, and the data file covered only the first 6 months. After consulting with AFMA and the industry, the 2005 catch was assumed to be the same as 2004 for the purposes of an up-to-date analysis.

There is no straightforward way to verify whether the two data-sets are compatible and the 2001-02 data were complete, particularly since the catch data were not rescued together with other comparable information such as fishing effort. Figure 4-2 compares the catches of the whole fishery with catches of 8 selected vessels that appeared to have comprehensive records for 1997 to 2005. The two series of catch data had similar temporal patterns, particularly during 2001 to 2005. The two data sources diverged in 2005. This was because the 2005 total catch was purposely set at the 2004 level as there were no comprehensive data available for 2005, but no such an adjustment was done for the selected vessels. If the rest of the fishery behaves in a way similar to those selected vessels, this consistency suggests the catch data AFMA rescued for 2001 and 2002 are comprehensive and the shipping records provided fairly good estimates for the landed catch although some discrepancy existed for years earlier than 2001.
Figure 4-1. Commercial lobster catch landings (tonnes total weight) taken in Australian waters of Torres Strait. Circles estimated from shipping records and triangles from the new logbook/docket book system.

Figure 4-2. Comparison of Torres Strait lobster catches (tonnes total weight) taken by 8 selected vessels and the whole fishery.
4.3. ANNUAL (MID-YEAR) POPULATION SURVEYS

4.3.1. Standardization of the annual population survey data

The abundance and biomass of the Torres Strait lobster population was first estimated using a fishery-independent diver survey in 1989, after a small scale pilot study in 1988. Annual population surveys have been conducted in all years since 1989. However, over the 17 year period, only two surveys had full spatial coverage, one in 1989 and the other in 2002. The 1989 survey was not well stratified because there was no seabed habitat and little lobster distribution information available. In addition, the age composition of the population was estimated using the size-frequency distribution of lobsters speared by a professional fisherman and it was believed biased towards large lobsters. In 1989 and 2002, sample sites were selected randomly within each stratum, and the allocation of the sample sites among strata was based on Neyman Allocation (Cochran, 1977), even though not strictly followed. Abbreviated population surveys were conducted in other years during 1989 to 2005 to estimate the relative abundance of the population with reference to the 1989 and 2002 benchmarks.

The sample design of the population surveys had to be modified over time to accommodate financial constraints, new dive regulations introduced in 2002, and the need to increased spatial coverage of the surveys. During 1990-1995 50 locations, each with two sites, were surveyed, but the survey was further scaled down to 42 locations during 1996-2001 because of financial constraints and logistical difficulties. During 1990-2001 two sites were sampled at each location (as was done in the original 1989 survey), but this was changed to one transect per location in 2003 to increase the spatial coverage of the survey.

As for sample design the sampling method was modified over time. The length of the surveyed transect was fixed at 500 m, measured using a line laid on the seabed or with a Chainman® device in some years, but variable during 1990-1995 when transects were conducted as 20 minute swims. Similarly, the width of the survey transect was fixed at 4 m sometimes, but left to be determined by divers’ visibility in other times. For more details about the annual population survey details see Pitcher et al. (1997) and Ye et al. (2005).

All the changes and inconsistency in survey design and implementation require standardization before the survey catch rates can be used as relative abundance indices. Pitcher et al. (1997) standardized the survey catch rates for 1989-1996. During that period, the survey transects were only fixed at 500 x 4 m using a line laid on the seabed in 1989, with transects distance determined by the 20 minute swim duration and transect width by divers’ visibility in other years. Pitcher et al. (1997) used the raw 20 minute swim counts for 1990-1996, and re-scaled the 1989 data to 20 minute swim counts using a relationship for transect length between the 20 minute swim distance and duration of the 500 m transects and for transect width by adjusting the visibility-determined width to 4 m. The adjustment formula Pitcher et al. (1997) used to convert visibility to transect swath width was

\[
\text{Swath width} = 3 \times 0.75 \times \text{visibility with a maximum swath width of 12 m.}
\]

The basis for this calculation was that divers were separated by 0.75*visibility and they scanned the area between them plus a similar area to the outside, but when visibility was 5 m or greater, divers swam about 4 m apart and each scanned about 4 m to the outside.

Ye et al. (2005) subsequently carried out a standardization of the 1989-2002 population survey data. They first developed a multiple regression model between transect distance (measured using the Chainman® device) and swimming time, current speed, depth and number of lobsters speared. The first three predictors had a positive impact on the distance swum, but the last predictor was negatively related to distance as a diver would swim a shorter distance when he speared more lobsters. After adjusting the distance of the survey transects to 500 m, a complex generalized linear model was used to extract the annual lobster abundance indices. This model consisted of two sub-models, one for the lobster catch rates and the other for the probability of caching lobsters at a sample site. The model-based estimates of mean annual catch rates were similar to the design-based estimates in general.

The swath width of the survey transects was fixed at 4 m only in 1989 and 2002 and determined by divers’ visibility in all other years before 2003 (Ye et al., 2005). Transect width was not standardized, but its influence on catch was expected to be incorporated through the models in which visibility was a
variable. However, as transect width was only fixed in two years, this assumption may impact the accuracy of the modelled catch rates.

Although the impact of visibility on swath width and subsequent catch per transect can be adjusted through models, the impact of visibility on swath width will vary amongst different divers. To reduce bias transect width has been fixed at 4 m since 2003 by divers using a measured spear. With the addition of 2003-2005 survey data, the relationship between Chainman distance and other measured variables were updated through stepwise selection. Among swimming time, current speed, depth and number of lobsters speared, only swimming time \( T \) and current speed \( C \) were finally selected,

\[
D = 12.66(23.45) + 17.68(1.16)T + 138.40(3.81)C
\]

where \( D \)=distance. The model explained 66.4\% of the data variation. Swath width was estimated from Pitcher et al. (1997), but in the present study maximum width was reduced to 7 m for age 2 lobsters and 6 m for age 1 lobsters based on experiments performed in the last three years’ and the opinions of experienced divers.

Table 4-1. Specifications of the lobster population survey implementation (sample design and transect methods) during 1989 to 2002.

<table>
<thead>
<tr>
<th>Year</th>
<th>No of transects/sites</th>
<th>GPS distance</th>
<th>Chainman distance</th>
<th>Width</th>
<th>Time swum</th>
<th>Sparing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>542(271)</td>
<td>No</td>
<td>Fixed at 500 m</td>
<td>Fixed at 4 m</td>
<td>Measured</td>
<td>No</td>
</tr>
<tr>
<td>1990</td>
<td>100(50)</td>
<td>No</td>
<td>Not used</td>
<td>Visibility determined</td>
<td>Fixed at 20 minutes</td>
<td>Yes</td>
</tr>
<tr>
<td>1991</td>
<td>100(50)</td>
<td>No</td>
<td>Not used</td>
<td>Visibility determined</td>
<td>Fixed at 20 minutes</td>
<td>Yes</td>
</tr>
<tr>
<td>1992</td>
<td>100(50)</td>
<td>Yes</td>
<td>Not used</td>
<td>Visibility determined</td>
<td>Fixed at 20 minutes</td>
<td>Yes</td>
</tr>
<tr>
<td>1993</td>
<td>100(50)</td>
<td>Yes</td>
<td>Not used</td>
<td>Visibility determined</td>
<td>Fixed at 20 minutes</td>
<td>Yes</td>
</tr>
<tr>
<td>1994</td>
<td>100(50)</td>
<td>Yes</td>
<td>Not used</td>
<td>Visibility determined</td>
<td>Fixed at 20 minutes</td>
<td>Yes</td>
</tr>
<tr>
<td>1995</td>
<td>100(50)</td>
<td>Yes</td>
<td>Not used</td>
<td>Visibility determined</td>
<td>Fixed at 20 minutes</td>
<td>Yes</td>
</tr>
<tr>
<td>1996</td>
<td>82(41)</td>
<td>Yes</td>
<td>Partially used</td>
<td>Visibility determined</td>
<td>Fixed at 20 minutes</td>
<td>Yes</td>
</tr>
<tr>
<td>1997</td>
<td>82(41)</td>
<td>Yes</td>
<td>Not used</td>
<td>Visibility determined</td>
<td>Fixed at 20 minutes</td>
<td>Yes</td>
</tr>
<tr>
<td>1998</td>
<td>82(41)</td>
<td>Yes</td>
<td>Fixed at 500 m</td>
<td>Visibility determined</td>
<td>Measured</td>
<td>Yes</td>
</tr>
<tr>
<td>1999</td>
<td>82(41)</td>
<td>Yes</td>
<td>Fixed at 500 m</td>
<td>Visibility determined</td>
<td>Measured</td>
<td>Yes</td>
</tr>
<tr>
<td>2000</td>
<td>82(41)</td>
<td>Yes</td>
<td>Fixed at 500 m</td>
<td>Visibility determined</td>
<td>Measured</td>
<td>Yes</td>
</tr>
<tr>
<td>2001</td>
<td>82(41)</td>
<td>Yes</td>
<td>Fixed at 500 m</td>
<td>Visibility determined</td>
<td>Measured</td>
<td>Yes</td>
</tr>
<tr>
<td>2002</td>
<td>354(313)</td>
<td>Yes</td>
<td>Fixed at 500 m</td>
<td>Fixed at 4 m</td>
<td>Measured</td>
<td>Yes</td>
</tr>
<tr>
<td>2003</td>
<td>89 (50)</td>
<td>Yes</td>
<td>Fixed at 500 m</td>
<td>Fixed at 4 m</td>
<td>Measured</td>
<td>Yes</td>
</tr>
<tr>
<td>2004</td>
<td>88(88)</td>
<td>Yes</td>
<td>Fixed at 500 m</td>
<td>Fixed at 4 m</td>
<td>Measured</td>
<td>Yes</td>
</tr>
<tr>
<td>2005</td>
<td>88(88)</td>
<td>Yes</td>
<td>Fixed at 500 m</td>
<td>Fixed at 4 m</td>
<td>Measured</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The fixed sample sites were selected from the original randomly allocated sites on the basis of high catch rates and representativeness to increase the effectiveness and precision of the annual population monitoring surveys. If the number of sample sites was kept constant over time, the bias in catch rates would remain consistent and might not be a serious issue for a time series of abundance indices. However, when the sample size changed, the bias became a problem, particularly when the sites that were omitted were predominantly those shown to have lower catch rates. During 1990 to 1995 a total of 50 locations were sampled but from 1996 to 2001 this number was reduced to 41 locations to
accommodate funding constraints (Table 4-1). The estimates of catch rates from the 50 locations were clearly lower than those using the 41 locations for age 1 lobsters, but less so for age 2 lobsters (Figure 4-3). This suggests that the catch rates estimated from the 41 locations in 1997-2001 and 2003 need to be adjusted downward accordingly.

Statistical models were developed to standardize the catch rate estimates from the 41 locations in 1997-2001 to those based on 50 locations. The time series of catch data is shown in Figure 4-4. Compared with Ye et al. (2005), the catch rates of 1997-2001 were relatively lower.

Figure 4-3. Difference in lobster catch rates estimated from the 50 (red) and 42 (black) sample locations.
4.3.2. Reliability of the survey abundance indices

Annual lobster population surveys have been carried out in each year since 1989. The major objective of the surveys is to provide relative abundance indices of the two lobster age classes. As the survey designs and scales have been modified through time (Ye et al., 2005), it is important to evaluate the reliability of the abundance indices.

The current logbook system used to monitor catch and effort of the freezer boat sector was voluntary when it started in 1994. Nevertheless, some vessels have consistently provided records of catch and effort for all years. After screening the whole logbook data-set, eight vessels were selected. If improvement in fishing efficiency is not significant, the catch per unit effort (CPUE) of these vessels should represent the abundance of the lobster stock, that is, CPUE can be used as an indicator of stock abundance. As the annual population surveys were conducted in May/June in most years, the June CPUE data from the selected vessels was used to compare with the survey catch rates of age 2 lobsters, given that the majority of the fishery catch comprised age 2 lobsters (Figure 4-5). Similar temporal patterns were observed in the data, although there were wide deviations in 1998 and 1999. This general agreement may suggest that the stock abundance indices derived from the annual mid-year surveys are good indicators of stock abundance.

The reliability of CPUE as an abundance index depends not only on catch records, but also on effort measurement. The CPUEs of the selected vessels were calculated here as kg per hour for a single tender. Fishing effort can also be measured as tender days. It was believed that tender-day is a better measure of fishing effort, and accordingly kg per tender-day should be used as the abundance index. A comparison of the June CPUEs using the two effort measures was depicted in Figure 4-6. The CPUE measures were significantly different from 1997 to 1999, but overall these two series had very similar temporal patterns. A further comparison was made of the annual CPUEs calculated using the two different effort measures (Figure 4-7). In this comparison the two CPUE series were even closer than the June CPUEs. This result justifies the use of kg/tender-hour in the previous comparison.
Figure 4-5. Comparison of the age 2 lobster catch rates (lobsters/transect) from the annual (mid-year) surveys with the CPUE (kg/tender-hour) of the selected vessels.

Figure 4-6. Comparison of CPUEs calculated from the June logbook records of the selected vessels using kg per tender-hour (blue circles) and kg per tender-day (red crosses) effort measures.
4.3.3. Population survey design

Survey design is critical in obtaining reliable abundance indices. Ecologists often choose a number of sampling stations in a non-random, more or less systematic fashion (Pearson et al., 1986). Each year replicate samples are taken within each station (Van der Meer, 1997). Recently, the importance of survey design has attracted greater attention and more statistically focused designs have been applied to some large monitoring programs. This kind of change in survey design is reflected typically in the Monitoring Survey of Ecologically Important Finfish and Invertebrates in the Virginia Portion of Chesapeake Bay (Montane and Lowery, 2005). The Chesapeake Bay Monitoring started in 1955 with non-randomly expert-selected stations, but in the 1970s, it used a semi-annual stratified random sampling; and in the 1990s it moved to a design of combing fixed and random stations. Monitoring surveys demand a long-term commitment of funding and research. A robust survey design plays a crucial role in obtaining reliable results, particularly when resource availability changes.

Van de Meer (1997) compared three survey designs that are frequently used to monitor year-to-year changes in the abundance of benthic animals:

Design 1 - Sampling stations are selected randomly each year
Design 2 - Sampling stations are selected randomly in the first year and then revisited in later years
Design 3 - Sampling stations are selected non-randomly in the first year and then revisited in following years.

He found that Design 1 yields the largest variance and the lowest power, and thus the largest detectable effect size and sample size are required to achieve a certain power. Design 2 generally results in a smaller variance of the estimators of year-to-year changes in abundance than Design 1, and therefore, a smaller sample size is needed to achieve a certain power. Design 3 produces the largest power, but a biased estimate of the mean for the whole area and an underestimated variance. Among the three designs, Design 2 performs better than Design 1 in terms of statistical power and better than Design 3 in terms of bias (for practical examples see Van der Meer (1997)).
Design 3 surveys sample only non-random stations or stations selected using expert-knowledge. The surveys cover only a portion of the total area and are of limited scale. Hence, the results only refer to a few sampled stations per se and the estimated mean and variance of the change in abundance cannot be extrapolated to the whole area. However, when the objective of the survey is to monitor the change of abundance over time, the fact that the estimates of the mean and its variance of the selected stations are biased estimates of the mean and variance for the whole area may not be really important. This is particularly true if the temporal change in abundance estimated using the selected stations can represent that of the whole area and if one realizes that the variance is underestimated.

The distribution of most benthic animals is very patchy in practice, some areas having a high density and others having no animals at all. When funding is sufficient for only a small sample size, which can only cover a very small portion of the distribution of a species, a small number of stations selected randomly will likely lead to a data-set of many zeros. A simple random sampling treats all stations equally and each station has the same probability of being selected. However, in practice, we know some stations have no fish and some stations have a high density and it is not sensible to sample the stations that have a very low probability to capture fish, particularly when the sample size is small. This is why Design 3 has the largest power. Therefore, for monitoring purposes, Design 3 may be more cost-effective when funding and other resources only allow for a very limited sample size.

The population monitoring survey used for the Torres Strait lobster fishery is a mixture of the three designs, closer to Design 3 because the sample size of fixed sites is much lower than that of the stratified random sample, only about 16% of the 2002 Benchmark Lobster Survey sample size with some strata excluded. The representativeness of the selected stations to the whole area may decline if the spatial distribution changed. The larger the number of the non-randomly selected stations, the lower the risk of reduced representativeness as spatial distribution changes over time.

The fixed 50/42 locations used during 1990-2001 had a limited spatial coverage (Figure 4-8). The 50 locations included only 3 in the Warraber Bridge and Warrior Back strata used in the 2002 Benchmark Lobster Survey, and 5 locations north of the Mabuiag stratum. The scaling down to 41 locations lost all these 8 locations. If the stock distribution shifts away from or varies within the limited area, the survey results would be biased.

The large scale population distribution can be represented by the mean densities of lobsters in each of the sample strata. If the relative densities between different strata changes from year to year, the distribution must have varied accordingly. The population surveys conducted during 1989-2005 showed that the spatial distribution of the lobster population had varied from year to year. For example, the highest density of age 1 lobsters was recorded in the South East stratum in 1991, but in 1990 the highest density was recorded in the Mabuiag stratum. Age 2 lobsters also had different distributions between 1990 and 1991 (Figure 4-9). For details of the mean catch rates of each stratum from 1989-2005, please refer to Appendix 1.
Figure 4-8. Distribution of sampled sites in some representative years, stratified random sample (271 locations in 1989), fixed site sample (50 locations in 1990, 42 locations in 1996), and stratified random sample (331 locations in 2002).
Figure 4-9. Comparison of Torres Strait lobster distribution between 1990 and 1991 based on the stratum mean (± SE) catch rates (lobsters/transect). Horizontal lines represent global mean (±SE) catch rates.

Variation in the spatial distribution of lobster may cause bias to the estimate of the population mean catch rate based on the fixed station survey, particularly when some strata were totally excluded. To reduce this potential bias, firstly the sample size of fixed stations in each stratum should be increased; secondly all strata should be included in the survey. Of course this assumes that there are sufficient funds available to sample each stratum throughout the fishery. For the reasons outlined above, we allocated additional sites in some strata in 2003, particularly those that had a very low number of sample sites, and we added some strata used in the 2002 Benchmark Lobster Survey such as Warraber bridge stratum (Figure 4-10). The additional sites were also selected from the 2002 Benchmark Lobster Survey that had a higher catch because adding randomly selected sites will not result in much improvement in the catch rate estimates as most of them will have no lobsters at all. In this way, the survey design remained unchanged. Without increased funding, one transect per location was surveyed instead of two transects per location as before.

After a trial in 2003, 88 sites over 6 strata were surveyed in 2004 and 2005. The mean catch rates estimated from the old 42 sites over 4 strata were compared with those from the 75 sites over 6 strata for 2002 and 2005 (Figure 4-11), excluding 8 sites that were not surveyed in 2002. The mean catch rates estimated from the old 42 sites show quite different patterns between 2002 and 2005 (Figure 4-11), but those estimates from the new 75 sites covering 6 strata exhibited similar patterns between the two years. This demonstrated strongly that the new design is more likely to represent the real distribution and the change in survey design made over the last two years was a step in the right direction.
Figure 4-10. Sites sampled in the mid-year survey from 2003-2005. Compared with the previous sample sites, the number of sites increased and spatial coverage improved.
Figure 4-11. Comparison of mean (± SE) catch rates in each stratum between 2002 and 2005 using the original repeated 42 sites. Horizontal lines represent global mean (±SE) catch rates. The relative catch rates of the four strata in 2005 were quite different from those in 2002.

Figure 4-12. Comparison of mean catch rates (lobsters/transect) in each stratum between 2002 and 2005 using the new 75 sites with vertical bars indicating one standard error. Horizontal lines represent global mean (±SE) catch rates. The relative catch rates of the six strata in 2005 were similar to those in 2002.
The revised survey sign had a better spatial coverage and consequently could reduce the bias caused if the spatial distribution of lobsters changed between years. However, there is a need to develop a relationship between the estimates from the new design and those from the old design to construct a standardised time series. The annual mean catch rates estimated from the 50 locations were generally higher than those estimated from the 75 sites (Figure 4-13). This is expected because the 50 locations selected for the fixed station surveys had the highest catch rates in the 1989 survey. The change from two transects per location to one transect per location did lead to slightly larger standard errors. This is theoretically justified and demonstrates the change in survey design was right. A statistical model can be developed and used to link the indices based on the revised surveys with those from the old surveys done before 2004.

**Figure 4-13.** Comparison of mean (± SE) catch rate estimates (lobsters/transect) between the old 50 locations and 75 sites.
4.4. PRE-SEASON POPULATION SURVEYS

The Protected Zone Joint Authority (PZJA) made a decision in August 2005 to adopt quota management for the Torres Strait lobster fishery in 2006. A quota management system requires setting a TAC for the fishery. Therefore, AFMA funded the first pre-season survey in November 2005. The main objective of the survey was to provide a forecast of the age 2 lobster population size at the beginning of the 2006 fishing season. It was planned that this population estimate would be used to estimate the TAC for the coming fishing season.

As discussed in the chapter, Development of methods for setting TACs, pre-season surveys are an effective way to estimate TACs. CSIRO provided technical advice on the design and scale of the pre-season survey as early as November 2003 at a Lobster Working Group meeting. That meeting recorded the following in its minutes:

**The working group determined that in principle it is possible to set an appropriate TAC in the Torres TRL fishery however the design and implementation of the current survey would need to be altered considerably. CSIRO researchers and the working group estimated that the costs of a redesigned survey would increase approximately 4 fold.**

Unfortunately, the funding available for the pre-season survey was not sufficient to conduct a survey that could provide an accurate and precise estimate of the absolute population size. As implementation of a TAC for 2006 was subsequently deemed impossible due to the time constraints, the TAC setting exercise was conducted as a trial, with quota management through a TAC deferred to 2007. Given the time constraints and available resources we formulated a pre-season survey design that would produce the best estimate of lobster abundance.

The full-scale stratified random population survey conducted in 1989 involved 542 transects and the Benchmark Lobster Survey conducted in 2002 involved 354 dive transects plus 21 additional towed video transects. The pre-season survey had enough resources to sample a maximum of 160 transects (based on 20 days of sampling and a maximum of 8 transects per day). It seemed clear that a stratified random sample design would not be the most effective way to estimate the pre-season population abundance. Considering the power of detecting changes, a fixed station survey was chosen, that is, the pre-season survey was designed as a monitoring survey. Monitoring surveys can provide relative abundance indices, but not absolute population estimates. However, if the population estimate was derived in one specific year, this year can then be used as a reference year to estimate population sizes of all other years by comparing the relative indices. This method is obviously prone to error if there is any bias in the population estimate for the reference year as this bias will pass on to all other years.

With a fixed station pre-season survey, there must be a reference year against which to estimate the total population. Unfortunately, no pre-season surveys had been carried out before 2005. Even the annual mid-year surveys had only two full scale surveys, 1989 and 2002, with which to compare against. The design of the 2002 Benchmark Lobster Survey was optimised using the available habitat and lobster distribution data, and the population estimate was presumed to be more accurate than the 1989 survey. Therefore, the pre-season survey was reference against the 2002 survey and adopted the 75 sites that were sampled mid-year in 2002, 2004 and 2005.

As discussed in the previous chapter, the reliability of the abundance indices estimated from fixed station surveys depends to a large extent on temporal consistency of the spatial distribution of the population. It is very questionable whether the lobster distribution in November/December is similar to that in May/June. Another issue that deserves serious attention is that the sample design of the 2002 Benchmark Lobster Survey did not include many sites in the eastern part of the Torres Strait fishery (Figure 4-8). By November, most age 2+ lobsters have migrated out of Torres Strait to breed and age 1+ lobsters may recruit to the vacated eastern area. A large number of lobsters are traditionally caught on the reef edges in the eastern part of the fishery, particularly along the Warrior reefs. The main objective of the pre-season survey was to estimate the abundance of age 1 lobsters, but very little is known about their distribution in this area. There was a need, therefore, to sample more sites in the
eastern part of the fishery to obtain information on lobster distribution in this area for current and future pre-season survey designs (Figure 4-10).

The pre-season survey catch rates are shown in Figure 4-14. There are some clear patterns evident in the distributions of 1+ and 2+ lobsters. Most age 2+ lobsters were recorded along the eastern part of the Torres Strait fishery in contrast to the distribution of age 0+ lobsters, which were most common along the western part of the fishery. Age 1 lobsters were distributed more evenly, but were most common in the south and east of the fishery.

For the purpose of estimating population size, the catch rates from the November 2005 pre-season survey were compared with those from the 2002 Benchmark Lobster Survey using the 75 repeated sites (Figure 4-15). Fewer age 2+ lobsters were recorded in November 2005 than in June 2002. However, the distribution of age 1+ lobsters was more consistent between the two surveys.

A further investigation of the comparative distributions of lobsters was made using the mean catch rates in each of the sampling strata. The patterns of relative abundance for both recruiting (1+) and fished (2+) lobsters were consistent between the two surveys (Figure 4-16) although the catch rate of age 2+ lobsters was very low. These results indicate that the spatial distribution of age 1+ lobsters is similar in June and November and that the 2002 survey could be used as a reference year to estimate the size of the 2005 recruiting population.

The distribution of age 1 lobsters was generally consistent between November and June. Therefore, the catch rates estimated from the sites that were sampled both in the November and June surveys could represent the relative abundances. Using the population size estimated by the Benchmark Lobster Survey in June 2002, the population in November 2005 could be calculated based on the relative catch rates. However, the following must be emphasized: (1) the above conclusion was based on one year’s data and needs to be tested further as more data become available; (2) Lobsters are migratory animals and are known to undertake small-scale movements within Torres Strait. It is not yet known if these movements occur continuously or at stages. Given that the above method of estimating pre-season lobster abundance is based on the assumption that the distribution of age 1 lobsters is consistent between June and November, some bias seems unavoidable. Although this method can still be useful if the bias is small or consistent over time, this is an expedient measure. (3) If possible, undertaking a benchmark pre-season survey, would be the most straightforward way to address the technical issues surrounding this method and to test the validity of this method. (4) It is not unusual to have large uncertainties in survey-estimated population sizes and it is often very costly to reduce these uncertainties to a given target level. Accounting for the uncertainty of the survey-estimates often proves more cost-effective.
Figure 4-14. Catch rates (lobsters/transect) of 0+, 1+ and 2+ lobsters at sites sampled during the 2005 November pre-season survey.
Figure 4-15. Comparison of the spatial distribution of survey catch rates (lobsters/transect) at the 75 sites repeated in June 2002 and November 2005.
4.5. SUMMARY

This chapter evaluated the quality of commercial catch statistics and annual (mid-year) and pre-season population survey data for the lobster fishery and analysed the weaknesses and strengths of the methods that have been used to collect these data. The new commercial catch data collection system implemented in 2003 has provided the most accurate landing statistics. The comparison of the annual catches of 8 selected vessels with the annual landings of the lobster fishery showed almost identical trends during 2001 to 2005 and similar trends during 1997 to 2000. This suggests that the catch data retrieved by AFMA for 2001 and 2002 are comprehensive and the estimates of annual catches from the shipping records are compatible with those from the new system.

The annual (mid-year) population surveys have been carried out since 1989 and the design and implementation of the surveys have undergone several modifications to accommodate financial constraints and logistical difficulties. The catch rates were successfully standardized to measured belt transect (500 × 4 m) counts for all years in this study. The resulting temporal trend in the relative abundance of age 2+ lobsters was similar to that of the CPUE of 8 selected vessels for the period over which logbook data were available. Although this comparison is not conclusive, it does suggest that the annual surveys provided indices that were representative of the actual abundance of the lobster population. Measured belt transects (500 × 4 m) are recommended for all future population surveys. Transects length should be controlled at 500 m using a Chainman® device and width should be controlled at 4 m using a measured rod.

The revision in survey design that has been achieved since 2003 includes (1) an extension of the survey to include more strata to increase spatial coverage; (2) an increase in the number of sample
sites within each stratum; and (3) a change from 2 transects per location to 1 transect per location. The analysis of this survey data demonstrated that the first two measures resulted in a better spatial coverage and consequently reduced the potential bias to the estimates of abundance caused by any temporal variation in lobster distribution. The third measure appears to have lead to slightly larger standard errors for the abundance estimates, but this was an inevitable impact to achieve the first two without increase in funding.

The pre-season population survey carried out in November 2005 adopted a fixed station sample design, which was not ideal but an expedient measure. The catch rate estimates from sites repeated during the pre-season survey and the 2002 Benchmark Lobster Survey were used as comparative relative abundance indices. The size of the 2005 pre-season lobster population was then calculated, using the population estimate from the Benchmark Lobster Survey. It should be noted that the ability of this survey design to produce reliable estimates of population size depends on the assumption that the spatial distribution of the lobster population was consistent between June and November. A simple comparison of the two surveys showed that the distribution of age 1+ lobsters was consistent during this period, but the distribution of age 2+ lobsters changed significantly.

Since a TAC can be feasibly set using the population size of age 1+ lobsters only, it could be concluded that the pre-season survey is suitable for this purpose. However, to provide a reliable recruiting (1+) population estimate there must be no significant change in the distribution of lobsters between the two surveys. There are also many issues that will demand further study in the future, particularly if a benchmark pre-season survey is not completed.
5. POPULATION DYNAMICS MODELLING

5.1. THE AGE-STRUCTURED FISHERY MODEL

The age-structured fishery model uses forward projection to estimate population numbers at age. This modeling approach is based on the principle that population numbers through time are determined by recruitment and total mortality at age through time. That is, if one knew the time series of inputs and outputs to the population and the initial population size at age, then one would have complete information on the population size, spawning biomass, and total mortality through time. In practice, one uses available sampling data and a statistical model of how the data were observed to estimate parameters to determine the time series of population sizes.

Population numbers at age through time are key variables in the age-structured model and the population numbers at age matrix $N=(N_{y,a})_{Y \times A}$ contains this information. This matrix has dimensions $Y$ by $A$, where $Y$ is the number of years in the assessment time horizon and $A$ is the number of age classes modelled.

Mid-year surveys of the Torres Strait rock lobster population have been conducted since 1989 (Ye et al., 2005). These surveys provide abundance indices for each age group, $I=(I_{y,a})_{Y \times A}$. If the survey catchability is $q$, which is constant over time and age, the population at age at the survey time $N(I_{y,a})_{Y \times A}$ is simply

$$N^I = I / q$$

The minimum size limit implemented in 1988 for the fishery prevents lobsters being fished until around September (about 14 months after settlement in the previous June). Given the natural mortality rate is $M$, which is assumed to be constant over time and age, recruitment can be back-calculated. However, as the survey indices contain errors, the error structure is assumed to be log-normal and recruitment is as follows

$$R_y = N^I_{y,1}e^{0.5M+VR_y}$$

where $R_y = N_{y,1}$ and the $VR_y$ are independent and identically distributed (iid) normal random variables with zero mean and constant variance.

Total mortality rates at age through time are also key variables in the population dynamics model. The total instantaneous mortality at age matrix $Z=(Z_{y,a})_{Y \times A}$ and the instantaneous fishing mortality at age matrix $F=(F_{y,a})_{Y \times A}$ both have dimensions $Y$ by $A$. Instantaneous natural mortality at age is assumed to be constant. Thus, for all years $y$, and age classes $a$, total mortality at age is the sum of fishing and natural mortality

$$Z_{y,a} = F_{y,a} + M$$

To determine total mortality, fishing mortalities need to be estimated. $M$ is often highly correlated with other parameters and is not estimable with only catch-at-age data (see for example, Schnute and Richards (1995)). For the lobster fishery, the absolute population size can only be estimated for the years in which an absolute stock survey was carried out and therefore, the natural mortality could be estimated. Estimation of fishing mortality at age is facilitated by making the simple assumption that fishing mortality can be modelled as a separate process. This assumption implies that $F_{y,a}$ is determined from the average selectivity pattern of age-a fish ($S_{a,p}$) in period $p$ and fully-recruited fishing mortality in year $y$ ($F_y$)

$$F_{y,a} = F_y S_{a,p}$$
The yearly component of fishing mortality is modelled as a lognormal deviation from average fishing mortality ($\overline{F}$),

$$F_y = \overline{F} e^{yF_y},$$  \hspace{1cm} (5)

where the $VF_y$ are iid normal random variables with zero mean and constant variance. The fishing mortality deviations ($VF_y$) are constrained to sum to zero over all years.

Fishery selectivity-at-age is usually modelled as being time-invariant throughout the assessment time horizon. This approach was chosen for parsimony and because there was believed to be substantial errors in the observed fishery age composition, especially in recent years.

The lobster fishery has only two age groups. Age 1 group is only fished in the last three months each year because of the minimum size regulation and the October-November hookah gear ban. Age 2 lobsters are larger than the minimum size limit and fished until they migrate out of Torres Strait to breed in September-October. Hence, it is assumed that age 2 lobsters are vulnerable to fishing for the first nine months. In 2002, the minimum size limit was increased from 100 mm tail length (TL) to 115 mm TL, the hookah ban was expanded to October-January and a ban on all commercial fishing in October-November was implemented. All of these new regulations were mainly designed to protect age 1 lobsters and to reduce the fishing pressure on the fishery. To capture the impacts of the regulations on age 1 lobsters, the selectivity was assumed to take a step-wise form. That is, $S_{1,1}$ for the first period of 1989-2001 and $S_{1,2}$ for the second period of 2002-2005. To reduce the number of parameters, selectivity of age 2 lobsters in both time periods were set to 1.

Population numbers at age through time are computed from the initial population numbers at age, recruitment through time, and total mortality at age through time. For each age class, indexed by “a”, the number at age is sequentially determined using a standard survival model for the age 1 group

$$N_{y+1,2} = N_{y,1} e^{-0.75M - 0.25Z_{y,1}},$$  \hspace{1cm} (6a)

and for age 2 lobsters

$$N_{y+1,3} = N_{y,2} e^{-0.75Z_{y,2} - 25M}$$  \hspace{1cm} (6b)

Fishery removals from the population are accounted for through the fishery catch numbers at age matrix $C=(C_{y,a})_{y,a}$. As the two age groups become fishable at different times, no generic formula can be found. Fishery catch at age in each year is computed in a standard manner from Baranov’s catch equation using population numbers, fishing mortality, and total mortality at age as follows for age 1 lobsters

$$C_{y,1} = N_{y,1} e^{-0.75M} \frac{F_{y,1}}{Z_{y,1}} (1 - e^{-0.25Z_{y,1}})$$  \hspace{1cm} (7a)

and for age 2 lobsters

$$C_{y,2} = N_{y,2} \frac{F_{y,2}}{Z_{y,2}} (1 - e^{-0.75Z_{y,2}})$$  \hspace{1cm} (7b)

Equations 1-6 describe the population dynamics of the lobster stock. This population dynamics model is consistent with that used by Ye et al. (2004), except that Ye et al. (2004) used an approximation to
the Baranov’s catch equation so that the age-structured model can be modelled using state-space methodology to incorporate process randomness in population dynamics (Millar and Meyer, 2000).

5.2. STATISTICAL ESTIMATION APPROACH

The population dynamics model is fitted to the observed catches-at-age and survey abundance indices-at-age using a maximum likelihood approach. The statistical model consists of 4 likelihood components \( L_i \). The model objective function \( \Lambda \) is the weighted sum of the likelihood components that reflects the relative importance of the data.

\[
\Lambda = \sum \lambda_i L_i
\]  

(8)

Each likelihood component is written as a negative log-likelihood so that the maximum likelihood estimates of model parameters are obtained by minimizing the objective function. The Automatic Differentiation Model Builder software is used to estimate a total of roughly 38 parameters. The likelihood components are described below.

5.2.1. Recruitment

From Equation 1, recruitment strength is modelled by lognormal deviations from survey estimates. A total of 17 recruitment deviation parameters \( VR_y \) are estimated based on the objective function minimization. The recruitment likelihood component \( L_1 \) is

\[
L_1 = 0.5Y \sum_y VR_y^2
\]  

(9)

where \( Y \) is the number of recruitment deviations.

5.2.2. Catch age composition

If an underlying multinomial distribution is assumed for catch at age as in Quinn and Deriso (1999) one appropriate goal is to minimize the goodness-of-fit objective function

\[
L_2 = 0.5YA \sum_y \sum_a (\ln(C_{y,a}^r) - \ln(C_{y,a}))^2
\]  

(10)

where \( C_{y,a}^r \) are observed catches at age in year \( y \), and \( A \) is the number of age groups.

5.2.3. Stock age composition

Stock age composition is assumed to be represented by the mid-year population survey. The estimated number of lobsters at age 1 from the population dynamics model is

\[
N_{y,1}^r = N_{y,1}e^{-0.5M}
\]  

(11a)

and for age 2

\[
N_{y+1,2}^r = N_{y,1}e^{-1.5M-0.25F_{y+1,1}-0.5F_{y,1}}
\]  

(11b)

Therefore, the proportion of lobsters at age at the time of the survey (June) in year \( y \) is calculated as follows

\[
P_{y,a} = \frac{N_{y,a}^r}{\sum_a N_{y,a}^r}
\]  

(12)

Similarly, the proportion at age observed from the survey is
\[ P'_{y,a} = \frac{I_{y,a}}{\sum_a I_{y,a}} \quad (13) \]

If the survey sample size for year \( y \) is \( N_s^y \), the observed number of fish at age in the fishery samples is computed as the survey sample size times the observed proportion at age for all variables. Under the assumption of multinomial distribution, the negative log-likelihood of the multinomial sampling model for the fishery ages (\( L_3 \)) is

\[ L_3 = \sum_y N_s^y \sum_a (P'_{y,a} \ln P'_{y,a} - P_{y,a} \ln P_{y,a})^2 \quad (14) \]

The second term in summation over the age index by “\( a \)” is a constant that scales \( L_3 \) to be zero if the observed and predicted proportions were identical.

### 5.2.4. Fishing mortality

Annual components of fishing mortality are modelled as lognormal deviations from average fishing mortality during the period 1989-2005. A total of 17 fishing mortality deviation parameters (\( VF_y \)) and one average fishing mortality parameter (\( F \)) are estimated based on the objective function minimization. The fishing mortality likelihood component (\( L_4 \)) is

\[ L_4 = 0.5Y \sum_y VF_y^2 \quad (15) \]

where \( VF \) is defined by Equation 5.

The weighting factors used for Equation 8 are: \( \lambda_1=100 \) for recruitment, \( \lambda_2=10 \) for catch age composition, \( \lambda_3=1 \) for survey abundance indices, and \( \lambda_4=10 \) for fishing mortality. The emphasis factors for each likelihood component reflect the reliability of the corresponding data, and the criteria for such choices are based on how each series of data was fitted, mainly by visual investigation.

Based on the model estimates of recruitment and the number of age 2 lobsters that survive until the end of December, a stock recruitment relationship could be established. Torres Strait rock lobsters emigrate in spring and breed during the subsequent summer (November-February) (Moore and MacFarlane, 1984; Moore and MacFarlane, 1986). Therefore, the number of age 2 lobsters at the middle of the breeding season should represent the size of the spawning stock. Ricker’s model was used in this study as follows

\[ R_{t+2} = \alpha S_t e^{-\beta S_t + \varepsilon_t} \quad (17) \]

where \( \varepsilon \) is iid normal variables with zero mean and constant variance.

### 5.3. RESULTS

Estimates of the model parameters are listed in Table 5-1. The standard deviations of the parameters suggest the estimates are relatively precise. The natural mortality rate was estimated at 0.732 year\(^{-1}\), the selectivity coefficient of age 1 lobsters was 0.468 for the 1989-2002 period and 0.368 for the years later than 2002. Recruitment was modelled as a lognormal deviation from the estimate that was back-calculated from the survey abundance indices, and the fully-recruited fishing mortality was modelled as a lognormal deviation from an average fishing mortality. These parameters were designed to better represent the error structure and to ensure the stability of the minimization process. Their meanings are not very straightforward and can be better understood after being transformed back to normal recruitment and fishing mortality estimates over years in the following sections.
The population dynamics model was fitted to the observed catches at age and the survey abundance indices for each age group using a weighted maximum likelihood approach. The model estimates of the catch at age were consistent with the observed catch data (Figure 5-1). However, there were opposite biases in the catch estimates between age 1 and age 2 lobsters; that is if the catch of age 1 lobsters was overestimated, for example in 2002 and 2003, the catch of age 2 lobsters was then more likely underestimated. This kind of trend is often seen when the model is fitted to a number of data sources.

The goodness of fit of the model parameters to the survey abundance indices is shown in Figure 5-2. The estimated population sizes of age 1 lobsters were very close to the observed data. However, the fit for the age 2 lobsters was less consistent, particularly over the last three years and in 2000-2001.
Figure 5-1. Comparison of catch at age (10^4 lobsters) between the observed and model estimated.
Figure 5-2. Comparison of population age composition (10^4 lobsters) between model and mid-year survey estimates.
The estimates of fishing mortality for age 2 lobsters ranged from 0.19 year\(^{-1}\) in 1989 to 0.65 year\(^{-1}\) in 2005 (Figure 5-3). There was an increasing, but variable trend in fishing mortality during 1989 to 1999, followed by a drop during 2000 to 2002 and a subsequent dramatic increase during 2003 to 2005. For age 1 lobsters there was an increasing trend in fishing mortality until 1999, with an inter-annual variation lower than that of age 2 lobsters. It is clear that the fishing mortality rate for age 1 lobsters did not increase as much as that of age 2 lobsters after 2002. This is because the new minimum size regulation, the commercial ban in October-November, and the hookah ban in December-January all reduced fishing pressure on age 1 lobsters, which was reflected in the estimate of the selectivity coefficient, 0.468 versus 0.368, a 21 % reduction.

The plot of the spawning stock and subsequent recruitment estimates derived from the population dynamics model was scattered (Figure 5-4). This poor relationship between stock and recruitment is common in fisheries. However, there was a general trend of large spawning stocks leading to large recruitment. This relationship seems fairly strong. For the purposes of further analysis, Ricker’s stock recruitment model was fitted to the data (Figure 5-5). The fitted line was adjusted by the \(e^{0.5\sigma^2}\) representing the average stock-recruitment curve (Hilborn and Waters, 1992; Quinn and Deriso, 1999). The fitted line is relatively consistent with the data and the parameter estimates had low standard errors (Table 5-2). The maximum recruitment is about 1100x10\(^4\) lobsters, resulting from a spawning stock of 330x10\(^4\) lobsters.

Table 5-2. Parameter estimates for Ricker’s stock recruitment model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>SE</th>
<th>t value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln((\alpha))</td>
<td>2.258</td>
<td>0.242</td>
<td>9.322</td>
</tr>
<tr>
<td>(\beta)</td>
<td>-0.003</td>
<td>0.001</td>
<td>-2.494</td>
</tr>
</tbody>
</table>

![Figure 5-3. Estimates of fishing mortality rates for both age groups (vertical bars indicate one-standard error)](image-url)
Figure 5-4. Plot of recruitment against spawning stock estimates ($10^4$ lobsters) output from the population dynamics model.

Figure 5-5. Fit of Ricker’s stock recruitment model to the model output data ($10^4$ lobsters).
5.4. DISCUSSION

Diagnostics of the model

The catch-at-age model described above was originally designed to estimate the survey catchability coefficient \( q \) in Equation 1 together with other parameters. However, the minimization process produced unreasonable estimates for model parameters. This is mainly because exploitation fraction and abundance are confounded (Quinn and Deriso, 1999). The time series of relative abundance indices derived from the fishery-independent surveys were then scaled to absolute population sizes using the 2002 Benchmark Lobster Survey data. In this way, the population size for each age group in each year was known and, therefore \( q \) no longer needs to be estimated (Quinn and Deriso, 1999).

However, the absolute population size in Australian waters was estimated at 8.7 million lobsters in 2002 with a 95% confidence interval of 6.68-9.66 million. A sensitivity analysis of the model outputs to the precision of the 2002 population estimate was carried out. The parameters that were most sensitive to the 2002 population estimate were \( M \) and \( F \). When the 2002 population size increased by 20%, the estimate of \( M \) increased by 2.32% and the average of the estimated \( Fs \) decreased by 8.66%. When the population size was lowered by 20%, \( M \) decreased by 6.66% and the average of \( Fs \) of age 2 lobsters increased by 24.8%. These results clearly demonstrated that the precision of the 2002 population estimate influences the model outputs, particularly when it was underestimated. Any future effort to estimate the absolute abundance of the Torres Strait lobster population with greater precision than the 2002 Benchmark Lobster Survey will allow greater certainty in the estimated model parameters.

The fishery-independent surveys were conducted only in Australian waters for most years. However, the lobster stock assessment covered Australian and PNG waters of Torres Strait. Hence, there is a need to scale up the estimate from the survey of Australian waters to the whole Torres Strait. Although the 2002 Benchmark Lobster Survey covered both countries, only 16 sites were sampled on the PNG side, compared with 359 sites on the Australian side (Ye et al., 2004). It is unlikely that the 2002 survey in PNG waters provided a reliable estimate of the PNG population. However, 64 sites were sampled in PNG waters in 2003 (Ye et al., 2005); a much better spatial coverage. Based on the 2003 survey data, it was estimated that the PNG waters accommodated about 10% of the total lobster population in the Torres Strait. Using this figure the total population size in 2002 was adjusted by adding 10% more to the absolute population estimate in Australian waters.

This study also estimated the natural mortality rate for the lobster stock. However, it is usually difficult, or impossible, to estimate natural mortality from catch data because the residual sum of squares surface is often flat over a wide range of natural mortality values (Quinn and Deriso, 1999). Schnute and Richards (1995) also found that natural mortality is difficult to estimate. However, in the present study, total population size was known each year from the mid-year population surveys. Hence, it is possible to estimate natural mortality from the population-at-age data because total mortality can be directly estimated from two consecutive population sizes of a single cohort, even without catch and effort data (Quinn and Deriso, 1999).

Age-structured analyses are usually applied to fish stocks of multiple age groups. The estimates of cohort size at different ages are more reliable for long-lived species than for short lived-species because the former simply means more data points can be used to estimate the number of recruits for each cohort. In contrast, the lobster stock has only two age groups and any bias in either age group can have a direct impact on the estimate of recruitment. The indices-at-age were derived from scientific surveys and usually of a high variance. To improve the reliability of model parameter estimates, other auxiliary data, such as commercial catch per unit effort data and information on fishing effort, should also be collected and incorporated into the model in the future.

Ye et al. (2004) estimated natural mortality for each year using a similar age-structured state-space model through a Bayesian approach. They built Ricker’s stock-recruitment model into the catch-age model, and recruitment was then estimated from its corresponding spawning stock. In this way
recruitment was not a parameter to be estimated each year as in this study, and the number of model parameters was greatly reduced. This is partially the reason why annual natural mortality rates could be estimated in Ye et al. (2004). In contrast, the present study estimated only a single natural mortality rate under the assumption natural mortality was constant over the study period and did not change with age. The reason the old model was not used in the present study was that the catch and survey data recorded in the last five years was erratic and did not fit to the model. For example, 2001 had a very low index for age 2 lobsters, but its resulting recruitment in 2003 was large (Figure 5-1). In contrast, the high survey index of age 2 lobsters in 2003 lead to a very low recruitment in 2005. Hence, by adding the last five years’ data, the age-structured state-space model failed to produce reasonable model estimates. The model developed in this study was not able to estimate a natural mortality for each year because the number of parameters was too large given the catch and survey indices at age without a stock recruitment relationship being built into the model. The natural mortality estimate of 0.73 year\(^{-1}\) falls well within the range of 0.49-0.77 year\(^{-1}\) estimated by Ye et al. (2004).

The model was fitted to data using a weighted maximum likelihood approach. The choice of the weighting factor \(\lambda\) in Equation 1 is one of the most critical aspects of catch-at-age analysis. From the theory of maximum penalised likelihood, it is not possible to estimate \(\lambda\); so it must be pre-specified before undertaking the analysis (Quinn and Deriso, 1999). In some case, there is a range of \(\lambda\) values that provide roughly the same estimates of population parameters (e.g. Deriso et al., 1985). However, in other cases, population estimates vary as a function of \(\lambda\), so that some method of determining \(\lambda\) must be sought. There are few methods available such as Kimura (1989), and much additional research effort is need in this area (Quinn and Deriso, 1999). In the present study, the choice of \(\lambda\) mainly relied on visual inspection of the model fit to the data and the existing information on parameters such as M and F. However, a sensitivity analysis showed that a 10 fold change of \(\lambda\) did not lead to much difference.

**Diagnostics of the model fit**

Residuals plots on a logarithmic scale are shown for abundance at age (Figure 5-6) and for catch at age (Figure 5-7). Overall there is no clear trend in the plots, suggesting the model adequately fits the data. However, the residuals of the catch estimates for both age groups do indicate trends, tending to go in opposite directions (Figure 5-7). From these residual plots, it seems clear that the model estimates for the last five years were not as good as those for the earlier years.

The logarithmic residuals of the Ricker model fitted to the spawning stock and recruitment estimates outputted from the catch-age analysis show no clear patterns (Figure 5-8), suggesting that the lognormal error distribution of recruitment is justified. However, the residuals increased significantly in the last few years.

The estimates of fishing mortality for the years earlier than 2001 are similar to those derived by Ye et al. (2004). Their estimates were 0.42 year\(^{-1}\), 0.55 year\(^{-1}\) and 0.41 year\(^{-1}\) in 1994, 1996 and 1999, respectively, in comparison with the current estimates of 0.45 year\(^{-1}\), 0.47 year\(^{-1}\), and 0.47 year\(^{-1}\). It should be emphasized that these small differences in the absolute fishing mortality estimates between two models do not impact the overall assessment of the stock.
Figure 5.6. Residuals of abundance-at-age estimates from the catch-age analysis of the rock lobster.

Figure 5.7. Residuals of catch-at-age estimates from the catch-age analysis of the rock lobster.
Figure 5-8. Logarithmic residuals of the Ricker stock recruitment model fit

Data issues

The current assessment of the Torres Strait lobster fishery used all catch and survey data available up to 2005. However, it must be noted that the 2005 catch data was not complete. The raw logbook and docket book records AFMA provided CSIRO showed that the 2005 data covered only the first six months. In order to include 2005 in the assessment, we assumed that the same amount of catch was landed in 2005 as in 2004 after consulting with AFMA. This should be taken into account when considering the model outputs because this assumption might have resulted in biased estimates for model parameters and population abundance. It would be ideal if all the necessary data were made available before stock assessment starts in the future.

The second issue is that the model requires information on catch at age. Unfortunately, over the five years, catch age composition data was not collected for the lobster fishery. Under the existing management regulations, the fishery mainly targets one cohort during a fishing season. The pulse variation in abundance within a season and the lack of fishing effort data make general production models unsuitable for this fishery. Catch-at-age models become the first choice. To run the model, the catch age composition in 2001-2002 was assumed to be the average of the 1989-2000 period. However, for 2003-2005, it is difficult to estimate the catch age composition because of the new size limit and the commercial and hookah bans introduced in 2002. According to individual growth information, lobsters became fishable on average in October. The additional closures further reduce the fishing pressure on age 1 lobsters. However, no such size limit and closures were implemented in PNG where about 25% of the total lobster catch was landed. As the present assessment covered the whole Torres Strait stock, we assumed, to our best knowledge together with some fishers’ views, that 15% of the lobsters caught were age 1.
5.5. PRODUCTIVITY OF THE LOBSTER STOCK

The primary aim of all fisheries around the world is to harvest fish. Consequently, the primary aim of fishery management is to ensure the fishery harvests as much/efficient as possible for an indefinite time period. If the amount of harvest from a population can last for an indefinite time, this amount must equal its surplus production, which is available for harvesting after replenishment of the population through recruitment and fish growth, and diminishment of the population through natural mortality. Under average conditions, surplus production can be harvested without changing the population’s size. This surplus production is also called equilibrium yield or sustainable yield. Obviously, equilibrium yield is a function of population size. When the population is small, equilibrium yield is low because the contribution of individual growth to the population productivity is limited by the small number of fish. However, when the population is very large, the equilibrium yield is also low because a population that is close to its carrying capacity has a high density-dependent effect that results in a high natural mortality. So, what is the population level that results in the largest equilibrium yield?

At equilibrium, the population reaches a balance between its replenishment through recruitment and fish growth and diminishment through natural and fishing mortality. So, estimating sustainable yield requires three kinds of parameters: growth, stock-recruitment and natural mortality. This study provided estimates of natural mortality and a stock recruitment relationship. Trendall et al. (1988) estimated growth parameters for the lobster population. In the following section, we outline the development of a fishery model that uses these parameters to estimate the sustainable yield of the lobster fishery under various fishing intensities.

If fishing activity of a fishery removes fish from a population by a rate of fishing mortality $F$, the equilibrium spawning stock under this fishing intensity can be expressed as a function of $F$ by combining Equation 6 with Equation 17, noting that $N_{y,1}=R_y$ and $N_{y,3}=S_y$,

$$S_e = (\ln \alpha - 2M - 0.25S_1 F - 0.75F) / \beta$$

(18)

where $S_1$ is the selectivity coefficient defined in Equation 4. A step-wise selectivity coefficient was used in Equation 4 to reflect the change in regulations. $S_1$ is used here because it describes the cases consistent with most years of the study period. Actually, both $S_1$ and $S_2$ can be used, and they just represent different management regimes. No large differences in $S_e$ would be expected by changing $S_1$ to $S_2$. Inserting Equation 18 into Equation 17 in turn gives recruitment at equilibrium under $F$,

$$R_e = \alpha' S_e e^{-\beta S_e}$$

(19)

where $\alpha' = \alpha e^{0.5 \sigma^2}$ for the curve to represent the average stock-recruitment relationship (Hilborn and Walters, 1992).

Yield is usually measured in weight rather than in number, and therefore, the catch equation (Equation 7) is not appropriate for yield calculation as it does not take into account individual growth. The lobster growth can be described by the following von Bertalanffy growth equation

$$L_m = 177(1 - e^{-0.386(m/12 - 0.411)})$$

(20)

where $L$ is carapace length in millimeters and $m$ is age in months (Trendall et al., 1988). Weight at age is then

$$W_m = 1.244 \times 10^{-3} TW_m^{2.955}$$

(21)

where $TW$ is tail width (mm) and

$$TW_m = (L_m - 1.089) / 1.433$$
where \( L_m \) is defined by Equation 20.

Catch biomass can then be approximated by the product of catch numbers-at-age and the monthly mean weight-at-age

\[
Y_c = \sum_{m=22}^{31} W_m R e^{-0.75M_{m-21}(FS_{1,m}+M)/12} \frac{FS_{1,m}}{FS_{1,m}+M} (1-e^{-(FS_{1,m}+M)/12})
\]  

(22)

where \( S_{1,m} \) is the selectivity coefficient \( S_{1,m}=0.47 \) for Month 22 to 24 and \( S_{1,m}=1 \) for Month 25 to 33, which are the selectivity coefficients for age 1 and age 2 groups estimated by the catch-age model. Equations 18-22 describe how equilibrium spawning stock, recruitment and yield change with fishing mortality rate (Figure 5-9). Sustainable yield has a parabolic relationship with fishing mortality, but is not symmetric as shown by the Graham-Schaefer surplus production model. This is not surprising. The current model considers explicitly the stock recruitment relationship and individual growth and is more tailed than the Graham-Schaefer production model (Schaefer, 1957).

The spawning stock at equilibrium decreases linearly with increasing fishing mortality (bottom left corner, Figure 5-9). This relationship can be easily justified by the analytical formula of Equation 18. Recruitment is more complex, decreasing monotonically, but not linearly with the increasing fishing mortality (right upper corner, Figure 5-9). This phenomenon is mainly caused by the stock recruitment relationship. The relationship between yield and spawning stock at equilibrium is a parabolic curve (bottom right corner, Figure 5-9), suggesting either high or low spawning stock has a low surplus production.

\( \text{Figure 5-9. Equilibrium spawning stock (10}^4 \text{ lobsters), recruitment (10}^4 \text{ lobsters), and yield (tons of total weight) under various fishing mortality levels.} \)

Figure 5-9 serves well to answer the question we asked before about what population level results in the maximum sustainable yield. From the relationship between yield and fishing mortality, we can
simply conclude that the maximum sustainable yield of the lobster fishery is about 640 tonnes total weight, which is equivalent to 268 tonnes tail weight. Ye et al. (2004) estimated the MSY of the lobster fishery to be 260 tonnes tail weight, very close to the current estimate. However, this should not be used to judge the reliability of the current model and its output.

The fishing mortality at which MSY is achieved was estimated to be about 0.5 year\(^{-1}\) (blue lines in Figure 5-9). This estimate is higher than Ye et al.’s (2004) estimate F\(_{\text{MSY}}\)=0.4 year\(^{-1}\). The corresponding spawning stock and recruitment required to produce MSY are also highlighted in Figure 5-9; 120x10\(^4\) spawning lobsters and 800x10\(^4\) recruits, respectively.

Fishery management is always about how much to harvest and how to harvest to maintain the long term sustainability of the fish population. Therefore, it is important to determine whether the lobster stock has been over-fished. Over-fishing is usually defined as the harvesting that results in MSY (S\(_{\text{MSY}}\)) being exceeded, or a population under the level that is chosen to achieve a certain target level of spawning stock/recruitment. Fishing mortality is a measure of fishing intensity, but alone is not appropriate to be used as an indicator to judge whether a fishery is or is not over-fished, particularly so for fisheries that target a short-lived species and a single cohort like the lobster fishery. This is because a fishing mortality rate larger than that required for the MSY would not drive the spawning stock below the S\(_{\text{MSY}}\) when recruitment is extremely large. For example, fishing mortality was estimated at 0.65 year\(^{-1}\) in 2005 (Figure 5-3), but the spawning stock by the end of the same year was 130x10\(^4\) lobsters, still greater than S\(_{\text{MSY}}\) (Figure 5-10).

Based on the criterion of spawning stock abundance, the fishery experienced over-fishing twice, i.e. producing a spawning stock lower than the S\(_{\text{MSY}}\), once in 1999 and the other in 2002 (Figure 5-10). In this sense, the lobster fishery has been sustainably fished through most of the study period. The present spawning stock status was estimated at 170x10\(^4\) and 130x10\(^4\) lobsters in 2004 and 2005 (Figure 5-10), respectively by the catch-age analysis. Therefore, it may be concluded that the lobster fishery is currently not over-fished.

Figure 5-10. Stock recruitment relationship (10\(^4\) lobsters) of the lobster fishery and the S\(_{\text{MSY}}\) and its spawning stock status in 2004 and 2005
Recruitment is highly variable in most fisheries, particularly so for those stocks that are short-lived like the Torres Strait rock lobster. A simple plot of recruitment against its corresponding spawning stock is often widely scattered. The fitted stock recruitment curve (Figure 5-10) represents the average recruitment under a certain level of spawning stock (Hilborn and Walters, 1992). However, a practical realization of recruitment given a spawning stock level can still vary widely. This is evident in the scattered distribution of the data points in Figure 5-10. More specifically, for example, the spawning stock was $150 \times 10^4$ lobsters in 2003 and produced $420 \times 10^4$ recruits in 2005, but a similar sized spawning stock in 1994 resulted in a recruitment of $1060 \times 10^4$ lobsters (Figure 5-10), 2.5 times the 2005 recruitment. This weak stock recruitment relationship is not unusual in fisheries and is the reason why a lognormal distribution of errors was assumed in Equation 17. Usually, a lognormal distribution will occasionally show very large recruitment; it has a long tail towards the upward end, and the amount of variation will be proportional to the average recruitment (Hilborn and Walters, 1992).

To understand the probability of a certain level of recruitment given a spawning stock, a full distribution of recruitment is needed. This probability distribution can be estimated through Monte Carlo simulations. First, $\alpha$ and $\beta$ were randomly drawn from the assumed distributions with the means, standard deviations and correlation coefficient estimated from the fitting of Ricker’s model to the data. Then, all the values of $\alpha$ and $\beta$ were inserted into Equation 19 to produce estimates of potential recruitment.

The distribution of recruitment estimates resulting from a spawning stock of $120 \times 10^4$ lobsters ($S_{MSY}$) is displayed in Figure 5-11. The distribution shows that there is only a 45% probability that the recruitment is larger than the level required for MSY, $R_{MSY}$ (indicated by the red line). Apparently, this probability is low, even in general sense. It should be noted that the target here is MSY. To obtain the MSY, recruitment must be at $R_{MSY}$, and in turn the fishery must have a spawning stock of $S_{MSY}$. There are many uncertainties in fish population dynamics, and the greatest uncertainty exists in the period from hatching to recruitment as survival rate in early life stages is highly influenced by environmental variables (Quinn and Deriso, 1999). After recruitment, natural mortality is still believed to vary with environmental conditions, but should be much less variable. In other words, the probability of obtaining MSY is much higher when the fishery achieves $R_{MSY}$ than $S_{MSY}$. Unfortunately, management cannot control recruitment directly, but only indirectly through managing spawning stock above a certain level. Hence, this is why we need to determine the probability of different recruitment sizes under a specific spawning stock.

Figure 5-11. Distribution of consequent recruitments ($10^4$ lobsters) when the spawning stock is at $S_{MSY}$. 
Figure 5-12. Distribution of consequent recruitments ($10^4$ lobsters) when the spawning stock is at $1.5S_{MSY}$.

To increase the probability of recruitment being larger than $R_{MSY}$ to 70%, the spawning stock must be $180\times10^4$ lobsters ($1.5$ times $S_{MSY}$; Figure 5-12). The target level of 70% is not a particularly high probability, but serves as a precautionary measure. The Torres Strait lobster fishery fished the spawning stock down beyond this level for many years; 10 out of the 17 years from 1989 to 2005. The data points also show clearly that a spawning stock larger than $180\times10^4$ lobsters consistently has a large recruitment (indicated by the green dashed line, Figure 5-10). Although a spawning stock between the two vertical lines (Figure 5-10) is larger than the $S_{MSY}$, the probability of a low recruitment is still high as shown by the data points.

In summary, the maximum sustainable yield of the Torres Strait lobster fishery (Australia + PNG) was estimated at 640 tonnes total weight. To achieve this MSY, the fishery has to allow $120\times10^4$ lobsters to escape to breed, on average, by the end of each fishing season. However, even with this level of escapement recruitment is highly variable in this fishery, and this spawning stock has only a 45% probability of producing a recruiting year-class larger than that required to achieve MSY. To increase the probability to 70%, the spawning stock has to increase by 1.5 times this level ($180\times10^4$ lobsters).

5.6. YIELD PER RECRUIT ANALYSIS

The classical yield-per-recruit objective is to exploit a given cohort in such a way that its full yield potential is realized (Beverton and Holt, 1957). In yield-per-recruit analysis particular attention is given to the effects of altering the two parameters that can be directly controlled – the amount of fishing, as measured by fishing mortality $F$, and the way fishing is distributed amongst different age-classes of fish, as measured by the age at first capture $t_c$. For a fish stock that consists of many age classes, calculation of yield from a given recruitment (yield-per-recruit) is not directly related to annual catches, but the long-term effects of different patterns of fishing. However, the catch of the lobster fishery is determined by a single cohort, and yield-per-recruit is directly associated with annual catch. This makes yield-per-recruit analysis more valuable for the lobster fishery.
Yield-per-recruit analysis requires only two parameter estimates, growth and natural mortality. Individual growth of the Torres Strait lobster was defined by Equation 21 and natural mortality was estimated to be 0.732 year$^{-1}$ from the catch-age model. For convenience, time $t$ in the growth equation used real time and $t_c$ was then expressed as the starting date of the fishing season. Under the assumption of knife-edge selectivity, the results of the yield-per-recruit analysis are shown in Figure 5-13. If lobsters become vulnerable to fishing when they are 2 years old ($t_c=25^{th}$ month), the maximum yield-per-recruit can be realized by controlling fishing mortality at 0.4 year$^{-1}$. However, by increasing the age at which lobsters become vulnerable to fishing the maximum yield-per-recruit is achieved with a higher fishing mortality. In the case of the Torres Strait lobster fishery, there is little advantage of altering the age at which lobsters become vulnerable to fishing (opening date) and fishing mortality beyond $t_c=25^{th}$ month and $F=0.4$ year$^{-1}$.

**Figure 5-13.** Yield-isopleth diagram for the Torres Strait lobster fishery. The figure shows lines of constant yield-per-recruit as a function of fishing mortality and seasonal opening date.

Under the current management regulations, free divers can start fishing on December 1 and hookah divers can start fishing on February 1. However for convenience, it was assumed here that the fishing season commences on January 1. The maximum yield-per-recruit occurs at $F=0.6$ year$^{-1}$, which is slightly higher than the estimate in Figure 5-9. This is expected because the yield-per-recruit analysis does not consider the positive influence of increased escapement and hence a larger spawning stock. This type of policy in terms of fishing mortality is known as an $F_{\text{max}}$ policy and has been widely used. However, in practice $F_{\text{max}}$ can frequently exceed sustainable harvest rates and is not considered as a conservative policy (Quinn and Deriso, 1999). A more precautionary reference point, called $F_{0.1}$, reduces the recommended $F$ to a level where the marginal increase in the yield-per-recruit curve becomes small (Figure 5-14, Gulland, 1983). For the lobster fishery, $F_{0.1}=0.28$ year$^{-1}$. 
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Figure 5-14. Yield-per-recruit as a function of fishing mortality $F$ under the assumption that the fishing season opens on January 1. $F_{0.1}$ is a more conservative harvest policy.

5.7. SUMMARY

A catch-age model was developed and fitted to the commercial catch statistics and fishery-independent survey abundance estimates from 1989-2005 using a maximum likelihood method. Based on the catch-age model estimates of recruitment and spawning stock, a stock-recruitment model was then established. Combining individual growth information with the stock recruitment relationship and natural mortality estimate, the maximum sustainable yield (MSY) of the Torres Strait lobster fishery (Australia + PNG) was estimated at 640 tonnes total weight with a fishing mortality $F=0.5$ year$^{-1}$. To achieve this MSY, the fishery has to allow $120\times10^4$ lobsters to escape to breed, on average, by the end of each fishing season. However, even with this level of escapement recruitment is highly variable in this fishery, and this spawning stock has only a 45% probability of producing a recruiting year-class larger than that required to achieve MSY. To increase the probability to 70%, the spawning stock has to increase by 1.5 times this level ($180\times10^4$ lobsters). The spawning stocks were $170\times10^4$ and $130\times10^4$ lobsters in 2004 and 2005, respectively. As the current spawning stocks are similar to the estimate of $S_{MSY}$, this fishery may be regarded as fully exploited at present.
6. DEVELOPMENT OF METHODS FOR SETTING TACS

6.1. INTRODUCTION

Setting a total allowable catch (TAC) is a measure to control the amount of fish removed from a fish population. The setting of TACs requires information about the current stock status, surplus yield at the current stock level, and goals of management. For example, if a fish stock has been over-fished, the TAC for this stock should be set lower than the surplus production at the current stock level so that the stock can recover. In contrast, if the stock is above the level estimated to provide maximum sustainable yield, a TAC could be set higher than the surplus production the current stock can produce. A practical process of setting a TAC for a fishery is much more complicated than this. Besides the sustainable productivity, many other factors also play a role in the setting of TACs, and should be taken into account; such as economic efficiency, impact on local communities and environment and response of the fishing industry etc. Therefore, the setting of a TAC involves two separate activities. Initially the estimation of a TAC is based on stock status and productivity, and secondly this TAC is adjusted to take into account social, economic, ecological and environmental consequences. Hence, whilst the estimation of TACs is a scientific process, in practice setting a TAC is also influenced by often complex political consultation amongst various stakeholders/interest groups. This study covers only the first part, i.e. the scientific estimation of TACs.

In estimating a TAC for a particular fishery, one of the first steps is to establish a production function. The usual fisheries population dynamics techniques can be utilized to establish the production function, using either production or age-based models. Production functions are used to determine the amount of catch taken from a particular fishery, whether it is a quota managed fishery or managed by other means such as input controls. However, setting a TAC requires a prediction for the potential production in the coming season, which is the key difference between TAC and input control fisheries and the most crucial for the success of TAC management. There are a variety of methods that can be used to estimate TACs. In this study three types of methods were investigated. Firstly, a full analytical method that used stock assessment outputs and production functions, secondly a method that was based on population estimate and production function, and thirdly methods were developed using a simple empirical model that requires only population survey data.

6.2. ESTIMATION MODELS FOR TACS

6.2.1. Spawning stock based model

If a stock-recruitment relationship has been established for a fishery, recruitment corresponding to a certain spawning stock size can be forecast. However, the oceanographic environment that influences larval advection varies greatly from year to year. As a result, the stock-recruitment relationship includes not only measurement errors, but also process errors. The combination of these errors leads to considerable uncertainty in the determination of a stock-recruitment relationship and the measurement of model parameters. Therefore, the stock-recruitment relationship is usually derived from variable data and appears weak in most fisheries. For realistic recruitment forecasts, these uncertainties must be incorporated into the forecasting process, and the probability of a resulting recruitment should be quantified, rather than simply inserting the stock size into a stock recruitment model for a single point estimate. This study used Monte Carlo simulation to quantify the probability of different recruitment levels given a certain spawning stock estimate of known confidence.

Once recruitment is estimated, subsequent catch can be estimated from the production function (Equations 6-7). This function requires three parameters, natural mortality, recruitment and fishing mortality. Natural mortality was known from the catch-age model, and recruitment was predicted from the stock-recruitment relationship. This leaves fishing mortality to be determined before the potential catch of the fishery in the coming season can be predicted. There are no comprehensive effort data available for the Torres Strait lobster fishery, and consequently no relationship has been established between fishing mortality and effort. Further, previous effort controls have only been applied to the
non-islander sector, and consequently it would be extremely difficult to forecast the amount of fishing effort likely in the coming season. For this reason in the present study it was assumed that the 2006 fishing mortality would equal the average fishing mortality rate over the study period from 1989 to 2005, 0.35 year\(^{-1}\).

Under the current size limit and closure regulations, age 1 lobsters comprise only a small proportion of the catch, and for convenience, it is assumed that the fishery catches only age 2 lobsters. Besides recruitment, the natural mortality estimate also involves uncertainty, and Monte Carlo random sampling was carried out to simulate the potential variation of natural mortality when the production function was used to predict catch.

6.2.2. Population-based model

The stock-recruitment relationships for most fish populations are usually variable with large errors in measurement. Therefore, in the case of the Torres Strait lobster population predicting the likely catch resulting from a spawning stock two years earlier involves large uncertainties. If the number of age 2 lobsters \(N_{y,2}\) at the beginning of each year can be estimated, the production function (Equation 7b) can directly be used to predict catch for that same year. Of course, this population-based (P-based) model also requires fishing mortality \(F_{y,2}\) to be specified.

The catch-age model provided population estimates of age 2 lobsters \(N_{y,2}\) and corresponding fishing mortality \(F_{y,2}\) for each year. These data can simply be used to test the functionality of this P-based method. However, the real intention of the method is to use the pre-season survey data to estimate \(N_{y,2}\) and then a TAC for the coming season if fishing intensity can be determined. The pre-season survey has been done only once in November 2005. To test the reliability of this model, the mid-season population estimates derived from the 1989-2005 annual surveys were used to estimate \(N_{y,2}\) through a simple approximation as described below. Subsequently, the survey-based estimates of \(N_{y,2}\) together with fishing mortality \(F_{y,2}\) derived from the catch-age model were used to forecast catch for each year. This method provided information on the reliability of using survey-based population estimates to forecast catch if fishing mortality is known.

The population estimates based on the annual population surveys conducted between 1989 and 2005 refer to the middle point of each year (May/June). The estimate of age 1 population can then be adjusted for natural death and catch taken before they reach age 2 to give an estimate of the age 2 population size at the beginning of each year \(N_{y,2}\). The following formula describes the estimation of age 2 population sizes \(N_{y,2}\) from the catch \(C_{y,1}\) and the survey-estimated population \(N'_{y,1}\) of age 1 lobsters in the middle of the year,

\[
N_{y+1,2} = N'_{y,1} e^{-0.5M} - C_{y,1} e^{-0.125M} \tag{23}
\]

Equation 23 was an approximation (Mertz and Myers, 1996) and does not use fishing mortality. Based on the survey estimate of the age 2 population and \(M\), annual catch can be predicted by the production function given fishing mortality for the coming season.

6.2.3. Empirical model

The above two methods use a production function of population dynamics to predict catch for the coming season where catch is a function of population size, natural and fishing mortality. Natural mortality varies greatly from year to year in the Torres Strait lobster population (Pitcher et al., 2002; Ye et al., 2004) because survival rates of short-lived species are highly influenced by environmental conditions. This natural variability together with its confounding with fishing mortality makes the estimation of natural mortality difficult, and thus \(M\) was treated as a constant and obtained from other information or approaches for many fisheries (Schnute and Richards, 1995; Quinn and Deriso, 1999). Although this study estimated a single natural mortality under the assumption that it does not change over time, this natural mortality estimate represents the average over the study period. When natural mortality is large and highly variable, its mean value could be quite different from the value in a
Specific year. As the estimation of TAC is focused on a single-year, the bias introduced by using a mean natural mortality may have significant consequence.

Even without the natural mortality issue, the production function still requires fishing mortality to be specified before a TAC can be estimated. This may not pose a serious problem to most fisheries. However, there are no reliable fishing effort data available for the Torres Strait lobster fishery and managers do not have full control of fishing effort in the fishery. Hence, it is difficult to forecast fishing mortality for the coming season, particularly when considerable latent effort exists and some fishing boats have the legal right to move between the Torres Strait and Queensland jurisdictions. These uncertainties that influence natural and fishing mortality provoke thought about the use of alternative empirical methods to estimate TAC that require less data and fewer parameters.

Forecasting is an established exercise in weather and climate studies and there are two different kinds of forecast in use. One uses physically derived dynamic climate models, and the other employs empirical (statistical) relationships based on historical data (Pezzulli et al., 2004). Recent comparisons suggest that empirical methods perform at least as well as dynamic coupled models (Barnston et al., 1999). Some studies even argue that empirical models perform better (e.g. Landsea and Knaff, 2000). The climate forecast situation is similar to the prediction of TAC in fisheries. The climate dynamics models, like the fish population dynamics models, are of great complexity and are able to describe causal mechanisms. However, the dynamics models need data to estimate the parameters and therefore, contain model structural and parametric errors. High data demands to develop and to run these models are another constraint. In contrast, empirical models do not focus on the details of causal mechanisms, instead concentrating on the forecast capability through statistical models. The simplicity of empirical models becomes an obvious advantage in terms of cost and when forecasting is a task that needs to be done within strict time constraints. This is the major reason for the exploration of empirical models in this study.

Empirical models rely on historical data to build statistical relationships between the dependent variable and predictors. The production function (Equation 7) shows that catch $C_{y,2}$ is a function of the population of age 2 lobsters $N_{y,2}$ and fishing mortality $F_{y,2}$ as natural mortality is assumed to be constant. If $F_{y,2}$ varies around a certain level within the study period, catch may then have a linear relationship with $N_{y,2}$, where the fishery removes catch proportionally. A simple plot of Torres Strait lobster catch against population size shows a linear relationship except one dot in the bottom right corner (Figure 6-1). This suggests that a simple model could be established. As forecast skill is the major concern here, three different empirical models were explored: linear, Beverton-Holt and hockey stick models.

![Figure 6-1. Scatter plot of catch of the Torres Strait lobster fishery against estimated population size for the years 1989 to 2005.](image)
a. Linear model

A linear model can be described explicitly in probability notation as follows

\[ C_{y,2} | N_{y,2} \sim N(\mu_{oy}, \sigma_o^2) \]  \hspace{1cm} (24)

with the mean given by

\[ \mu_{oy} = \beta_o + \beta_1 N_{y,2} \]  \hspace{1cm} (25)

that is, a linear function of the predictor \( N_{y,2} \). The standard statistical symbol \( | \) denotes “given” (conditional upon) and \( \sim \) denotes “is distributed as.”

When developing statistical models, an accurate estimate of forecast skill is useful in evaluating an empirical procedure’s ability to produce a useful prediction rule from a historical dataset. To avoid artificial skill, the empirical model can be evaluated using a cross validation “leave one out” model (Wilks, 1995; Elsner et al., 1994; Pezzulli et al., 2004). To produce a forecast for year \( y \), only data at other years different than \( y \) have been used to estimate model parameters and errors.

The 95% confidence interval for \( C_{y,2} \) given \( N_{y,2} \) is defined by

\[ \hat{\mu}_{oy} \pm 1.96 \hat{\sigma}_{oy} \]  \hspace{1cm} (26)

where \( \hat{\mu}_{oy} = \hat{\beta}_0 + \hat{\beta}_1 N_{y,2} \) is the catch predicted mean for a particular year and \( \hat{\sigma}_{oy} \) is the predicted standard deviation given by

\[ \hat{\sigma}_{oy} = \hat{\sigma}_o \left[ 1 + \frac{1}{n} + \frac{(N_{y,2} - \bar{N}_{y,2})^2}{nS_y^2} \right]^{1/2} \]  \hspace{1cm} (27)

where \( n=N-1 \) is the total number of years used in the cross validation,

\[ \bar{N}_{y,2} = \frac{1}{n} \sum_{i \neq y} N_{i,2} \]

is the long-term mean of \( N_{y,2} \),

\[ S_y^2 = \frac{1}{n} \sum_{i \neq y} (N_{i,2} - \bar{N}_{y,2})^2 \]

is the sample estimate of the population variance and

\[ \hat{\sigma}_o = [1/(n-2) \sum_{i \neq y} (C_{i,2} - \hat{\mu}_{oi})^2]^{1/2} \]

is the estimated empirical model standard deviation (Draper and Smith, 1998).

b. Beverton-Holt model

A model similar to the Beverton-Holt stock-recruitment model can also be used

\[ C_{y,2} | N_{y,2} \sim LN(\mu_{oy}, \sigma_o^2) \]  \hspace{1cm} (28)

where the mean is given by

\[ \mu_{oy} = \frac{\alpha N_{y,2}}{1 + \beta N_{y,2}} \]  \hspace{1cm} (29)
a non-linear function of the predictor. LN means lognormal distribution.

c. Hockey-stick model

If the 1992 data was not an outlier in the catch-population relationship, but represents actual variation of the lobster fishery production, it is possible that the catch might level off when abundance reaches a certain level, probably due to limited fishing capacity of the fishery. Therefore, a step function of a hockey stick model can be used

\[
C_{y,2} | N_{y,2} \sim N(\mu_{oy},\sigma_{o}^2)
\]

(30)

where the mean is defined by

\[
\mu_{oy} = \begin{cases} 
\beta_0 + \beta_1 N_{y,2} & N_{y,2} < \tau \\
\beta_2 & N_{y,2} \geq \tau 
\end{cases}
\]

(31)

Confidence interval can be calculated as for the linear model.

6.3. RESULTS

6.3.1. The SS-based model

By randomly sampling the estimates and standard deviations of the spawning stock (170x10^4 lobsters) at the end of 2004 and model parameters (\(\alpha\) and \(\beta\), Equation 19) with the estimated correlation coefficient, the stock recruitment model estimated the resulting probability distribution of recruitment in 2006 (Figure 6-2). The most likely value was 892x10^4 recruits and the 95% confidence interval ranged from 644x10^4 to 1440x10^4 recruits. The confidence interval is large, but is not unusual for fishery recruitment forecasts.

Using the recruitment forecast, the production function was then used to forecast the potential catch in the coming season. The mostly likely catch of age 2 lobsters in 2006 was 535 tonnes (total weight) with a 95% confidence interval of 296 to 1028 tonnes. It should be noted that the probability distribution is skewed towards the left.

6.3.2. Population-based model

Before proceeding to use the survey-estimated population to forecast the coming season’s catch, the Population-based (P-based) model was tested using the estimates of \(N_{y,2}\), \(F_{y,2}\) and \(M\) outputted from the catch-age model. The forecasts were very close to the observed catches (Figure 6-4). However, as all parameters used in the prediction were model-estimated from the catch-age analysis, it is not surprising that the predictions compared well with the observed catches. Further, both the catch statistics and survey population estimates were used to fit the catch-age model.

Annual catches were forecasted using the production function (Figure 6-5) based on the survey estimated \(N_{y,2}\), \(F_{y,2}\) and \(M\). The observed and predicted catches were comparable for all the years, except 2005, for which the prediction was far higher than the observed. This is likely because both the fishing mortality and the age 2 population size were overestimated in 2005. However, overall this shows that the survey data can be used to predict catches.
Figure 6-2. Forecasted recruitment in 2006 (10^4 recruits) versus probability based on the 2004 spawning stock size estimated by the catch-age model. Mode=892x10^4 recruits, Median=964x10^4 recruits, and Mean=1007x10^4 recruits.

Figure 6-3. Forecasted catches of age 2 lobsters in 2006 (tons of total weight) versus probability based on the recruitment forecast.
Figure 6-4. Comparison between the observed catches of the Torres Strait fishery and forecasts based on the catch-age model output and the production function (Equation 7) for 1989-2005.

The estimated age 2 lobster population at beginning of 2006, from the November 2005 pre-season survey data was $440 \times 10^4$ lobsters. Although fishing mortality in 2006 is not known, it was assumed here to be the average estimated during 1989 to 2005, $0.35 \text{ year}^{-1}$. When combined with the natural mortality estimate from the catch-age model, the 2006 catch was predicted at 515 tonnes (total weight), with a 95% confidence interval of 360 to 673 tonnes (Figure 6-6). The probability distribution appeared symmetric because the major uncertainty came from $N_{y,2}$ in Equation 7b as the M estimate had a low standard deviation.

Figure 6-5. Comparison between the observed catches of the Torres Strait fishery and forecasts based on survey data and the production function (Equation 7) for 1989-2005.
6.3.3. Empirical model

The three empirical models were fitted to the observed catches and the survey-estimated population sizes that were adjusted by catch and natural death (Equation 23). To discount the influence of outliers on regression results, robust regression was used in this study (Venables and Ripley, 2002). The fits of the three models to data were similar (Figure 6-7).

To select the best among the three models, both Akaike Information Criterion (AIC, Akaike, 1974) and Bayesian Information Criterion (BIC, Schwarz, 1978) were used based on Venables and Ripley (2002). The B-H model had the lowest AIC and BIC.

<table>
<thead>
<tr>
<th>Model</th>
<th>AIC</th>
<th>BIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>102.38</td>
<td>104.04</td>
</tr>
<tr>
<td>Hockey stick</td>
<td>101.10</td>
<td>103.60</td>
</tr>
<tr>
<td>Beverton-Holt</td>
<td>99.21</td>
<td>100.87</td>
</tr>
</tbody>
</table>

The forecasting skill of the three models was evaluated based on the cross validation prediction for the study period 1989-2005. The predictions from all of the models captured the variation of the observed catches well (Figure 6-8). The B-H model seemed slightly better than the others, providing catch forecasts for all years within the 95% prediction interval, except for the 1992 forecast which was on the edge of the confidence interval. However, the 95% confidence intervals were wide, which reflected the large uncertainty in forecasting catch for the coming season. The forecast prediction interval did not vary much from year to year, indicating stability of estimates such as $\sigma^2$.

The time series of standardized catch forecast errors is shown in Figure 6-9. If the catch forecast model is appropriate, the standardized forecast errors should be distributed as independent normally...
distributed random variables with zero mean and unit variance. This appears to be the case for all models from Figure 6-9. Although there is some indication of serial correlation suggesting the need for future model extensions, the standardized forecast errors appear to have a constant variance and be well centred on zero. However, the linear model has a large error outlier in 1992.

Both the forecasting skill and model selection information (AIC and BIC) suggest that the B-H model performed better than the other two. The major difference between the models occurred at the lower and upper ends of the predictor (Figure 6-10). Although the hockey stick model reaches an asymptote at the high end, it does not have the flexibility of the B-H model at the lower end. The more parameters used in the hockey stick model is also an advantage.
Figure 6-7. The fits of the three empirical models, Linear model (top), Hockey stick (middle) and Beverton-Holt (bottom).
Figure 6-8. Torres Strait lobster modeled catch forecasts. Linear (top), Hockey stick (middle) and Beverton-Holt (bottom). Observed values (circles), forecast (thick line) and the 95% confidence intervals (dashed lines).
Figure 6-9. Standardized Torres Strait lobster modelled catch forecast errors (Z). Linear (top), Hockey stick (middle) and Beverton-Holt (bottom).
Figure 6-10. Comparison of the three empirical catch forecast models, Linear (dotted line), hockey stick (red solid line), B-H (blue solid line), observed data (circles).

Given the pre-season lobster survey population estimate of 440x10^4 age 2 lobsters at the beginning of 2006, the empirical models forecasted the annual catch from 499 to 523 tonnes (total weight; Figure 6-11). The hockey stick model had the largest 95% confidence interval of 219 to 797 tonnes and the linear model had the narrowest confidence interval of 416 to 595 tonnes. The B-H model had the highest catch forecast of 523 tonnes with a mediate confidence interval of 392-656 tonnes (Figure 6-11). Overall the modal catch forecasts of the three empirical models were very similar.
Figure 6-11. Distribution of Torres Strait lobster catch forecasts for 2006 based on the empirical model.
The resulting forecasts are summarized in Table 6-2. The SS-based model forecasted the 2006 catch to be from 296 to 1028 tonnes (total weight) with a most likely (mode) value of 535 t. In contrast, the P-based model forecasted catch to be from 360 to 673 t with a modal value at 515 t. In comparison with the results of the SS-based model, the P-based models produced a similar modal value, but a much lower upper 95% value of 673 t versus 1027 t. The empirical models produced similar modal catch forecasts of 499 to 523 tonnes, but the hockey stick model had the largest confidence interval among the three empirical models. The B-H model catch forecast, including the modal value and confidence interval, was very close to that of the P-based model.

Table 6-2. Summary of the TACs estimates from the three models

<table>
<thead>
<tr>
<th>Model</th>
<th>Catch</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS-based</td>
<td>535</td>
<td>296</td>
<td>1028</td>
<td>F=0.35/year</td>
</tr>
<tr>
<td>P-based</td>
<td>515</td>
<td>360</td>
<td>673</td>
<td>F=0.35/year</td>
</tr>
<tr>
<td>Empirical (linear)</td>
<td>502</td>
<td>416</td>
<td>595</td>
<td>None</td>
</tr>
<tr>
<td>Empirical (hockey stick)</td>
<td>499</td>
<td>219</td>
<td>797</td>
<td>None</td>
</tr>
<tr>
<td>Empirical (B-H)</td>
<td>523</td>
<td>392</td>
<td>656</td>
<td>None</td>
</tr>
</tbody>
</table>

6.4. DISCUSSION

6.4.1. Estimation models

Monte Carlo simulation techniques were used to produce probabilistic forecasts of the coming season’s lobster catch to provide the information needed to make scientific conclusions about setting an appropriate TAC. The catch forecasts included the uncertainty both of the model parameters and of the input variables, estimated from the pre-season lobster survey or the catch-age model. Therefore, the forecasts provided probability information on the possible catches. This information helps explain the probabilistic nature of a fishery production system in that even with the same estimates of spawning stock or population size catches can vary even though fishing mortality was controlled at a specific level. Further, although modal forecasts were provided in this study, they should not be treated as point estimates.

The models developed in this study produced similar modal values for the 2006 catch (Table 6-2). However, the 95% prediction bounds are quite different. The SS-based model had the widest catch forecast interval of 296 to 1028 t, more than double that of the P-based and empirical models. This large interval for the SS-based model is logical and understandable because (1) the SS-based model relies on the stock recruitment relationship to forecast recruitment and then uses recruitment to forecast catch. Due to the extreme variability of marine ecosystems, the forecasting ability of the stock recruitment model is usually not high. (2) There is a two year delay when forecasting catch from a given spawning stock whereas there is only a few months delay when forecasting catch from the population size at the beginning of the same year. Survival rates are more variable during the early life history, leading to greater uncertainty in the catch forecast. The confidence interval of the catch forecast was widest for the SS-based model and therefore, this model is less preferable than the other models.

The P-based and empirical models produced very similar forecasts both in terms of modal catch and 95% prediction interval (Table 6-2). However, the P-based model requires information on fishing intensity and natural mortality. There is no comprehensive effort data available for the Torres Strait lobster fishery, and no effort control has been implemented over the whole fishery. Hence, it is not straightforward to forecast fishing mortality for the coming season because fishing effort may vary with abundance. For example, when the stock is low, fishers may fish less due to the low and unviable catch-rate, or those who are dual endorsed may move to the east coast of Queensland. It is also worth noting that fishing mortality may not be the same even if the numbers of fishing vessels and fishers involved in the fishery are unchanged because catchability is likely to vary with stock abundance.
In contrast to the SS-based and P-based models, the empirical models involve no assumptions about the fishing capacity of the fishery at all and are therefore, easy to apply. However, although the empirical models describe the past population-catch relationship well, this relationship may change after the introduction of a quota management system if the system works differently from the old input controlled system. This would be particularly true if the TAC set for the fishery deviated greatly from the historical population variation pattern. This suggests that future extensions may be required to the empirical model or the new data under the quota management system should be excluded in the estimation of TAC. Of course, the latter approach is less preferable.

Good quality forecasts are expected to have both small prediction errors (high precision) and reliable forecast uncertainty estimates. For the empirical models, a formal cross validation method was employed to evaluate their forecasting skill. In contrast, the P-based model is not a statistical model and so no formal method is available to evaluate the forecasting skill. However, the P-based model catch forecasts used survey-population estimates and can be treated as forecasts based on real data. Therefore, the difference between the observed catch and the forecasted catch should give information on its forecasting skill. Table 6-3 compares the mean and variance of standardized forecast errors for the P-based and empirical models. The results for the P-based model were derived when it used the survey-estimated population sizes (Figure 6-3) because it is believed that use of the survey results for future TAC estimation is more realistic. The mean standardized forecast error shows that the B-H model performed best, slightly positively biased, followed closely by the P-based model. Among the empirical models, the hockey-stick model is the most biased. Although the hockey-stick and linear models were biased in opposite directions, the variances of their forecast errors were very similar. In this analysis a variance larger than one indicates that the prediction uncertainty of the forecast was underestimated (Pezzulli et al., 2004). Therefore, it may be concluded that the B-H empirical and P-based models outperformed others in estimating the TAC for the lobster fishery although it should be noted that fishing mortality was assumed to be known for the P-based model in the forecast.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-based</td>
<td>0.092</td>
<td>1.000</td>
</tr>
<tr>
<td>Empirical – linear</td>
<td>-0.169</td>
<td>1.596</td>
</tr>
<tr>
<td>Empirical – hockey stick</td>
<td>0.335</td>
<td>1.354</td>
</tr>
<tr>
<td>Empirical – B-H</td>
<td>0.084</td>
<td>0.897</td>
</tr>
<tr>
<td>Perfect forecast</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

The P-based and empirical models represent two completely different approaches. The first is based on a production function, and the second relies on statistical relationships between measured parameters. Contrasting the results of one with the other may help detect any unpredictable outcomes of the catch forecasting methods in the future. Therefore, it is recommended that results of both the P-based and empirical catch forecast models should be used in future estimation of TAC.

When the SS-based and P-based models are used to estimate TACs, fishing mortality must be determined in advance. Fishing mortality is more likely to be estimated after catch and fishing effort are known. Determining fishing mortality for the coming season is not straightforward because even if the numbers of fishing vessels and fishers involved in the fishery are kept unchanged fishing mortality will vary unpredictably due to changes in catchability influenced by stock abundance. The simplest way to predict fishing mortality would be to assume that it will be at the same level as the last season or it will equal the average of the past few years as adopted in this study. However, this approach does not account for any new management goals and is not recommended for practical applications. It will be necessary to set TACs based on management objectives if they are to be used as a measure of controlling fishing mortality.
Given the importance of management goals, as discussed above any estimate of TAC should not only account for the prevailing biological conditions, but should also account for the specific management reference points such as MSY, F_{0.1}, S_{MSY} (Gulland, 1984). One of the objectives stated in the management plan of the Torres Strait lobster fishery is to ensure the stock remains above the level that produces a maximum sustainable yield. For operational reasons, this criterion should be translated to spawning stock level by the end of the fishing season. From the previous chapter, the spawning stock that will produce MSY is termed S_{MSY}. If S_{MSY} is the target reference point for management, the corresponding fishing mortality F can then be calculated as follows, given the population size of age 2 lobsters N_2 is known from pre-season surveys

\[ F = \frac{4}{3} \ln \frac{N_2}{S_{MSY}} - M \]

where M is natural mortality rate. S_{MSY} can be replaced by any other spawning stock targets that are more conservative or more suitable as previously discussed.

### 6.4.2. Risk and uncertainty in the estimation of TACs

It is important to bear in mind that there are three forms of risk closely associated with the setting of TACs:

1. TACs that are set too high risk causing stock collapse, to the detriment of both the fishing industry and fishing communities as well as the environment,
2. TACs that are set too low risk failing to generate the socio-economic benefits from fishing at the optimum sustainable yield,
3. Other environmental risks – for example negative interactions with non-target species can occur as an unintended side-effect of the way the fishery is carried out and the catch level that is set.

Item three has minor importance as the Torres Strait rock lobster fishery is a selective fishery and has very little interaction with other species.

Alongside these different kinds of risk, it is also crucial to recognize the uncertainties involved in the process of setting TACs:

1. Scientific uncertainties arise because ecosystems are complex and dynamic, and subject to long-term change as well as chaotic and chance events. These factors contribute to uncertainty in predicting stock recruitment, the response of fish stocks to changing fishing effort or TACs, or the interactions between fisheries and other aspects of the environment;
2. There are management uncertainties over, for example, how fishing activity will respond to different policy and regulatory mechanisms, as well as from uncertainties over the degree of compliance;
3. There is often uncertainty among the needs and values of different stakeholders, in terms of the overall objectives of fishery management and the effects of socio-economic pressures.

To address the above risks and uncertainties, a full and effective precautionary approach is needed. In principle, a precautionary approach to fishery management is any approach that reduces the likelihood of stock collapse or significant impact on the supporting environment. Selecting the appropriate mechanism and choosing the degree of precaution to be used is a matter for political judgement by decision-makers.

### 6.4.3. Timing of TAC advice

The advice fisheries scientists can provide on future fish catches, and hence TACs, is very much a function of how far ahead the advice has to be given (Pope, 1984). The shorter the time between the advice being given and being used the more precise and accurate it is likely to be. As the time delay extends, variability in the recruitment levels of new year-classes of fish, unknown catch levels in intermediate years and changes in the exploitation pattern all add sources of error to the prediction. The results of the SS-based model demonstrated this as forecasting catch from a given spawning stock includes considerable uncertainty due to inherent variability of the stock-recruitment relationship and...
of natural mortality in the early life history. Thus in principle managers need to think of ways of shortening the time between advice being given and being used (Pope, 1984). This could be achieved by setting provisional TACs and then adjusting the level, if necessary, nearer to the time of application in the light of fresh evidence. This problem of timing is a serious problem for fisheries scientists which managers should perhaps be more aware of (Pope, 1984).

### 6.4.4. Difficulty of setting TACs

Setting TACs requires a forecast of catch, and the accuracy of the forecast depends on the variability of the catch. Clearly with slow-growing, low-mortality stocks, the yield will come from fish from a number of ages and will thus tend to average out some of the variation in recruitment. On the other hand, fast-growing, high-mortality stocks will have yields that vary with recruitment. Thus yields will tend to vary least from year to year for low-mortality stocks and for stocks with low variation in recruitment. For such stocks of fish, simple approaches to estimating TACs may be adequate (Gulland, 1984). The main safeguards required will be checks that mortality or recruitment levels are not systematically changing. For stocks with a high variation in recruitment and with a small number of ages contributing to the catch, more elaborate methods will be required and predictions will only be reliable for short-time periods (Gulland, 1984; Pope, 1984). The prospects are not good for setting reasonable TACs on fish stocks with high mortalities and variable recruitments. Figure 6-12 shows a schematic representation of this problem. The simplicity, difficulty or impossibility of setting TACs which are precise and accurate is seen as a function of recruitment variability and of the number of ages of fish present in the fishery.

![Figure 6-12](image)

**Figure 6-12.** Schematic representation of the difficulty of setting TACs, based on recruitment variability and the number of year-classes in the fishery (after Pope, 1984)
The Torres Strait ornate rock lobster (*Panulirus ornatus*) population is comprised of only 3 age groups; recently-settled (0+), recruiting (1+) and fished (2+). About 90% of the commercial catch is comprised of 2+ lobsters due to the current minimum size and seasonal closure regulations. Recruitment is variable, by a factor of 6 as shown by the survey data (Figure 6-1). The combination of highly variable recruitment and single cohort fished puts the Torres Strait lobster fishery at the bottom left corner of Figure 6-12; indicating that it is impossible to set a precise and accurate TAC. It is crucial for scientists, managers and the industry to be aware of this challenge.

The accuracy and precision of the various methods employed in estimating a TAC are of obvious scientific concern, but there is no simple answer to this problem. It may be approached in several ways. The most convincing method would be to compare the forecasts with real results. This can only be done after the methods used over several years. However, people often like to have some sense about how well the methods can perform before being put into practical use. For this purpose, cross validation was carried out in this study to evaluate the forecasting skill of various empirical models. For analytical methods, historical data were also used to test their reliability. These methods provide a relatively accurate measure of a model’s ability to produce useful predictions. But, these predictions are only “hindcasts” of historical data. Future forecasting is obviously more difficult, particularly so when the observed predictor falls beyond the range of historical data.

This study developed methods for estimating TACs of the Torres Strait rock lobster fishery. The study was funded as a 6-month additional task to the 2 year CRC project Task 1.3. These methods should be regarded as preliminary and require great refinement and further development. Finally, estimating TACs is only part of the quota setting process. Managing fish stocks using TACs and quotas faces many challenges (Shepherd, 2003). To ensure the success of the quota management system, management procedures must be developed and implemented.

### 6.5. SUMMARY

Three models were developed and tested to estimate TACs of the Torres Strait lobster fishery. The first was a spawning stock–based model. This model forecasted catch from spawning stock using a stock-recruitment relationship and a recruit-catch production function. The second model was a population-based model, which estimated catch from the age 2+ population size based on a population-catch production function. The third models were based on empirical relationships and did not use production functions derived from population dynamics. Uncertainty in model parameters and input variables such as spawning stock and the population estimate of age 2+ lobsters were incorporated through Monte Carlo techniques. Therefore, these catch forecasts were probabilistic forecasts that allow estimation of the distribution of possible catches instead of point estimates as in deterministic analysis.

The forecast 2006 catch from the spawning stock-based model was 296 to 1028 tonnes (total weight) with a most likely (mode) value of 535 t. In contrast, the population-based model forecasted catch to be from 360 to 673 t with a modal value at 515 t. The empirical models produced similar modal catch forecasts of 499 to 523 tonnes.

The forecasting skills of the models were evaluated using cross-validation techniques for the empirical models and using standardized forecast errors for the other models. The population-based model and the Beverton-Holt empirical model outperformed the others in estimating the TAC. Therefore, it is recommended that these two models be used to estimate TACs for the lobster fishery.

The combination of highly variable recruitment and catch comprised of a single cohort makes the estimation of TAC for the lobster fishery extremely difficult. It is crucial for scientists, managers and the industry to be aware of this challenge. Although some methods have been developed in this study, they should be regarded as preliminary and require many refinements and further development. To ensure the success of the quota management system, management procedures must be developed and implemented.
7. HABITAT DISTRIBUTIONS AND LOBSTER ABUNDANCE

7.1. INTRODUCTION

Fishery-independent surveys of the Torres Strait ornate rock lobster (Panulirus ornatus) population have been conducted annually since 1989. The main aim of these surveys was to determine the relative abundance of recruiting (1+) and fished (2+) lobsters for subsequent stock status assessments. These surveys were funded by AFMA during 1989-2003, whilst the 2004 and 2005 annual surveys and the 2005 pre-season survey were funded through the Torres Strait CRC. Whilst the key objective of this research was to assess the sustainability of the lobster fishery, as outlined in Section 1.3, documenting the influence of seabed habitats on the lobster population was also identified as a key research priority. Seabed habitat data has been collected during all annual population surveys (1989-2005) and the pre-season survey (2005). The data comprised estimates of percent cover of the substrate categories including: mud, sand, rubble, consolidated rubble, pavement and live coral. In addition, the percent cover of seagrass and counts of pearlshell (Pinctada maxima) were recorded in each year. This data when compared with lobster distribution data allows an assessment of the influence of seabed habitat on the lobster population. This chapter presents the results of this investigation and highlights the potential of some future studies on the influence of habitat on lobsters.

The 1989 and 2002 mid-year surveys and the 2005 pre-season survey were the most extensive population surveys, involving the greatest numbers of sample sites and the widest geographic coverage. For this reason, we restricted our analysis of the influence of habitat on lobster distribution to these years. The 1989 Torres Strait lobster stock abundance survey involved visual census of 542 sample sites distributed throughout the ~25,000 km² area of the fishery (Pitcher et al., 1992b). Subsequently, the Benchmark Lobster Survey, involving 375 sites, was undertaken in 2002 to provide an updated estimate of stock abundance and to determine if the distribution of lobsters had changed since 1989 (Ye et al., 2004). The 2005 pre-season lobster survey, involving 154 sites, was undertaken to provide a current and precise estimate of recruiting (1+) lobster abundance, to allow calculation of a total allowable catch (TAC) for the 2006 season. It should be noted that the pre-season survey was conducted at a different time of year (November) than all previous surveys (May), and we have not accounted for any seasonal variation in seabed habitat that may exist.

The dynamics of tropical seagrass meadows has been shown to influence the abundance of many animals that rely on seagrass either directly or indirectly. Further, seagrass cover may be an appropriate proxy for primary productivity in Torres Strait, given its widespread distribution. For these reasons we also assessed the inter-annual changes in seagrass abundance and discussed the possible influence of seagrass on lobsters. For this analysis we used data from the abbreviated annual lobster population surveys conducted during 1990-2005.

7.1.1. Study area

The seabed habitat in the study area (Figure 7-1) is heterogeneous, ranging from bare mud and sand to complex coral reefs and seagrass meadows. The distribution of seabed habitats was determined during several historical research surveys conducted by CMAR, including the 1989 lobster stock abundance survey. The boundary of the study area has been defined to cover the geographic extent of the 1989, 2002 and November 2005 surveys (Figure 7-2).

The 1989 and 2002 mid-year surveys and the 2005 pre-season survey were the most extensive population surveys, involving the greatest numbers of sample sites and the widest geographic coverage (Figure 7-2). In addition to lobster counts, the habitat at each of the survey sites was recorded using standardized substrate and biota categories developed by CMAR.

Water depth throughout the study area rarely exceeds 20 m, except in the southeast.
Figure 7-1. Map of Torres Strait showing the lobster study area (white frame). The base image qualifies the bathymetry of the region with shallow (10 meter) seagrass beds typical in the north-west. The red line represents the Australia/Papua New Guinea Seabed jurisdiction line and the blue line represents the extended Fisheries jurisdiction line.
Figure 7-2. Map of study area showing distribution of the 1989, 2002 and CRC Torres Strait November 2005 survey sites.
7.2. METHODS

7.2.1. Standardised lobster abundance

Lobster abundance data collected during the 1989 and 2002 population surveys were combined and analysed with the lobster abundance data collected during the November 2005 pre-season population survey. The recruiting (Age 1+) and fished (Age 2+) lobster counts for each survey transect were standardised to individuals per 2000 m² transect and mapped as bubble plots. These standardised lobster abundance data were compared with and regressed against the recorded habitat and substrate data to allow assessment of the possible influence of habitat on lobster distribution and abundance.

7.2.2. Substrate mapping

Three separate maps of substrate type distribution were produced based on the combined CRC TS 2005 survey data and related historical (1989, 2002) survey data. To ensure the substrate type categories were comparable between the surveys, the percent substrate records from all surveys were merged into 3 classes. Namely:

- Soft sediment - combined sand and mud substrate types
- Rubble (loose/hard substrate) – combined rubble and boulder substrate types
- Rock (pavement) – combined consolidated rubble and pavement substrate types

Each merged substrate dataset was interpolated to provide a thematic surface layer to allow an assessment of substrate distribution. The interpolation used the ArcGIS Inverse Distance weighting formula with data from repeated survey sites averaged (Figure 7-4). This interpolation technique estimates cell values in a raster from a set of sample points that have been weighted so that the farther a sampled point is from the cell being evaluated, the less weight it has in the calculation of the cell's value. Hence, this method preserves the percent substrate type value at the sample site and decreases the percent value as distance from the survey site increases.

The resulting substrate distribution maps were then compared with the standardised 1+ and 2+ lobster catch rates and statistically modelled to investigate the correlation between substrate and lobster abundance. A loess smoothing function was used to show the relationship between lobster abundance and substrate cover in the plotted figures.

7.2.3. Epibenthic habitat mapping

Pearlshell counts, percent live coral and percent seagrass data from the 1989, 2002 and November 2005 surveys were mapped as bubble plots to allow assessment of the distribution of epibenthos. These distributions were compared visually with the standardised 1+ and 2+ lobster catch rates and statistically modelled to investigate the correlation between epibenthos and lobster abundance. A loess smoothing function was used to show the relationship between lobster abundance and epibenthos in the plotted figures.

7.2.4. Inter-annual seagrass change

A total of 41 survey sites have been repeated each year during the mid-year lobster population surveys between 1989 and 2005. The percent seagrass recorded at these 41 sites was mapped for each year to assess inter-annual change in seagrass distribution during 1989 – 2005 (Figure 7-13). The study area was divided into four quadrants (as indicated by the red dashed lines in Figure 7-13) to allow an analysis of the spatial trends in seagrass abundance. The locations of the quadrants were based on the likely interaction between seagrass and lobster abundance, based on expert knowledge. The north-west quadrant is known to support the largest seagrass meadows whereas the southeast quadrant supports very little seagrass. The average percent seagrass for each region was graphed (Figure 7-14) to allow temporal and spatial assessment of seagrass distribution. Note that data for years (1990-1993 and 1996/7) have not been prepared for this analysis.
7.3. RESULTS

7.3.1. Standardised lobster distribution

The distributions of recruiting Age 1+ and fished Age 2+ lobsters were mapped for the years 1989, 2002 and 2005 (Figure 7-3), highlighting the spatial distribution of lobsters during this period, and their relationships with reefs and land masses.

![Distribution of Age 1+ and Age 2+ lobsters](image)

**Figure 7-3.** Distribution of Age 1+ and Age 2+ lobsters standardized from the 1989, 2002 and November 2005 surveys.

None of the substrate or epibenthos types were significantly correlated with recruiting or fished lobster abundance (Table 7-1). However, soft sediment was weakly inversely correlated with lobster abundance while rock was weakly directly related with lobster abundance.

<table>
<thead>
<tr>
<th></th>
<th>AGE 1+</th>
<th>AGE 2+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft sediment</td>
<td>-0.3316</td>
<td>-0.2005</td>
</tr>
<tr>
<td>Rubble</td>
<td>0.0369</td>
<td>0.0217</td>
</tr>
<tr>
<td>Rock</td>
<td>0.3678</td>
<td>0.2301</td>
</tr>
<tr>
<td>LiveCoral</td>
<td>0.0599</td>
<td>0.0030</td>
</tr>
<tr>
<td>Pearls</td>
<td>0.0145</td>
<td>0.0592</td>
</tr>
<tr>
<td>Seagrass</td>
<td>0.0056</td>
<td>-0.0041</td>
</tr>
</tbody>
</table>
7.3.2. Substrate distribution

The overall distribution of substrates throughout the region shows a large central area (60x140 km) of predominately homogeneous soft sediment, surrounded by areas of harder substrates mainly associated with the eastern and western land bridges (Figure 7-4). The northwest and southeast regions are heterogeneous, with a mixture of substrate types at a much finer spatial scale.

Figure 7-4. Diagram of substrate types within the study area.

7.3.2.1. Correlation with Lobster counts

The correlations between the standardised Age 1+ and Age 2+ lobster abundance data and each of the averaged percent substrate types was calculated and plotted. As the overall correlation between lobster abundance and substrate types is relatively weak (Table 7-1) and given the high number of coincident values, a loess smoothing function (span: Age 1+ = 0.6; Age 2+ = 0.8) was added to the plots to depict the underlying trends in the data.

The plots for both Age 1+ (Figure 7-5) and Age 2+ lobsters (Figure 7-6) against soft sediment showed a decreasing trend in lobster abundance with increasing percent soft sediment. In contrast, lobster abundance was generally low for transects with low percent rock, likely due to the need for adequate shelter.

It should be noted that the relationships between lobster abundance and substrate are heavily influenced by the spatial scale of sampling. At each site divers recorded the number of lobsters observed and the total percent of each substrate type along a 500 x 4 m belt transect. Whilst this technique summarises the lobster substrate ratio at the transect scale, it does not capture any fine scale incidences that likely occur. For example, lobsters can be abundant in a small area of a transect dominated by soft sediment.
Figure 7-5. Plots of standardized lobster counts for Age 1+ against percent soft sediment, rubble and rock substrate types. The loess trend (red line) is shown.

Figure 7-6. Plots of standardized lobster counts for Age 2+ against percent soft sediment, rubble and rock substrate types. The loess trend (red line) is shown.
Figure 7-7. Overlay of standardized lobster counts for Age 1+ and Age 2+ on average rock substrate recorded during the 1989, 2002 and 2005 population surveys.

The overlay of Age 1+ and Age 2+ lobsters with the rock substrate highlights the general preference shown by lobsters for rock dominated substrates rather than those predominately composed of soft sediments (Figure 7-7). The overlay also shows clearly the predominance of lobsters along the eastern and western margins of the study area, coincident with the land bridges joining Australia and Papua New Guinea.
7.3.3. Epibenthic habitat distributions

The maps of pearl counts, percent live coral and percent seagrass observed during the 1989, 2002 and 2005 lobster stock surveys illustrated the distributions of these epibenthic habitats throughout the study area (Figure 7-8). Pearls, live coral and seagrass were absent or in very low abundance throughout the homogenous central region. Seagrass was abundant throughout the northwest region, which is also an important area for age 2+ lobsters. In contrast, live coral was more abundant along the eastern margin of the study area, likely due to less turbid waters there.

![Maps of pearl counts, percent live coral and percent seagrass.](image)

**Figure 7-8.** Maps of pearl counts, percent live coral and percent seagrass.

7.3.3.1. Correlation with Lobster counts

The relationships between the standardised Age 1+ and Age 2+ lobster counts against each of the epibenthic habitat distributions were plotted (Figure 7-9, Figure 7-10). The correlations between lobster abundance and epibenthic habitats were weak or non-existent (Table 7-1) with values ranging from 0.003 – 0.06 and the plots for pearls and percent live coral are governed by outliers. However, the percent seagrass plot was sufficiently scattered to warrant a loess smoothing function to depict any underlying trends in the data. The resulting smoothing did not indicate any correlation between seagrass cover and lobster abundance in the study area.
Figure 7-9. Plots of standardized lobster counts for Age 1+ against pearl counts, percent live coral and percent seagrass. Loess (trend) line in red.

Figure 7-10. Plots of standardized lobster counts for Age 2+ against pearl counts, percent live coral and percent seagrass. Loess (trend) line in red.
The low correlation between standardised lobster abundance and seagrass cover may have been due to the restriction of water depth, as seagrass cover was high in the shallow northwest, while lobsters were equally abundant in the shallow northwest and the deeper waters of the southeast.

Table 7-2 highlights the increased correlation between lobster abundance and seagrass cover using the 269 sites in the northwest region against the correlation for the entire region. The plots in Figure 7-11 show the relationship between lobster abundance and seagrass cover for the northwest zone for both Age 1+ and Age2+ lobsters.

**Table 7-2.** Correlation coefficients for standardized lobster counts for Age 1+ and Age 2+ against seagrass cover for the entire study area and subset to the northwest quadrant only.

<table>
<thead>
<tr>
<th></th>
<th>AGE 1+</th>
<th>AGE 2+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seagrass (study area)</td>
<td>0.0056</td>
<td>-0.0041</td>
</tr>
<tr>
<td>Seagrass (NW only)</td>
<td>0.0223</td>
<td>0.0248</td>
</tr>
</tbody>
</table>

**Figure 7-11.** Plots of standardized lobster counts for Age 1+ and Age 2+ against percent seagrass in the northwest zone. Loess (trend) line in red.

The plots of lobster abundance against percent seagrass for the northwest region suggest that the relationship between lobsters and seagrass in this region may be indicative of that exhibited throughout the entire region for areas shallow enough to support seagrass. Seagrass cover may be one of the significant factors influencing lobster spatial distribution.

### 7.3.4. Inter-annual seagrass change

The dynamics of tropical seagrass meadows has been shown to influence the abundance of many animals that rely on seagrass either directly or indirectly. Further, seagrass cover may be an appropriate proxy for primary productivity in Torres Strait, given its widespread distribution. For these reasons we also assessed the inter-annual changes in seagrass abundance and discussed the possible
influence of seagrass on lobsters. For this analysis we used data from the abbreviated annual lobster population surveys.

The abbreviated annual lobster population surveys consist of 41 sites repeated during 1989 – 2005 and attributed with percent seagrass values for each year. The following analysis of the repeat sites is based on those years with complete seagrass data entered into the database. The years (1990 – 1993 and 1996/7) have yet to be integrated into this database. Figure 7-12 shows the distribution of seagrass throughout the study area since 1989 and the four quadrants used in the analysis. The blue stars, predominately in the southeast quadrant, denote repeated sites that had no seagrass.

Figure 7-12. Distribution of seagrass over the period 1989 - 2005. The red dashed lines delineates the region into four quadrant Zones (NW, SW, NE, and SE) for spatial analysis.

Maps of seagrass distribution were produced for each year to illustrate the variation during the 1998-2005 period (Figure 7-13). The series of maps shows how seagrass, predominantly in the northwest quadrant, decreased during 1998-2001 and then returned. Seagrass ‘dieback’ events were recorded in 1992/93 and 1999/2000, likely as a result of increased turbidity and these events were considered a likely cause of the higher-than-average natural mortality of lobsters in those years (Ye et al., 2005).
Figure 7-13. Maps depicting the change in seagrass distribution over the period 1998-2004. The red dashed lines delineate the region into four quadrants (NW, SW, NE, and SE) for analysis.

The changes in seagrass distribution illustrated in the above map series (Figure 7-13) are highlighted in Figure 7-14 which shows the mean percent seagrass for each quadrant over the period studied. The percent cover of seagrass decreased during 1998-2001 in the northwest (Zone 1) with a similar trend in the southwest (Zone 2) quadrant. Together these two quadrants account for over 82% of the seagrass observations since 1989 with the remaining sites in the southeast quadrant (Zone 4). There are no repeat sites visited in the northeast quadrant (Zone 3).
7.4. DISCUSSION

This chapter provides a preliminary analysis of the influence of seabed habitat on the lobster population, which has been identified as a key research priority for the Torres Strait Tropical Rock Lobster fishery. The seabed habitat data collected during all annual population surveys (1989-2005) and the pre-season survey (2005) has been mapped and analysed along with the lobster abundance data. The habitat data is comprised of estimates of percent cover of standard substrate categories including: mud, sand, rubble, consolidated rubble, pavement and live coral. In addition, the percent cover of seagrass and counts of pearlshell (*Pinctada maxima*) were recorded in each year.

Due to the variable survey techniques employed over the period of the lobster population surveys the lobster data required standardizing to counts per 500 × 4 m transect and the substrate categories were combined into three comparable classes (substrate types – soft sediment, rubble and rock). We have also assessed the inter-annual changes in seagrass abundance and discussed the possible influence of seagrass distribution on lobster abundance. For this analysis we used data from the abbreviated annual lobster population surveys (41 repeated sites).

The 1989, 2002 and 2005 pre-season surveys were the most extensive population surveys, involving the greatest numbers of sample sites and the widest geographic coverage. For this reason, we restricted our analysis of the influence of habitat on lobster distribution to these years. Overall the results show either non-existent or low (0.003-0.367) correlations between both Age 1+ and Age 2+ lobsters and each of the seabed habitats. However, this low correlation may be unjustified for some habitat types. For example, the transect surveys recorded the number of lobsters observed and the total percent of substrate type along a 500 x 4 m transect. This technique basically summarizes the lobster substrate ratio at the transect scale and does not capture any fine scale incidences that may/likely occur. Such as, all lobsters observed in rock outcrops which may represent only a small portion of the transect area. This may justify the observation that, at the regional scale, lobster populations dominate the heterogeneous rocky areas in the study area.

The most significant region-wide correlations with lobster abundance are soft sediment and rock substrates. As expected there was a decreasing trend in lobster abundance with increasing percent soft sediment and an increasing trend in abundance with an increase in percent rock. These relationships are evident in the maps of substrate and lobster abundance. Lobsters are most abundant throughout the

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**Figure 7-14.** Average annual percent seagrass for each zone. Zone 1 (Northwest), Zone 2 (Southwest), Zone 3 (Northeast - no data), Zone 4 (Southeast).
Sustainability of the Torres Strait Rock Lobster Fishery

rocky heterogeneous regions in the west and east of the study area and are almost absent in the expansive soft sediment region within the central portion of the study area.

The distributions of pearlshell, live coral, and seagrass were investigated and found to be uncorrelated with lobster abundance at the region-wide scale. The maps of seagrass distribution clearly showed dominance in the northwest quadrant of the study area. By confining the correlation to lobster abundance to the northwest quadrant, there was a 5 fold increase in significance of the correlation between seagrass and both Age 1+ and Age 2+ lobster, suggesting that multiple and varying factors are influencing the lobster population at various scales. Future analyses should be conducted at the regional scale to identify those seabed habitats that are influencing lobsters.

The inter-annual change in seagrass abundance was investigated using data recorded since 1989. It was evident in both the annual map series and the plotted averaged seagrass cover over the study area, that a seagrass dieback occurred during 1999-2001, predominately in the northwest quadrant. Survey averages show that while the southeast zone suffered a 50 % drop between 1999 and 2001, the seagrass dominated northwest region suffered an 80 % decline between 1998 and 2001. Both quadrants had recovered by 2004. This dieback was coincident with the lowest lobster catch recorded in 2001.

The preliminary results here suggest that the dominant seagrass beds in the northwest quadrant of the fishery influence the population dynamics of lobsters. However, if seagrass abundance influences lobster population size and distribution, then what are the factors driving the lobster population dynamics in the southeast - an area with minimal seagrass cover, yet relatively high lobster density? The difference in seagrass cover across the Torres Strait study area highlights the heterogeneity of the seabed habitats likely to influence survival and growth of lobsters. Although there may be environmental factors that influence lobsters throughout the fishery such as temperature and primary productivity, there are likely to be several more regional factors that influence lobsters indirectly. Future studies should address the regional influences of seabed habitat on lobster abundance.
8. ENVIRONMENTAL CORRELATES

8.1. INTRODUCTION

The density and abundance of ornate rock lobsters *Panulirus ornatus* are known to fluctuate markedly between years. The fishery-independent population survey data collected since 1989 indicates that year-class density can vary by a factor of 4.6 for recruiting (1+) lobsters and by a factor of 11 for fished (2+) lobsters. The factors that likely influence and determine year-class density in Torres Strait include: the size and breeding success of the adult population, larval mortality, larval advection in the Coral Sea, and ontogenetic mortality.

There does not appear to be a consistent relationship between the strength of the 2+ population migrating out of Torres Strait (as a proxy for the breeding population) and the subsequent density of recruiting (1+) lobsters two years later (see Chapter 5). This is not to say that the number of 2+ lobsters migrating out of Torres Strait does not influence recruitment; however, it does indicate that other factors may be important in determining year-class density and abundance. In this chapter, we report on some preliminary investigations into the influences of some other possible environmental parameters on the density, growth and mortality of lobsters in Torres Strait. These include; water temperature and wind speed in Torres Strait, and the dynamics of the Coral Sea gyre.

8.2. WATER TEMPERATURE (TORRES STRAIT)

Sea water temperature has been historically recorded in Torres Strait in situ using water temperature data loggers and remotely using satellite sea surface temperature (SST) temperature probes. These data-sets were combined to produce a continuous sea water temperature record for Torres Strait (nominally for Thursday Island), for the period mid-1992 to the end of 2004.

8.2.1. Water data loggers

Water temperature was recorded using data loggers at the Ports Corporation of Queensland wharf in Thursday Island (approx location 10° 35.017S, 142° 13.6002E) by CSIRO (1992 – 1997) and AIMS (1998 – 2003) (Figure 8-1). The data was collected at 4-8 m below lowest astronomical tide level (LAT). AIMS also collected shallow water temperature data, generally at lowest astronomical tide (LAT). The temperatures recorded at this depth were consistent with the temperature data recorded deeper in the water column, indicating that the water column is well mixed in Torres Strait.

![Figure 8-1. Water temperature (degrees Celsius) recorded using data loggers at 4-8 m below LAT at the Ports Corporation of Queensland wharf in Thursday Island by CSIRO and AIMS during 1992-2004.](image-url)
8.2.2. Satellite SST

Satellite derived SST data was downloaded from the LAS server website (web address). The data is derived from satellite measurements made using the AVHRR series of instruments flying on the NOAA TIROS environmental satellite series. The data is scaled to 4 km grids and is calculated as 15 day moving median values, with a new value calculated every 6 days. Although there are shorter compositing periods (down to one day), cloud reduces the visibility of the ocean surface in individual scenes and the longer compositing period provides the better data coverage. However, the data is somewhat smoothed, reducing the sharpness of changes in temperature.

NOAA acknowledges that the overall error of the satellite SST data is about one degree Celsius. However, errors will vary according to the numbers of records composited at a particular point. This is because the compositing process tends to remove the effect of undetected cloud in a group of scenes by selecting the 65th percentile of the composited data at each spatial point.

We downloaded all the available data for Torres Strait from this website, which covered the period from late-1993 to 2005. There are some records earlier than this, but this data has yet to be loaded into the database.

SST data was downloaded for the entire Torres Strait and also for an area in the NW and SE to check for spatial variation in SST. The area delineated for the SST downloads was as follows (top left hand and bottom right corners):

- Torres Strait: 9.45° S, 142° E to 11° S, 143° E
- NW Torres Strait: 9.45° S, 142° E to 10° S, 142.5° E
- SE Torres Strait: 10.45° S, 142.5° E to 11° S, 143° E

The data was reformatted into a suitable format and imported into a Microsoft Access database. Land and cloud values were tagged and average temperature values were calculated for each 6 day sample period for each area.

Apart from some anomalous records (e.g. January 1997), the SST data appeared to be relatively precise (Figure 8-2). The SST data derived for the different areas of Torres Strait were similar, although the NW data was slightly higher than the SE data, usually by no more than a degree or so in any one year (Table 8-1), with an overall difference of 0.58° C over the 11 years of the data coverage (Table 8-1).

![Figure 8-2. Satellite derived SST (degrees Celsius) for Torres Strait and separately for NW and SE Torres Strait.](image-url)
8.2.3. Combined temperature data

Where there was overlap between the SST and in situ temperature data, the satellite derived SST data was about one degree lower than the AIMS logger data (Figure 8-3), which matched the estimated error for the satellite derived SST data as per the NOAA website. The satellite derived SST data was about 2 degrees lower than the CSIRO logger data, indicating that the calibration of the CSIRO data may have been inaccurate and produced biased temperature data (Figure 8-3).

![Figure 8-3. Water temperature (degrees Celsius) recorded in Torres Strait insitu using data loggers and remotely using satellites to derive SST.](image)

To standardize the different datasets, we carried out a regression of the SST data against the AIMS data and then regressed the adjusted SST data with the CSIRO logger data. This gave us a time series of calibrated water temperature for the Torres Strait (Figure 8-4).

The regression of AIMS data against satellite SST data is as follows:
Satellite SST=0.9582 AIMS – 0.0484
N=333, Adjusted squared multiple R: 0.831, Standard error of estimate: 0.776 (P<0.001)
We then adjusted the satellite SST data using this regression formula and regressed this data against the CSIRO data, for the period to the end of 1996 (due to high levels of anomalous data in 1997).

The regression of MOD_TS_SST to CSIRO data is as follows:
\[
\text{CSIRO} = 0.9780 \times \text{MOD_TS_SST} + 0.989
\]
N=183, Adjusted squared multiple R: 0.888, Standard error of estimate: 0.704 ($P<0.001$)

*Figure 8-4.* Standardised water temperature (degrees Celsius) recorded in Torres Strait using CSIRO data loggers (blue), satellite derived SST (red) and AIMS data loggers (green).

Water temperature in Torres Strait had a strong seasonal pattern varying from 30-32 degrees in summer to 24-25 degrees in winter. Summer water temperatures were quite variable, probably associated with variable winds and rain periods during the summer monsoon months (Figure 8-4, Wind section).

We then constructed average temperature indices that would be relevant in studying the influence of temperature on lobster growth and mortality. Initially temperature was averaged over the calendar year. We also averaged temperature over the winter to winter period (July to June) to correlate with the first year life of lobsters in Torres Strait (and subsequently with juvenile growth and mortality) (Figure 8-5). Water temperature averaged over calendar years varied from a low of 27.1°C in 1997 to a high of 28.3°C in 1996. Water temperature average over the July to June period varied from a low of 26.5°C in 1997 to a high of 28.3°C in 1992.

*Figure 8-5.* Average water temperature (degrees Celsius) recorded in Torres Strait over calendar years (January to December); and financial years (July to June next year) during 1992-2004.
The influence of water temperature on growth of lobsters in Torres Strait was investigated by comparing the average temperature for the July to June period with the average size of recruiting (1+) lobsters measured during the annual population surveys carried out in May/June (Figure 8-5), and the estimated growth of lobsters from 1+ to 2+ lobsters over that same period (Figure 8-7). In neither case did there appear to be a significant relationship between average temperature over the period and size (as a proxy for growth) of lobsters in Torres Strait.

$$y = -0.8969x + 64.671$$
$$R^2 = 0.0294$$

Figure 8-6. Graph of average water temperature for the period July to June the next year versus the size of the 1+ lobsters at the end of that period. The line represents linear regression of the data.

$$y = 0.0497x + 24.95$$
$$R^2 = 7E-05$$

Figure 8-7. Average water temperature (degrees Celsius) for the period July to June versus the average size of recruiting (1+) lobsters sampled during annual population surveys in Torres Strait at the end of that period. The line represents linear regression of the data.
We also compared the average temperature data to estimates of natural mortality rate calculated from the relative densities of 1+ and 2+ lobsters recorded during the annual population surveys (Figure 8-8). Again there did not appear to be a significant relationship between the two parameters.

**Figure 8-8.** Average water temperature (degrees Celsius) for the period July to June versus the estimated natural mortality rate of 1+ to 2+ lobsters recorded from annual population surveys during the same period.

### 8.3. WIND SPEED

Wind speed and direction data was obtained from the Bureau of Meteorology (BOM) for two sites in Torres Strait; Thursday Island and Horn Island. Generally the data consists of two measurements of wind speed and direction per day, at 0900 and 1500. The data was averaged for each day (Figure 8-9). There appears to be a slight change in the wind speed corresponding to the change of the station location from Thursday Island to Horn Island in 1993, with the earlier Thursday Island data generally being higher wind speed than the Horn Island data.

**Figure 8-9.** Daily average wind speed (km/h) for the period 1989 to 2004 for Thursday Island (1989 to 1993) and Horn Island (1994 to 2004).
The typical annual cycle of wind speed in Torres Strait is for variable, but generally lighter winds during the summer monsoon, often from the NW, and then moderate to strong SE winds during the winter (e.g. 2004, Figure 8-10).

![Figure 8-10. Daily average wind speed for 2004 showing the typical wind speed pattern in Torres Strait.](image)

To analyse both the direction and speed of the wind, we converted the average wind speed and direction to a vector value in the E-W plane using the sine of the wind direction. This converted the wind speed and direction into a net E-W plane actual wind vector, with a positive number representing a wind vector in a westerly direction (i.e. easterly winds) and a negative number a wind vector in an easterly direction. Values were averaged for each day.

Wind vectors reinforced the pattern of variable winds predominantly from the NW during the summer (monsoon) and strong SE winds during the winter months (Figure 8-11, Figure 8-12).

![Figure 8-11. Wind vectors in the E-W plane for the period 1989 to 2004 for Thursday Island (1989 to 1993) and Horn Island (1994 to 2004) with a positive number representing a westerly direction and a negative number representing an easterly direction.](image)
To investigate the relationship between lobster recruitment strength and wind vector strength, we averaged the wind vectors for the months April to August, given that this is probably the mean peak period for larval settlement into Torres Strait (Dennis et al., 1997) and therefore, the time when the cross-shelf wind factors have most influence on transport of peurulus larvae across the shallow shelf. There was some variation in the average vector strength during April to August between years, although recent years are quite consistent (Figure 8-13).

We then compared the average wind vector strength for each year to the settlement strength (recently-settled (0+) lobsters) in Torres Strait. Settlement strength in year X was calculated by dividing the density of the recruiting (1+) year-class in year X+1 by the density of the fished (2+) year-class in year X-1 (Figure 8-14). Neither relationship was significant indicating that the average wind vector strength did not influence recruitment.
Figure 8-14. Average wind vector strength recorded in Torres Strait for April to August for each year versus settlement strength for that period estimated from densities of the following year’s recruiting (1+) year-class and fished (2+) lobsters one year earlier.

We also compared the average wind vector strength for each year to the relative settlement strength (Figure 8-15). That is, the settlement index calculated as the following year’s 1+ year-class divided by the previous years 2+ year-class (as a proxy for the breeding biomass). This relationship was also not significant.

Figure 8-15. Average wind vector strength recorded in Torres Strait for April to August for each year versus relative lobster settlement strength.

8.4. LARVAL ADVECTION AND INFLUENCE OF THE CORAL SEA GYRE

An oceanographic model of the mesoscale circulation in the NW Coral Sea was developed to determine trajectories of larvae released by regional breeding populations of ornate rock lobsters *Panulirus ornatus* and assess the fate of these larvae (Pitcher et al., 2005). The project used a mixture of ocean modeling approaches in order to simulate the circulation of the Coral Sea (for details, see Pitcher et al., 2005 and Griffin et al., 2001).
The actual larval advection model is based on an individual based, forward-stepping transport model. As such, hatching, vertical swimming, mortality, growth, metamorphosis, and finally settlement of the puerulus are inputs into the model and based on the best information available. Probably the greatest unknown is the distribution of hatching around the gyre. For the purpose of the study, 7 arbitrary regions were identified as likely breeding and settlement areas used by the same ornate rock lobster *Panulirus ornatus* stock. The regions were: East PNG, Yule Island, Torres, York, Cook, Hinchinbrook and Southern GBR (Figure 8-16).

The model produced estimates of the relative larval settlement to each region bordering the Coral Sea gyre for each year (Figure 8-17), from the same hatching regions spread throughout the area surrounding the gyre. The model also produced estimates of the relative number, from an original 2000 theoretical larvae released, settling in each region during each month (Figure 8-18).

*Figure 8-16.* Modelled intensities (top) and locations (bottom) of *P. ornatus* egg production within the NW Coral Sea (from Pitcher et al., 2005).
Figure 8-17. Annual- and multi-year-average number of larvae settling in each region around the NW Coral Sea, with the contributions from the various spawning populations distinguished (from Pitcher et al., 2005).
Figure 8-18. Monthly-averaged rates of larval lobster settlement in each of the regions around the NW Coral Sea from the model simulation (from Pitcher et al., 2005).
We used the estimates settlement of larvae to Torres Strait from the model to compare with estimates of recruitment to the Torres Strait fishery, represented by the density of recruiting (1+) lobsters the following year (Figure 8-19, Figure 8-20). As the lobster settlement indices from the model included all larvae that crossed the 200 m isobath, we also included settlement to the Cape York region, and Cape York and Torres Strait combined, as larvae delivered to Cape York could theoretically be transported to Torres Strait by prevailing currents during that time of year.

![Graph: Model settlement index vs recruitment index for Torres Strait, Cape York, and combined areas.](image)

**Figure 8-19.** Indices of ornate rock lobster *Panulirus ornatus* settlement from larval trajectory modeling for the Torres Strait area (Torres raw), Cape York area (Cape raw) and for these areas combined versus recruitment as indicated by the density of the next years 1+ year-class.

\[ y = 0.1768x - 2.0512 \]
\[ R^2 = 0.615 \]

![Graph: Model settlement index vs recruitment index for Torres Strait area.](image)

**Figure 8-20.** Indices of lobster settlement from larval trajectory modeling for the Torres Strait area versus recruitment as indicated by the density of the next years 1+ year-class.

While there didn’t appear to be any relationship between settlement to Cape York or combined larval settlement from the model outputs to recruitment (Figure 8-19), the relationship between the modeled larval settlement and recruitment appears to be a good one (Figure 8-20). However, in some years, some of the modeled larval settlement occurs after August (e.g. year 2000, Figure 8-18). Previous research has indicated that the larval settlement period for *P. ornatus* in Torres Strait is most likely between April and August. When we restricted the settlement period to April to August, there was still a significant relationship but not as strong as the unrestricted relationship (Figure 8-21), however, the...
regression was more proportional, with the very low settlement estimate in 2000 reflected in a low estimate of recruitment.

![Graph with regression equation and R² value](image)

**Figure 8-21.** Indices of lobster settlement from larval trajectory modeling for the Torres Strait area (for the period April to August only) versus recruitment as indicated by the density of the next years 1+ year-class.

Interestingly, when we plot the model settlement indices against relative recruitment (being the density of the 1+ lobsters in the next year divided by the density of the 2+ lobsters the previous year, Figure 8-22), the relationship between settlement and recruitment breaks down, especially for 1995, where there was a relatively high recruitment from a very small 2+ population the previous year. This could indicate that there is a decoupling of the stock recruitment relationship between the Torres Strait 2+ population and subsequent recruitment in some years.

![Graph with regression equation and R² value](image)

**Figure 8-22.** Indices of lobster settlement from larval trajectory modeling for the Torres Strait area (for the period April to August only) versus estimates of relative recruitment as indicated from the density of the next years 1+ year-class divided by the density of the previous years 2+ year-class.
8.5. DISCUSSION

The abundance of the ornate rock lobster *Panulirus ornatus* population in Torres Strait is likely to be influenced by several factors, ranging from the strength of the breeding year-class to environmental parameters in Torres Strait. Therefore, it is not surprising that when assessing the influence of each factor in isolation it is difficult to find significant relationships.

However, there appears to be a significant relationship between the modelled larval settlement indices and the recruitment of larvae to Torres Strait, and this area of research warrants further studies. Some of the future research identified during the larval trajectory study was in the development of better mesoscale oceanographic models, and a better understanding of the mortality and biology of larvae and the source of recruits, including recruitment from east of the Corals Sea (Pitcher et al., 2005). However, this does highlight potentially a very important controlling mechanism for the strength of the fishery year-classes in Torres Strait. This is not surprising given the long larval duration of *P. ornatus* and the potential variability in mesoscale ocean currents. The impact of climate change is perhaps an important factor to take into account for the future recruitment to the Torres Strait lobster fishery.
9. ACHIEVEMENT OF OUTCOMES

Three surveys of the Torres Strait lobster population were completed during this project. The two annual (mid-year) surveys in April/May 2004 and 2005 provided relative abundance indices for stock assessment of the Torres Strait lobster fishery, and the pre-season survey in November 2005 provided a population estimate for setting a TAC for the fishery. These survey data together with the commercial catch statistics are the primary data for studies on population dynamics and the long-term sustainable productivity of the lobster fishery. The extension of the survey data series have improved the data quality and made possible the updated stock assessment of the lobster fishery.

A catch-age model was developed for the Torres Strait rock lobster fishery. The model was used to estimate natural and fishing mortality as well as spawning stock and recruitment. The maximum sustainable yield was estimated to be 640 tonnes total weight. To achieve the maximum sustainable yield, spawning stock should be kept beyond 120 x 10⁴ lobsters by the end of each fishing season. The estimated spawning stock in 2005 was similar to the level that would produce the recruitment associated with maximum sustainable yield. Therefore, the lobster fishery is considered to be fully exploited. These parameters have provided clear indicators about the current stock status, long-term productivity and the relationship between catch and fishing intensity. This information has helped set appropriate management objectives and keep the effort reduction of the industrial sector and a cap on the number of licences in the islander sector over the last two years for the long-term sustainability of the fishery and benefits of various stakeholders.

As a result of the decision by the PZJA to adopt a quota management system for the Torres Strait lobster fishery a number of methods were developed to estimate a TAC for the lobster fishery. The development of TAC estimation methods paved the way for the implementation of TAC management and will subsequently facilitate the execution of the 50-50 resource allocation between the industrial and islander sectors.

The results of this project have been presented at a number of key meetings including the Lobster Working Group meeting and the lobster Resource Assessment Group meeting and these results have influenced the industry, managers and stakeholders to adopt more effective and precautionary measures in managing the lobster fishery, for example, setting the target reference point of spawning stock and taking into account uncertainties in setting a TAC.

10. RECOMMENDATIONS

The annual (mid-year) population surveys provided relative abundance indices for both age groups of the lobster population. The survey abundance indices and commercial catch statistics are the primary data that enables stock assessment because there is no reliable fishing effort data available for this fishery. The pre-season survey conducted in November 2005 adopted a fixed station design as a compromise between the funds available and determining an accurate and precise estimate of the size of the lobster population before the season starts. It would be more suitable to determine the absolute population size in this case as the estimated TAC will be based mainly on the results of the pre-season survey. Unfortunately, the fixed station sampling was not able to estimate absolute abundance independently, and it was more appropriate to use the catch rate estimate from the fixed station survey as a relative index. Therefore, for an absolute population estimate, the relative index could be compared with another survey that can provide both the absolute population estimate and relative abundance. As there have been no pre-season surveys conducted before 2005, the 2002 Benchmark Lobster Survey served as the closest choice. However, the sufficiency of this expedient approach relies on (1) the consistency of the spatial distribution of lobster population between the two surveys and (2) the accuracy of the 2002 population estimate. Although the consistency seems retained between May 2002 and November 2005, the accuracy of the 2002 estimate was never easy to prove. If the 2002 estimate was biased, this bias will be passed on to any population estimate derived from relative indices and a reference year’s population estimate. Therefore, it is recommended that the absolute population estimate from the pre-season survey be used with caution and that annual (mid-year) and pre-season surveys should be done in parallel for at least 3-4 years so that the distributional
consistency can be further monitored and a more reliable relationship between estimates from the annual (mid-year) and pre-season surveys could be established.

The stock assessment based on the catch-age model established a stock recruitment relationship and estimated the maximum sustainable yield of the Torres Strait lobster fishery. To achieve the maximum sustainable yield, fishing must be controlled at a certain level. The control of fishing is often directly measured by fishing mortality F and the fishing mortality corresponding to MSY is termed F$_{MSY}$. It must be emphasized that F$_{MSY}$ is a concept at equilibrium. The typical characteristics of the Torres Strait lobster population dynamics make F$_{MSY}$ an inappropriate target for management. Escapement and subsequent spawning stock left at the end of each fishing season is a better target. However, recruitment to the lobster fishery is highly variable, and Monte Carlo simulations show that controlling the spawning stock at the level (S$_{MSY}$) that is associated with the MSY has only a 45% probability of producing a recruiting year-class larger than that required to achieve the MSY. To increase the probability to 70%, the spawning stock has to increase by 1.5 times S$_{MSY}$. It is recommended that S should be larger than S$_{MSY}$ for precautionary reasons.

The estimation of TACs is obviously a crucial aspect of TAC management. This project developed a number of models for estimating TAC of the lobster fishery. Based on the evaluation of forecasting skill, the population-based and the Beverton-Holt empirical models are preferable and should be used in future although all the developed models are preliminary and should be tested further. The combination of highly variable recruitment and single cohort fished makes the estimation of TAC for the lobster fishery extremely difficult. It is crucial for scientists, managers and the industry to be aware of this challenge. To ensure the success of the quota management system, management procedures must be developed and implemented.

11. REFERENCES


12. ABBREVIATIONS & GLOSSARY

AFMA  Australian Fisheries Management Authority
CMAR  CSIRO Marine and Atmospheric Research
PZJA  Protected Zone Joint Authority
PNG NFA Papua New Guinea National Fisheries Authority
TRL  Tropical Rock Lobster

13. APPENDIX 1: INTELLECTUAL PROPERTY

Data collected during the annual and pre-season population surveys, including lobster counts, lobster size-frequency, seabed abiotic and biotic components and environmental variables are currently stored at the CSIRO Marine Laboratories, Cleveland as CMAR is the current custodian of AFMA funded research data. This would also apply to data collected during the PNG stock survey 2004. This data would be made available to other research agencies through written approval from AFMA and/or PNG NFA.

14. APPENDIX 2: STAFF

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![Graphs showing density of lobsters in different strata from 1989 to 2005.](image-url)
Sustainability of the Torres Strait Rock Lobster Fishery

1993 Age 1

1993 Age 2

1994 Age 1

1994 Age 2

1995 Age 1

1995 Age 2

1996 Age 1

1996 Age 2