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Modelling and risk analysis of the western rock lobster (*Panulirus cygnus*) fishery of Western Australia

C. S. Yap
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**Modelling and Risk Analysis
of the
western rock lobster
(*Panulirus cygnus*) fishery
of Western Australia**

**C.S. Yap
Master of Applied Science
(Mathematics and Planning)**

1995

ABSTRACT

The predictive power for short-term forecasting of selected biomass dynamic models was examined using the standardised catch and effort data from the 1944/45 to 1990/91 season of the western rock lobster. Risk analysis of the fishery based on the predicted fishing efforts with the Deriso-Schnute delay-difference model indicates a high probability of recruitment failure. Some hypothetical management strategies of reducing fishing effort were evaluated by taking into consideration the total catch and biological risk to the fishery.

DECLARATION

"I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree of diploma in any institution of higher education; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text."

Signature

Date 12.2.96

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND TO THE RESEARCH

The western rock lobster, Australia's most valuable single-species fishery, was worth around A\$200 million to the fishermen for the 1989/90 season. The annual series of catch and effort data from the Fisheries Department of Western Australia in Figure 2.1 shows that while the total catch has remained at around 10.5 million kg for the last ten years, the fishing effort shows an increasing trend. The catch per unit effort averaged around 1.645 kg per pot for the 1950 season whereas it averaged 0.68 kg per pot for the 1986/87-1990/91 seasons. This downward trend in the catch per unit effort data indicates the possibility of endangering the fishable stock of the western rock lobster.

1.2 OBJECTIVES OF THIS RESEARCH

This research analyses the risk aspect of the stock if the current trend in fishing effort is maintained. As a result of the analysis, an investigation using some hypothetical strategies of reducing the fishing effort to achieve a target catch rate without inflicting serious biological damage to the stock was carried out. This research also involves selecting the most

appropriate model using only the catch and effort data for short-term prediction of catches for the western rock lobster fishery.

1.3 DEFINITIONS OF TERMS

Some commonly mentioned terms in this thesis are the following:

"Berried" females - those female rock lobsters carrying the fertilised eggs.

Biomass - the total mass of the rock lobsters (measured in kilograms).

B_t - biomass of the fishable rock lobsters at time t .

Catch - the annual landed rock lobsters caught by both the professional and amateur fishermen (measured in kilograms).

Fishing Effort - the total number of pots lifted by the fishermen for each season.

Effective fishing effort - the standardised fishing effort.

Juvenile rock lobsters - rock lobsters whose carapace length is less than the minimum legal size of 76 mm.

k - the age at recruitment to the fishable stock.

$N_{a,t}$ - represents the number of rock lobsters age a (greater than or equal to k) at year t .

N_t - total number of rock lobsters age k and greater at time t .

Phyllosoma larvae - the larval stage of rock lobsters.

Puerulus larvae - last larval stage.

Recruitment - those rock lobsters attaining the legal size of 76mm carapace length thus entering the exploitable population.

"Red" lobsters - those rock lobsters (caught at the beginning of January until the end of the season) which are in a more sedentary phase of their life history and because of their deep red colour are more valuable on overseas markets.

Risk - the percentage of time the biomass of the spawning stock falls below 20% of the virgin biomass.

Spawning Stock - (breeding stock) assumed equal to the biomass of lobsters at the beginning of the fishing season less the biomass of new recruits.

Surplus production - represents the sum of the biomass of new recruits together with the growth of existing members after accounting for death due to natural mortality.

"White" lobsters - those rock lobsters which have just moulted and are very pale in colour. They undertake extensive migrations from inshore to offshore waters.

W_k - weight of rock lobster at recruitment.

Working day - obtained by dividing total pot lifts by pot quota held by all fishermen.

1.4 BRIEF OUTLINE OF THIS THESIS

Chapter two gives a brief discussion on the development of the western rock lobster fishery from an under exploited fishery to its present stage where there is concern that the reduction of its breeding stock might jeopardise the fishery.

The proposed models to be used for the risk analysis of the western rock lobster are presented in chapter three. The formulation of the widely used biomass dynamic model by Schaefer (1954, 1957) and its variations by Pella and Tomlinson (1969) and that of Marchessault and Salla (1976) are also presented. Derivation of the Deriso-Schnute delay-difference models is also presented along with the required process models for growth, survival, and recruitment.

Chapter four gives a brief description of the life history of the western rock lobster. For the risk analysis of the fishery, it is essential that the

proposed model possesses good forecasting ability. The suitability of the proposed biomass dynamic models are evaluated using the standardised catch and fishing effort data from the 1944/45 to 1990/91 season. The evaluation suggests that the Deriso-Schnute delay-difference model is more appropriate than the other models considered.

In many fisheries around the world, recruitment failure occurs when the spawning biomass falls below 20% of the virgin biomass (Peterson and Smith 1982; Francis 1991). Hence, in this thesis, risk to the western rock lobster fishery is taken to be the percentage of time the biomass of the spawning stock falls below 20% of the virgin biomass in the 1991/92 to 1995/96 seasons. The risk associated with the management of the western rock lobster fishery is examined using the Deriso-Schnute delay-difference models in chapter five. Results of the analysis indicate that there is a 73% chance that the spawning stock will fall below the critical level. Hence, some hypothetical management strategies of effort reduction are proposed and then evaluated. The analysis based on the catch and effort data from the 1994/45 to 1990/91 season indicates that recruitment failure is more likely to happen in the 1991/92 and 1992/93 season if there is no plan to reduce the fishing effort.

CHAPTER 2

THE WESTERN ROCK LOBSTER

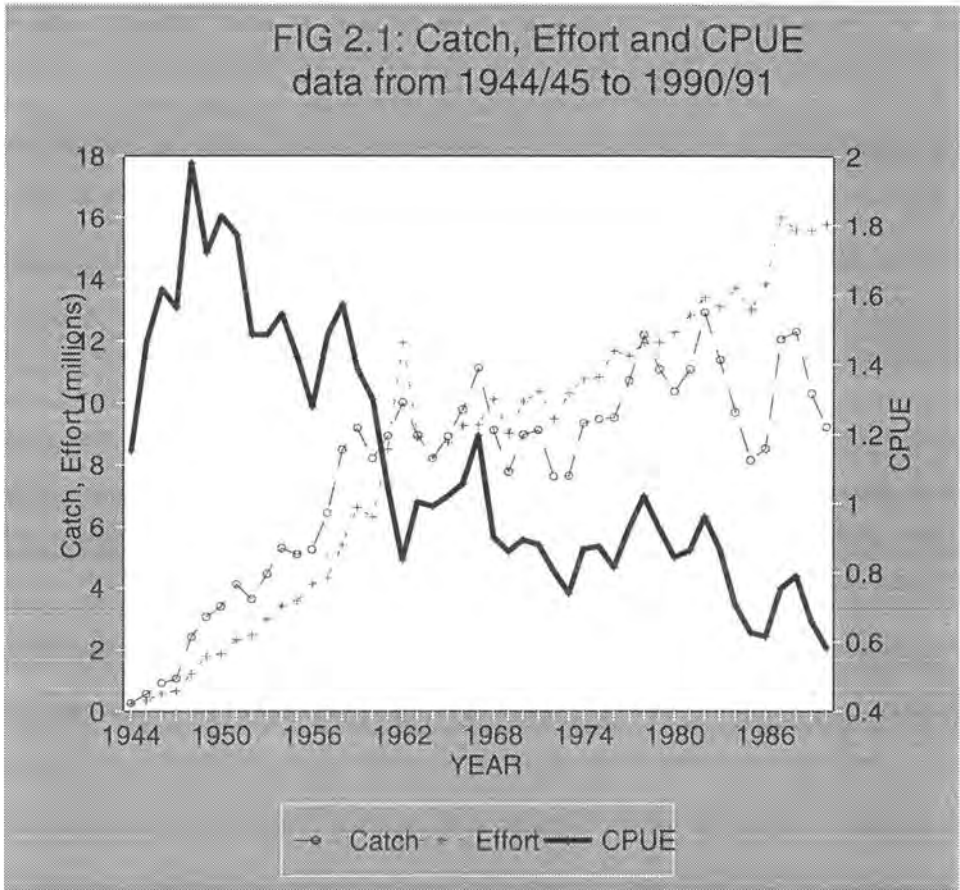
FISHERY

2.1 INTRODUCTION

The fishery for the western rock lobster *P. cygnus*, is one of the major rock lobster fisheries in the world and the most valuable single-species fishery in Australia. It represents approximately 20-25% of the country's gross income from fisheries products (Brown, Caputi and Hall, in press). Over the 10 years to 1990/91, the annual catch averaged around 10.5 million kg. The catch for the 1989/90 season was worth approximately \$200 million to the fishermen (Hall and Brown, 1990). Most of the rock lobsters were exported to the USA (40.5%), Japan (40.3%) and Taiwan (19.2%) (Monaghan 1989).

The development of the western rock lobster fishery in Western Australia from an under exploited fishery in the 1930s to the present fully-exploited fishery can be represented by the graph of annual catches in Fig 2.1. The commercial fishery for *P. cygnus* began with the establishment of a small fishery at the Abrolhos Islands during the Second World War to supply canned rock lobster tails to the armed forces. Without efficient methods of fishing, the fishery was restricted to the shallow reefs. The rock lobsters were captured using pots, which were pulled by hand from a small

FIG 2.1: Catch, Effort and CPUE data from 1944/45 to 1990/91



number of sailing craft. The catches from the 1930s to 1944/45 were around 250,000 kg. After the Second World War, with the availability of new technologies like marine engines and power winches for pulling the pots, the fishermen began to fish intensively in the shallow reefs and expanded into deeper water. With the establishment of a small export industry in the late 1940's, the catch grew to 1,062,477 kg in the 1947/48 season. As the price being paid for the rock lobster tails continued to grow, the number of boats and men involved in the industry increased. By the late 1950's the fishery supported over 1,000 fishermen who, with more

efficient boats, took approximately 9.19 million kg of rock lobsters (Morgan 1977).

As shown in Figure 2.1, the growth in effective fishing effort (refer to section 4.2) from 5.4 million pot lifts in 1958/59 to 11.95 million pot lifts in the 1962/63 season did not produce any significant increase in the catches (similar observations can be obtained from nominal fishing effort). The resulting downward trend in catch per pot lift (based on nominal fishing effort) prompted many fishermen to approach the government with proposals to prohibit the entry of additional boats and limit the number of pots per boat. The limited entry regulation was introduced on 1 March, 1963 (Hancock 1981), and limited the number of rock lobster boats in the industry to existing boats and fixed the number of pots per boat to 3 pots per foot (Morgan 1977). Both regulations limited the total number of rock lobster pots licensed in the industry with the objectives of achieving optimal utilisation of the resource, reasonable economic return to the fishermen, and orderly exploitation or fishing to minimise conflicts among commercial fishermen and between commercial and recreational fishermen (Meany 1979).

The limited entry regulation was introduced, as indicated above, to stabilise both the catch and the catch per unit effort. The catch per unit effort from the 1964/65 to 1972/73 seasons in Figure 2.1 showed a downward trend which was accompanied by an upward trend in the effective effort. Morgan (1977) noted that this increase in effective effort was the result of an increase in the number of days worked per boat per month and an increase in the mean number of boats working per month.

The dramatic improvement in the efficiency of the fishing vessels and navigational equipment enabled the fishermen to increase the effective fishing effort from 10.32 million pot lifts in 1973/74 to 13.02 million pot lifts in 1985/86. For instance, the improved seaworthiness of the vessels is one of the factors which enabled the fishermen to obtain 19.4 working days per month (open season was from 15 November to 30 June) in 1990/91 compared to 17.0 working days per month in 1973/74 when the open season was from 15 November to 14 August. The increase in effective effort together with the use of advanced technology in fish finding resulted in the catch increasing from 7.65 million kg in 1973/74 to a peak of 12.92 million kg in 1982/83. Subsequently, the catch started to decline to 8.17 million kg in 1985/86.

Caputi and Brown (1986) have predicted a very low recruitment for the 1985/86 and 1986/87 seasons using the abundance of 3-year-old and 4-year-old rock lobsters. With the high levels of effort operating on the predicted recruitment, it was feared that subsequent breeding stock would be reduced drastically and that this would adversely affect both future settlement of puerulus and recruitment to the fishery. Therefore it was recommended that the pot numbers be reduced temporarily by 10% for the 1986/87 season (Phillips and Brown, 1989). In addition to the temporary reduction of pot numbers, a permanent reduction of 10%, at 2% per year from 1987/88 to 1991/92, was implemented in 1987 (Hall and Brown 1990). The continued reduction in catch per unit effort for the 1987/88 to 1990/91 seasons in Figure 2.1 could be due to a combination of advances in vessels, fish-finding technology, and fishing gear (Brown, Caputi and Hall, in press).

2.2 FISHING AREAS

The fishery now operates from the shallow water of the inshore reefs to the edge of the continental shelf with depths of 200m, between North West Cape (21° 44'S) to just south of Cape Leeuwin (34° 24'S). However, the majority of the commercial catch is taken from the Arolhos Islands, and the coastal areas between Kalbarri (27° 43'S) and Mandurah (32° 43'S), from the shallow reef areas to a depth of 180 m. Fishing in deeper water is often limited by difficult sea and weather conditions off the coast.

2.3 FISHING SEASONS

The fishing season for *P. cygnus* may be divided into three distinct phases; the "whites" fishery, the "coastal red" fishery, and the Arolhos Islands fishery.

At the time of writing, the "whites" fishery runs from the 15th of November and extends to December (George, 1958). During this phase of the fishery, fishermen set their pots in shallow waters close to the shore and take large quantities of newly moulted, immature rock lobsters. Tagging studies (George, 1958) have shown that these "whites" rock lobsters, between 4 and 6 years old, undertake a migration towards the deeper water of the continental shelf with depths of 30m to 150m during

November and December. As the "whites" season progresses, the fishermen set their pots further and further away from the shore as they follow this migration of the lobsters into deeper water. The majority of the "whites" are 4 year old (Morgan, Phillips and Joll, 1982) with a mean size around the minimum legal size of 76 mm carapace length (George, 1958; Chittleborough, 1970).

The "coastal red" fishery commences at the beginning of January and continues until the season closes on 30 June. During this phase, most fishermen work closer to the coast while some fishermen, with larger vessels in particular, continue to fish in deeper water.

With no processing establishments in the Abrolhos Islands, the rock lobsters are held in floating crates and later transported by carrier boat to the processing factories at Geraldton. This mode of transportation sometimes resulted in significant mortality of rock lobsters. During the "whites" fishery when the weather was very hot and the rock lobsters were below average conditions, the mortality of the lobsters was very pronounced. Hence it was decided that the Abrolhos Islands fishery should operate from the 15th of March when the weather is much cooler and should end on the 30th of June (Morgan 1977).

2.4 FISHING PRACTICES

All the commercial catch of *P. cygnus* is caught by pots. The three main types of pots used are batten, stick or cane beehive or iron beehive.

Phillips, Morgan and Austin (1980) give a more comprehensive discussion on their constructions and suitability. To attract the rock lobsters into the traps, baits such as fish heads, whole small fish, sheep heads, cattle hocks or cattle hide, as discussed by Brown and Barker (1985/86), are used. The traps are set individually and lifted each morning depending on the weather and expected catch rate, and reset after rebaiting if necessary.

To reduce the mortality of undersized rock lobsters due to overexposure on board, it is illegal to take a trap on board while still sorting rock lobsters from a preceding trap and all undersized rock lobsters must be returned to the sea within 5 minutes (Brown and Caputi 1986, Phillips and Brown 1989). In addition, the number of escape gaps (54 X 305 mm) in traps was increased from one to either 3 or 4 (Brown and Caputi 1986) to allow undersized rock lobsters the opportunity to leave the pots before they are lifted by fishermen.

2.5 PROCESSING

Apart from small local and export markets for frozen whole (6.7%) and live (4.4%) rock lobsters, all of the catch is marketed as frozen whole cooked (48.7%) and frozen tails (40.2%) (Brown, Caputi and Hall, 1992). Processing factories are located at Geraldton, Dongara, Jurien Bay, Cervantes, Lancelin, Cape Leschenault, Ledge Point, Perth, and Fremantle. Rock lobsters are delivered live to the factories where they are "tailed" (where the heads are either discarded or processed as fertiliser).

The intestinal tract from the "tail" is removed and the tails are graded into various weight categories and packed into 11.4 kg cartons and deep frozen.

2.6 MAJOR MANAGEMENT REGULATIONS

The majority of the management measures or regulations have been implemented to contain the expansion in fishing effort to ensure that there will be sufficient breeding stock to produce the necessary recruitment and avoid the decline in recruitment. These regulations have been reviewed by Bowen (1971), Morgan (1977), Hancock (1981) and Phillips and Brown (1989). Some of the major management regulations (Phillips and Brown 1989) are:

- 1897 Minimum legal whole weight of 340g. This is equivalent to minimum size of 76 mm carapace length which is currently in force in the fishery.
- 1899 All "berried" females (i.e those females carrying external eggs) caught must be returned to the sea.
- 1962 Closed season: Coastal fishery closed from August 16 to November 14, Abrolhos Islands fishery closed from August 16 to March 14.
- 1963 Limited Entry: In March 1963, the maximum number of

rock lobster boats was fixed at 858, at the same time the number of traps per boat was limited to 3 per foot length of boat.

1965 The boat replacement policy which requires a boat to be replaced with one of exactly the same length prevented fishermen from obtaining additional traps under the 3 traps per foot of boat length regulation.

1966 A 51mm X 305mm escape gap was introduced into all traps to allow undersized rock lobsters to escape before the trap is brought to the surface.

1971/72 The escape gap was increased to 54mm X 305mm from 51mm X 305mm.

1973 Multiple entrances in traps were banned.

1977/78 The fishing season was shortened to protect newly mated females and to constrain fishing effort. Closed season: the Coastal fishery closed from July 1 to November 14, while the Abrolhos Islands fishery closed from July 1 to March 14.

1981 Maximum diameter or length of traps was set at 1m to control the efficiency of oversized traps.

- 1984 The maximum volume for traps was set at 0.257m^3 .
- 1986 The number of escape gaps in the traps was increased to 3 or 4 depending on the position of gaps to allow undersized rock lobsters to escape before traps are lifted on board.
- 1986 The number of traps of all licence holders were reduced temporarily by 10% for the 1986/87 season. This measure was introduced following very low level of recruitment being predicted for the 1986/87 season.
- 1987/91 For the next 5 years, the number of traps of all licence holders were reduced by 2% (of the 1986/87 season) for every year.

2.7 CONCERN FOR THE STOCK

The annual series of catch and effective fishing effort data as in Figure 2.1 shows that while the total catch has remained at around 10.5 million kg for the last ten years, the effective fishing effort shows an upward trend; the result of this is the reduction of the catch per unit effective effort from an average of 1.645 kg per pot lift for the 1950 season to an average of 0.68 kg per pot lift for the 1986/87 to 1990/91 seasons. This downward trend in the catch per unit effective effort indicates possible depletion of the fishable stock. This thesis investigates some hypothetical management strategies with the aim of reducing the risk of future spawning stock

falling below a "critical" level.

CHAPTER 3

THE MODELS

3.1 INTRODUCTION

The fundamental model used as a basis for fishery stock assessments and management decisions (Figure 3.1) describes the dynamics of an exploited fish (single species) population in terms of the total biomass, rather than numbers.

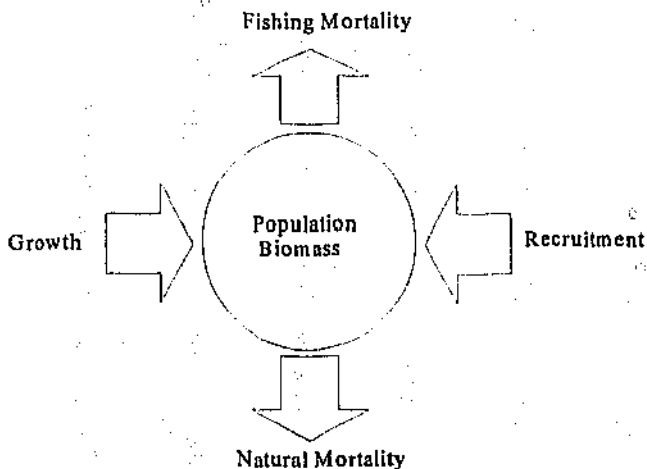


Figure 3.1 Fundamental model of fish population dynamics

By ignoring immigration and emigration, the four forces affecting the biomass of an exploited fish population are the growth of the existing fishable population, recruitment of new members to the resource, fishing mortality (removals by man) and natural mortality. Before the introduction of the delay-difference model by Deriso (1980), the population dynamic models used in fish stock assessments could be divided into the simple biomass dynamics models and the age-structure models with more flexible applications.

The widely used biomass dynamic models assume the growth rate of the total population biomass to be some function of biomass and fishing effort or effective fishing effort while ignoring scientific representation of the biological processes of growth, recruitment, mortality, and age characteristics.

Detailed age-structure models described in Ricker (1975) are defined using parameters for growth, natural mortality, and recruitment. However, a detailed age-structure model requires not only reliable information regarding the growth, mortality, and recruitment parameters of the population, but also the manner in which they might change with exploitation; often, only the recruitment process is assumed to be density dependent while the other parameters are held constant.

A compromise between the simple biomass dynamic model and the detailed dynamic pool model is the delay-difference model introduced by Deriso (1980). This model incorporates the effects of seasonal breeding and approximates the behaviour of the Beverton-Holt age-structured

model.

3.2 BIOMASS DYNAMICS MODELS

During the early stages of a fishery, where data are not available to make detailed analysis of growth, mortality, and recruitment, the biomass dynamics models are widely used for stock assessments. These models require only catch and (effective) fishing effort data.

3.2.1 FORMULATION OF BIOMASS DYNAMICS MODELS

A fundamental model of fish biomass (in units of weight) dynamics as in Figure 3.1, may be expressed as

$$\begin{aligned} \text{New Biomass} = & \text{Old Biomass} + \text{Recruitment} + \text{Growth} \\ & - \text{Mortality} - \text{Catch} \end{aligned} \quad (3.1)$$

The above expression suggests that there are four main factors which affect the biomass of the exploited stock; growth of existing members and recruitment of new members which will increase the biomass of the stock; catch by fishermen and natural mortality (includes all other deaths) which will decrease the biomass of the exploited stock.

Using surplus production to represent the sum of recruitment and growth minus the natural mortality, then the above biomass equation can be

rewritten as

$$\text{New biomass} = \text{Old biomass} + \text{Surplus Production} - \text{Catch} \quad (3.2)$$

From the above expression, a simple model of the fish biomass dynamic can be formulated if the surplus production can be expressed as a function of biomass. In the absence of fishing, as cited by Ricker (1975), Graham postulated that by assuming biomass equilibrium (new biomass = old biomass), the instantaneous rate of change of surplus production of a stock can be expressed as the following differential equation (Ricker 1975):

$$\frac{dB}{dt} = rB \left(1 - \frac{B}{B_{\infty}} \right) \quad (3.3)$$

where B is biomass of the stock,

r is the intrinsic growth rate of the population, and

B_{∞} is the maximum biomass of the stock.

Integrating the above differential equation with respect to time t gives the logistic growth curve of Verhulst (Ricker 1975),

$$B = B_{\infty} (1 + \exp(-r(t - t_0))) \quad (3.4)$$

where t_0 is the start time.

By including the catch, C , in the Graham model, the result is the simple population model

$$\frac{dB}{dt} = rB \left(1 - \frac{B}{B_{\infty}} \right) - C \quad (3.5)$$

The above model states that the growth rate of the total population biomass is equal to its natural logistic growth rate minus the catch rate. However the above model in its present form requires direct estimates of stock biomass for model fitting, which unfortunately are usually not readily available in the fishery world.

3.2.1.1 SCHAEFER MODEL

To eliminate the need for direct estimates of stock biomass in the simple production model of equation (3.5), Schaefer (1954, 1957) assumed the catch to be proportional to fishing effort and stock size, resulting in the following formulations:

$$\frac{dB}{dt} = rB \left(1 - \frac{B}{B_{\infty}} \right) - C \quad (3.6a)$$

$$C = qfB \quad (3.6b)$$

$$U = qB \quad (3.6c)$$

where r is the intrinsic growth rate of the population,

B is the biomass of the fishable population,
 B_{∞} is the maximum biomass of fishable population.
 C is the instantaneous catch,
 q is the catchability coefficient,
 f is the effective fishing effort, and
 U is the instantaneous catch per unit effort.

Equation (3.6c) states that U is proportional to the biomass only and therefore it can be used as an index of population biomass under the following assumptions: the fish are uniformly distributed over the fishing areas, fishing efforts are randomly distributed, and each unit of fishing effort is independent of each other.

The Schaefer model in its current form predicts only the equilibrium yield and does not predict the trajectory of the stock (Roff 1980). Hence to forecast the catch, catch per unit effort, or the stock biomass of the western rock lobster, the differential equation of the Schaefer model will be replaced with an analogous difference equation as in Walters and Hilborn (1976) and Uhler (1978).

The proposed model in discrete difference equations may be expressed as:

$$B_t = (1+r)B_{t-1} - \frac{r(B_{t-1})^2}{B_{\infty}} - C_{t-1} \quad (3.7a)$$

$$C_t = qf_t B_t \quad (3.7b)$$

$$U_t = qB_t \quad (3.7c)$$

where B_t is the fishable biomass at time t ;
 r is the intrinsic population growth rate;
 B_{t-1} is the fishable biomass at time $t-1$;
 B_{∞} is the maximum fishable biomass;
 C_t is the total catch at time t ;
 C_{t-1} is the total catch at time $t-1$;
 f_t is the effective fishing effort at time t ;
 U_t is the catch per unit effort at time t .

3.2.1.2 PELLA AND TOMLINSON MODEL

In the Schaefer model, the surplus production curve (equations 3.6) must be perfectly symmetric in relation to population biomass. To account for possible skewness in the surplus production curve, Fox (1970) proposed an asymmetrical surplus production curve based on Gompertz growth. In this thesis, the generalised model of Pella and Tomlinson (1969) which treats both the Schaefer and Fox model as special cases will be considered. With an extra parameter m , the generalised model when expressed in analogous difference equation form can be defined by the following set of equations

$$B_t = (1+r)B_{t-1} - \frac{r(B_{t-1})^m}{B_{\infty}} - C_{t-1} \quad (3.8a)$$

$$C_t = qf_t B_t \quad (3.8b)$$

$$U_t = qB_t \quad (3.8c)$$

where B_t is the fishable biomass at time t ;
 r is the intrinsic population growth rate;
 B_{t-1} is the fishable biomass at time $t-1$;
 B_∞ is the maximum fishable biomass;
 C_t is the total catch at time t ;
 C_{t-1} is the total catch at time $t-1$;
 f_t is the effective fishing effort at time t ;
 U_t is the catch per unit effort at time t ; and
 m is a dimensionless constant.

3.2.1.3 MARCHESSEAU DELAYED RECRUITMENT MODEL

Silliman (1971) noted that the assumption of instantaneous recruitment in the models does not allow for reproductive lag in population growth. As many fish (especially the western rock lobster) first enter the fishery many years after hatching, possible time lag should be investigated. To account for reproductive lag in population growth, Walter (1973) introduced an explicit term for the time lag in the Schaefer model

$$\frac{dB_t}{dt} = rB_t - \frac{B_t^2}{B_\infty} + cB_t \cdot B_{t-w} - qf_t B_t \quad (3.9a)$$

$$C_t = qf_t B_t \quad (3.9b)$$

$$U_t = qB_t \quad (3.9c)$$

where B_t is the population biomass at time t ;
 B_∞ is the maximum biomass of the stock;

r is the intrinsic growth rate of the population;

C_t is the total catch at time t ;

U_t is the catch per unit effort at time t ;

q is the catchability;

f is the fishing effort at time t ;

w is the time lag; and

c is a dimensionless constant.

In the model, the rate of recruitment is interpreted as directly proportional to the product of the current stock and spawning stock. As it is difficult to quantify this relationship between the current and spawning populations, Marchesseault and Salla (1976) proposed that the rate of recruitment be dependent only on the spawning population B_{t-w} . The proposed model with an explicit stock-recruitment relationship can be expressed in difference equations as:

$$B_t = (1+r)B_{t-1} - \frac{r(B_{t-1})^2}{B_m} + cB_{t-w} - C_{t-1} \quad (3.10a)$$

$$C_t = qf_t B_t \quad (3.10b)$$

$$U_t = qB_t \quad (3.10c)$$

where B_t , r , C_t , B_m , U_t , q , f , and c are defined as in the Schaefer and Walter models.

Other modifications of the Schaefer model can be found in Schnute (1977), Walter (1973), and Jensen (1984). Some criticisms associated with the above-mentioned models are: the assumption that the offspring

age instantaneously to adulthood; the parameters in the model have no direct relation to observable phenomena - hence the estimated parameters usually cannot be supported by estimates which are independent of the models. Despite their limitations, these models are widely used because mathematically, they are relatively simple and require only catch and effort data for model fitting.

3.3 DERISO-SCHNUTE DELAY-DIFFERENCE MODEL

The simple biomass dynamic models as described earlier require only catch and effort data and were widely used in stock assessments during the early stages of the fishery when little or no biological data were available. However, in fisheries such as the western rock lobster fishery where valuable biological data are available, it would be "risky" to ignore these data while performing stock assessments. One model which incorporates some of these biological data is the delay-difference model proposed by Deriso (1980) and elaborated by Schnute (1985). The delay-difference model is a biomass dynamics model which incorporates the obvious time lags due to growth and recruitment with parameters which are biologically meaningful and can be measured directly.

3.3.1 DERIVATION OF DERISO-SCHNUTE DELAY-DIFFERENCE MODEL

The derivation of the delay-difference models is based on specific process

models for growth, survival, and recruitment. These process models and assumptions are then substituted into a general population biomass equation to arrive at the delay-difference equation.

3.3.1.1 ASSUMPTIONS

Apparently, all fish from the time of birth follow an S-shaped growth curve (Ricker, 1975). The initial portion of the growth curve with increasing slope corresponds to the faster growing young fish, while the decreasing slope of the latter part of the curve represents the growth of older fish with slower growth rate. By dividing the S-shaped growth curve at the point of inflexion (Ricker 1975), the growth can be represented by the following equations:

$$W_t = a e^{Kt} \quad (3.11)$$

$$W_t = b - c e^{-Kt} \quad (3.12)$$

where W_t represents the weight of fish at time t ;

b and c are some constants; and

K is the Brody growth coefficient.

Equation (3.11) with exponential rate of change represents the faster growing young fish. Older fish where the rate of growth tends to be slower, may be described by equation (3.12). Studies of exploited fish populations have concentrated mainly on the more mature fish. Hence, equation (3.12) or equivalent forms would be more appropriate in many

instances (Ricker, 1975).

Schnute (1985) used another form of equation (3.12) which involved the Ford growth coefficient (Ricker 1975, p 222, equation 9.17). Using $p = \exp(-K)$, the growth equation may be written as

$$W_t = \alpha + pW_{t-1} \quad (3.13)$$

where W_t is the weight of an animal in year t ;
 W_{t-1} is the weight of an animal in year $t-1$;
 α is a constant;
 K is the Brody's growth coefficient; and
 p is Ford's growth coefficient.

Mortality in a fish population can be due to fishing, predation, disease, accident, cannibalism, and other causes of death. Ricker (1975) noted that in general, all mortality rates may be expressed numerically as either

- (i) a percentage of the fish which die from all causes during the year; or
- (ii) an instantaneous mortality rate: If the number of all deaths in a small interval of time is proportional to the number of fish present at any instant, then the rate at which the numbers in the population are changing may be expressed as

$$\frac{dN}{dt} = -ZN; \quad (3.14)$$

where Z is the instantaneous total mortality coefficient;
 N is the population size in number; and
 t is the time.

Since it is the biomass rather than the numbers in the population which will be modelled, a more appropriate expression may be

$$\frac{dB}{dt} = -ZB \quad (3.15)$$

where B is the biomass of the fishable population.

The solution of the differential equation (3.15) is

$$B_t = B_{t-1} \exp(-Z) \quad (3.16)$$

where B_{t-1} is the initial biomass; and
 B_t is the biomass after one unit of time.

An equivalent and simpler representation of the model involving survival rate (rather than mortality rate) may be written as

$$B_t = sB_{t-1} \quad (3.17)$$

where s is the proportion surviving over one year.

Ricker (1975) noted that all the causes of death in a fish population may be divided into fishing mortality, which corresponds to the catch by man, and all the other causes of death, known as natural mortality. It can be assumed that the annual survival rate at any year, $s_t = \exp(-Z_t)$ can be written as the product of a constant natural survival rate σ , and a time-varying survival from fishing, ϕ_t :

$$s_t = \sigma \phi_t \quad (3.18)$$

where $\sigma = \exp(-M)$;

$\phi_t = \exp(-E_t)$; and

E_t is the effective fishing effort at time t .

With the above assumption, the number of fish age $a+1 \geq k+1$ at the beginning of year $t+1$, $N_{a+1,t+1}$ can be represented by

$$N_{a+1,t+1} = s_t N_{a,t} \quad (3.19)$$

where $N_{a,t}$ represents the number of fish age $a \geq k$, the age at recruitment to the fishable stock at the year t .

If W_a represents the weight of a single rock lobster aged a in time t , then the biomass, B_t is

$$B_t = \sum_{a \geq k} W_a N_{a,t}$$

Another significant assumption is that fish of age $a \geq k$ will experience uniform fishing mortality while younger fish are not vulnerable to the

fishery. This implies that the catch C_t at any time, t , can be expressed as

$$C_t = (1 - \phi_t) B_t \quad (3.20)$$

where ϕ_t is the fraction of the population that survives fishing.

In most fish populations, the number of recruits to the fishery is usually determined at the egg and larval stages. Although the mortality rates will vary due to environmental factors, the annual recruitment to the fishery, R_t which is the number of rock lobsters reaching weight W_k at any time t , can be assumed to be related to the size of spawning stock at the end of year $t-k$ by some function, f . Mathematically, the relation can be expressed as

$$R_t = f(S_{t-k}) \quad (3.21)$$

$$\text{where } S_{t-k} = B_{t-k} - C_{t-k} \quad (3.22)$$

The most widely used stock-recruitment relationships in the study of fish population are described below.

Ricker Stock-Recruitment Relationship

This stock-recruitment model is based on the biological assumption that the mortality rate of the eggs and juveniles is proportional to the size of

the spawning stock (Hilborn and Walters, 1992). Hence, Ricker's model will be more appropriate when the main regulatory mechanism is due to cannibalism, or when the effect of higher density slows down the growth of young fish to the exploitable size (Ricker, 1975). The form of the model used here is

$$R_t = aS_{t-k} \exp(-bS_{t-k}) \quad (3.23)$$

where R_t is the biomass of the recruits at time t ;

S_{t-k} is the biomass of the spawning stock at time $t-k$;

a is the recruits-per-spawner at low stock sizes;

b describes the drop in recruits-per-spawner with increasing stock size.

Beverton-Holt Stock-Recruitment Relationship

The Beverton-Holt stock-recruitment model assumes that the mortality rate of juveniles is proportional to the size of the cohort at any time prior to recruitment. This model will be more appropriate in situations when the availability of shelter or food becomes the main regulatory mechanism. The preferred form of the Beverton-Holt stock-recruitment model is

$$R_t = \frac{\lambda S_{t,k}}{(\beta + S_{t,k})} \quad (3.24)$$

where R_t is the biomass of the recruits at time t ;

S_{t-k} is the biomass of the spawning stock at time $t-k$;
 λ is the maximum number of recruits produced; and
 B is the spawning stock needed to produce (on average)
 recruitment equal to $\lambda/2$.

3.3.1.2 GENERAL DERIVATIONS

If N_t and B_t represent the total stock number and biomass of fishable population respectively (age k and older, weight W_k and heavier) at the start of year t , then

$$N_t = \sum_{a \geq k} N_{a,t} = \sum_{a \geq k+1} N_{a,t} + N_{k,t} \quad (3.25)$$

and

$$B_t = \sum_{a \geq k} W_a N_{a,t} \quad (3.26)$$

where W_a is the weight of a single rock lobster aged a in year t .

Substituting equation (3.25) into equation (3.26);

$$\begin{aligned} B_t &= W_k N_{k,t} + \sum_{a \geq k+1} W_a N_{a,t} \\ &= W_k R_t + \sum_{a \geq k+1} W_a N_{a,t} \quad \text{since } R_t = N_{k,t} \\ &= W_k R_t + \sum_{a \geq k+1} W_a s_{t-1} N_{a-1,t-1} \quad \text{from (3.19)} \\ &= W_k R_t + \sum_{a \geq k+1} (\alpha + p W_{a-1}) s_{t-1} N_{a-1,t-1} \end{aligned}$$

$$= W_k R_t + \alpha s_{t-1} \sum_{a \geq k+1} N_{a-1,t-1} + p s_{t-1} \sum_{a \geq k+1} W_{a-1} N_{a-1,t-1}$$

$$B_t = W_k R_t + \alpha s_{t-1} N_{t-1} + p s_{t-1} B_{t-1} \quad (3.27)$$

where α is a constant; and

p is Ford's growth coefficient.

From equation (3.25), equation (3.19), and $R_t = N_{k,t}$, the number of fish age k and more, N_t may be written as

$$N_t = \sum_{a \geq k} N_{a,t} = \sum_{a \geq k+1} N_{a,t} + R_t$$

$$= s_{t-1} \sum_{a \geq k+1} N_{a-1,t-1} + R_t$$

$$N_t = s_{t-1} N_{t-1} + R_t \quad (3.28)$$

Equation (3.28) can be combined with equation (3.27) to arrive at the delay-difference equation containing only the biomass.

From the equation (3.27),

$$N_{t-1} = \frac{B_t - W_k R_t - p s_{t-1} B_{t-1}}{\alpha s_{t-1}} \quad (3.29)$$

and substituting $t-1$ by t and t by $t+1$;

$$N_t = \frac{B_{t+1} - W_k R_{t+1} - p s_t B_t}{\alpha s_t} \quad (3.30)$$

Substituting both (3.29) and (3.30) into (3.28) will result in

$$\frac{B_{t+1} - W_k R_{t+1} - p s_t B_t}{s_t} = B_t - W_k R_t - p s_{t-1} B_{t-1} + \alpha R_t$$

which after some algebraic manipulations becomes

$$B_{t+1} = s_t B_t + p s_t B_t - p s_t s_{t-1} B_{t-1} - (W_k - \alpha) s_t R_t + W_k R_{t+1}$$

Using $\alpha = W_k - p W_{k-1}$, the result is Deriso-Schnute's delay-difference model represented as

$$B_{t+1} = s_t B_t + p s_t B_t - p s_t s_{t-1} B_{t-1} - p s_t W_{k-1} R_t + W_k R_{t+1}$$

or

$$B_{t+1} = (1+p) s_t B_t - p s_t s_{t-1} B_{t-1} - p s_t W_{k-1} R_t + W_k R_{t+1} \quad (3.31)$$

Equation (3.31) implies that biomass for year $t+1$ can be predicted from (i) the surviving biomass from year t , $s_t B_t$, (ii) the growth of surviving individuals from year t , $p s_t B_t - p s_t s_{t-1} B_{t-1} - p s_t W_{k-1} R_t$, and lastly (iii) the new recruits added to the stock, $W_k R_{t+1}$.

To account for different behaviours for individual fish stocks, Deriso (1980) proposed a stock-recruitment function, R_t which has the Beverton-Holt and Ricker models as special cases. The model uses

$$R_t = \frac{aS}{(1 - bcS)^c} \quad (3.32)$$

where c (with values $-\infty$, -1 , 0 , and 1) will determine the general form of the model. Different formulations of the model can be found in Hilborn and Walters (1992) and Schnute (1985). Please refer to Schnute (1985) for discussion of its properties.

CHAPTER 4

MODEL SELECTION

4.1 LIFE HISTORY OF *P. CYGNUS*

Mating of the western rock lobster, *P. cygnus* normally occurs during winter/early spring (July-August). After the eggs are extruded and fertilised (October-December), the females will then carry the fertilised eggs on the pleopods for a period up to 9 weeks before hatching (Chittleborough, 1979).

On hatching the phyllosoma larvae swim to the surface, and the majority of them are transported and distributed over a wide area of the south-eastern Indian Ocean during their 9-11 months larvae life (Phillips and Brown 1989). At the end of the planktonic life, the late phyllosoma larvae are transported towards the continental shelf of Western Australia by the water circulation of the south eastern Indian Ocean (Phillips et al., 1979). The late phyllosoma larvae moults to the peurulus stage in the water beyond or just on the continental shelf of Western Australia. The peurulus stage completes the planktonic cycle by swimming approximately 40 km across the continental shelf and settling in the shallow inshore limestone reef areas along the coast (Phillips, 1981). The peak settlement of peurulus along the coast of Western Australia occurs between September

and January (Phillips, Brown, and Rimmer 1979).

After settling on the limestone reef areas, the peurulus stage metamorphoses into a juvenile rock lobster, with a carapace length of approximately 8 mm (Phillips, Morgan, and Austin 1980) and then spends the next 4 to 5 years on the shallow "nursery" reefs (Chittleborough, 1975). In their first years after settlement, these small benthic rock lobsters live in holes and crevices in the shallow limestone reefs to a depth of 10 m. The older juveniles are found under the limestone reef ledges during daylight or while foraging for food in the surrounding sea grass beds at night (Joll and Phillips 1984).

Each year in November and December, the juveniles between 4 and 6 years old migrate from the shallow reef areas into the adult population in the outer continental shelf into depths of 30-150 m (George, 1958). These migrating rock lobsters are usually the very pale, newly moulted animals commonly referred to as "whites" (Morgan, Phillips, and Joll 1982). Most "whites" are composed of the 4 and 5 year old juveniles (Morgan, Phillips and Joll 1982). For the remainder of the year, the rock lobsters are non-migratory, have a deep red colour and are commonly referred as "reds".

The minimum legal size for the western rock lobster fishery (carapace length 76 mm) is generally less than the variable size at first breeding of the females (Morgan, 1972). At the Abrolhos Islands the majority of breeding females are below 76 mm carapace length while in the coastal situation, the reproductive maturity of females generally occurs 12-24 months after reaching the legal size.

4.2 CATCH AND FISHING EFFORT STANDARDISATION

The western rock lobster fishery is considered a fully exploited fishery with an exploitation rate of about 85% through the entire life after recruitment to the fishery, and an annual exploitation rate in excess of 60% (Phillips and Brown 1989; Bowen and Hancock 1989). Since most of annual stock assessments conducted are based on the commercial catch and effective fishing effort data (Table 4.1), it is essential that the catch and effort estimates are accurate (e.g. account for under reporting of catch) and unbiased (e.g. adjust the efficiency of fishing effort due to advancements in fishing technology). In Brown, Caputi and Hall (in press), the authors (i) examine the methods used to obtain the nominal catch and fishing effort estimates for the western rock lobster, (ii) identify the biases and inaccuracies in the time series of catch and fishing effort data, and (iii) describe the process used to adjust or standardise the data.

Table 4.1: Catch and Effective Fishing Effort

Season	Catch (Million Kg)	Effective Fishing Effort (Million Pollifts)
1944/45	0.277	0.240
1945/46	0.556	0.380
1946/47	0.921	0.570
1947/48	1.062	0.680
1948/49	2.415	1.220
1949/50	3.063	1.780
1950/51	3.396	1.860
1951/52	4.114	2.320
1952/53	3.649	2.460
1953/54	4.455	3.000
1954/55	5.293	3.430
1955/56	5.099	3.590
1956/57	5.247	4.110
1957/58	6.435	4.330
1958/59	8.487	5.400
1960/61	9.188	6.630
1961/62	8.203	6.310
1962/63	8.931	8.510
1963/64	10.010	11.952
1964/65	8.950	8.907
1965/66	8.220	8.276
1967/68	9.779	9.260
1968/69	11.111	9.297
1969/70	9.127	10.120
1970/71	7.773	9.022

Season	Catch (Million Kg)	Effective Fishing Effort (Million Potlifts)
1971/72	8.977	10.039
1972/73	9.125	10.368
1973/74	7.626	9.478
1974/75	7.646	10.326
1974/75	9.357	10.758
1975/76	9.474	10.828
1976/77	9.519	11.669
1977/78	10.707	11.521
1978/79	12.189	11.933
1979/80	11.090	11.946
1980/81	10.370	12.286
1981/82	11.094	12.845
1982/83	12.922	13.428
1983/84	11.383	13.108
1984/85	9.691	13.730
1985/86	8.166	13.026
1986/87	8.529	13.872
1987/88	12.066	16.015
1988/89	12.312	15.594
1989/90	10.298	15.590
1990/91	9.220	15.790

4.3 EVALUATION / SELECTION OF MODELS

The catch-effort data from 1944/45 to 1990/91 of the western rock lobster may provide us with some insight regarding the past and present size of the stock. Hence, with the "right" models, one may be able to predict the general status of the stock under various levels of fishing effort.

4.3.1 FORECASTING POWER

The size of the residuals after fitting a model to the catch and effort data will give a good indication of the goodness of fit of the model. However, there is no evidence of its accuracy or ability to forecast future catch, catch per unit effort, or biomass. Hence, the evaluation or selection of models should be based on the forecasting power of the models rather than the goodness of fit of models to the catch and effort data.

To test the forecasting power of the models, the forecast values of the catch per unit effort, U_t , will be compared with the observed catch per unit effort, U_t , using the time-series of catch and effort data not used in parameter estimations.

The usual method of evaluating the forecasting power of models is to measure the mean square error (MSE) which may be defined as:

$$MSE = \frac{1}{N} \sum \frac{(U_t - U_t)^2}{U_t} \times 100\% \quad (4.1)$$

where N is the number of forecasts.

However, it is possible that the selected model (lowest MSE) might have poor forecasting power if its predicted values differ widely from the observed values. So mean absolute percentage error will be used in the evaluation or selection of models. The Mean Absolute Percentage Error (MAPE) to be used may be defined as:

$$\text{MAPE} = \frac{1}{N} \sum \frac{|U_t - U_t|}{U_t} \times 100\% \quad (4.2)$$

where N is the number of forecasts.

As a measure of model acceptability with respect to precision, 20% has been adopted as the maximum acceptable level (Roff 1980). This implies that a model with MAPE greater than 20% will be considered to be unsuitable for risk analysis.

Another issue which needs to be considered in parallel to MAPE, is the bias of the forecasts. To measure forecast bias, the statistic which will be used is the mean percentage error (MPE) written as

$$\text{MPE} = \frac{1}{N} \sum \frac{(U_t - U_t)}{U_t} \times 100\% \quad (4.3)$$

where U_t is catch per unit effort at time, t , and
 U_t is predicted catch per effort at time, t .

If no bias is present then one would expect the MPE to be zero. In this thesis, the range of the acceptable MPE is from -20% to 20%.

4.3.2 MODEL FITTING

As the catch and effort data from 1944/45 to 1990/91 are time series data, one should consider the possible functional relation between each observation (predicted biomass, catch, or catch per unit effort) when fitting models to the data. Hence, it is better not to treat each of the observation as an independent observation but to assume that each of the observations at any time depends on previous values.

4.3.2.1 FITTING THE TIME SERIES CATCH AND EFFORT DATA

To consider the time series nature of the catch and effort data of the western rock lobster, the variation from each of the independent (observed) variables should be taken into consideration. This means that the observed value of a variable at any time, t , can be written (as in Hilborn and Walters 1992) as

$$X_t^{obs} = f(X_t, v_t) \quad (4.4)$$

where X_t^{obs} is the observed value of X at time t ,
 f is an observation error function, and

v_t represents the observation error at time t .

Under the assumption of observation error, using the Schaefer model as an example, the model may be written as

$$B_{t+1}^{obs} = B_{t+1} + v_{t+1} \quad (4.5a)$$

$$B_{t+1} = (1 + r)B_t - \frac{rB_{t-1}^2}{B_{\infty}} - C_t \quad (4.5b)$$

where B_t^{obs} is the observed value of the true biomass at time t ,

v_t is a normally distributed random variable with mean zero and standard deviation σ_v at time t .

If one assumes that all prediction errors come from measurement (observation) errors, an initial estimate of the population biomass, B_0 , can be used by the biomass dynamics models to predict the whole time-series of biomass using the observed levels of effective fishing effort. The values of the parameters are repeatedly adjusted to minimise the unweighted sum of squares, Φ given by

$$\Phi = \sum_{t=1} (U_t - \hat{U}_t)^2 \quad (4.6)$$

where U_t is observed catch per unit effective fishing effort in year t ,

\hat{U}_t is the predicted catch per effective fishing effort in year t .

The non-linear parameter estimation techniques used by *Solver* in Excel Ver. 4 are used to fit the models.

4.3.2.2 FITTING THE BIOMASS DYNAMICS MODELS

Fitting the biomass dynamics models involves estimating the virgin biomass, B_0 , together with the three parameters q , r , B_m of the Schaefer model. Hilborn and Walters (1992) noted that the extra parameter B_0 will increase the existing severe parameter confounding between the three parameters of the Schaefer model. To avoid estimating B_0 , the starting population biomass, B_1 is estimated using the expression, $B_1 = C_1 / (1 - \exp(-qE_1))$ by using the appropriate catch and effective fishing effort data (Hilborn et al 1992).

The catch and effort data for 1945/46 to 1985/86 are used to fit both the Schaefer model and the generalised model (Pella and Tomlinson 1969); while the catch and effective fishing effort data for the 1944/45 season is used to estimate the initial population biomass, B_1 . Estimates for the biomass for the fishing seasons, 1944/45 to 1985/86 were not allowed to exceed the carrying capacity of the stock, B_m . Table 4.2 summarises the estimates for the parameters and the statistics used to measure the forecasting power.

Table 4.2: Estimates of the parameters and the desired statistics of the Schaefer model and the Pella and Tomlinson model.

Parameter	Schaefer	Pella & Tomlinson
q	0.026	0.026
B_{∞}	66.032	62.582
r	0.556	0.561
m	-	1.987
SSE	1.006	1.003
MPE	-45.614	-45.162
MAPE	45.614	45.162

Catch and effort data from 1944/45 to 1946/47, 1944/45 to 1947/48, and 1944/45 to 1948/49 are used to set up the initial system state for the delayed-recruitment models with time-lag equal to 3 years, 4 years and 5 years respectively. Similarly, the model with time-lag of 3 years, 4 years and 5 years are fitted to data from the 1947/48 to 1985/86, 1948/49 to 1985/86, 1949/50 to 1985/86 seasons respectively. For biological reality, the parameter c must be greater than zero to reflect the positive contribution of recruitment on the overall dynamics of the population. With the estimated parameters, the catch and effective fishing effort data from 1986/87 to 1990/91 are used to determine the forecasting power of all the models. Table 4.3 summarises the results for the delayed-recruitment models.

Table 4.3: Estimates of the parameters and the desired statistics for the delayed-recruitment models.

Parameter	Time Lag (years)		
	3	4	5
q	0.017	0.018	0.015
B _∞	99.063	93.297	104.247
r	0.353	0.379	0.336
c	-1 E -6	-1 E -6	-1 E -6
SSE	0.886	0.924	0.762
MPE	-24.084	-24.331	-18.625
MAPE	24.084	24.331	19.235

From above estimates in Table 4.3, the parameter, c, with time lag of 3, 4, and 5 years are negative. So the delayed-recruitment models are unacceptable as a positive value is required to reflect the contribution of recruitment to the population.

4.3.2.3 FITTING THE DELAY-DIFFERENCE MODELS

Fitting the delay-difference models under observation errors requires estimates of the initial population biomass B₁ and B₂ to predict the whole biomass time-series using the observed catch and effective fishing effort

data. The estimated biomass for the 1944/45 season through the 1949/50 season, obtained by dividing the catch with the corresponding value, $[1 - \exp(-qE)]$ is used to set up the spawning stocks to initialise the system; the 1948/49 and 1949/50 data are used to estimate the respective starting biomass B_1 and B_2 . Fitting the delay difference models is based on the catch and effective fishing effort data from 1950/51 to 1985/86. Estimates of catch per unit effective effort from the 1986/87 to 1990/91 seasons are used to determine the forecasting power of the model.

Morgan, Phillips and Joll (1982) found that Ricker's stock-recruitment relationship (equation 3.23) provided an adequate description for the spawning stock and puerulus larvae of the western rock lobster. With the discovery of some inconsistencies in the logbook data and that the peak of the breeding season of *P. cygnus* may not be exhibited in the logbooks, the Ricker stock-recruitment function will not be suitable for the western rock lobster fishery (Phillips and Brown 1989). Hence, the recruitment function in the delay-difference model will assume the Beverton-Holt recruitment function (equation 3.24).

In the delay-difference models, there is a total of seven parameters comprising W_k , W_{k-1} , p , M , q , α , and β , that need to be estimated from the catch and effort data. Since it is not possible to obtain satisfactory estimates of all the parameters using the catch and effective effort data alone, it becomes necessary to incorporate independent estimates of some of the parameters (W_k , W_{k-1} , p , and M) into the models (Hall and Brown 1989; Zheng and Walters 1988).

The weight at recruitment, W_k , and the pre-recruitment weight, W_{k-1} , are found to be 0.41 kg and 0.30 kg (Hall and Brown 1989) after converting the minimum legal carapace length of 76 mm and the estimated pre-recruitment carapace length of 68 mm (Caputi and Brown 1986; Hall and Brown 1989), using the weight-length relationship:

$$W = 2.196 \times 10^{-6} L^{2.8034} \quad (4.6)$$

where W is the weight of a rock lobster; and

L is the carapace length of a rock lobster.

Morgan (1977) provided an estimate of Brody's growth rate, K , as 0.565. This was determined by fitting the von Bertalanffy growth equation while describing the growth process of adult *P. cygnus*. Using the relationship, $p = \exp(-K)$ (Ricker 1975), the Ford growth coefficient, p , is found to be 0.568.

Using $p=0.568$, $W_k=0.41$ kg, $W_{k-1}=0.30$ kg, and $M=0.226$ (Morgan 1977), the estimates for the parameters, q , α , and β are:

$$q = 0.032$$

$$\alpha = 2.326$$

$$\beta = 0.030$$

with $SSE = 0.479$.

Using the above estimated parameters, the statistics, MPE and MAPE were -11.20% and 13.834 respectively.

4.3.3 DISCUSSION

From Table 4.2, both the Schaefer model and the Pella and Tomlinson model are rejected since their MAPEs were greater than 20%, indicating poor forecasting power. The delayed-recruitment models are rejected because the estimates of the recruitment parameter, c , are negative. Hence, only the delay-difference model of Deriso-Schnute with a Beverton-Holt recruitment function with the statistics, $MPE = -11.02$ and $MAPE = 13.834$ is used for the risk analysis of the western rock lobster.

CHAPTER 5

RISK ANALYSIS AND RESULTS

5.1 RISK ANALYSIS AND MANAGEMENT

In most established fisheries around the world, the main objective of management is to construct a strategy which will reduce the risk of depleting the resource and benefit the fishing and related industries (Hilborn and Walters 1992; Francis 1991; Peterson and Smith 1982).

To achieve this, fishery managers have to evaluate various scientific information and analyse the possible consequences of each of their strategies. A large proportion of this scientific information includes the estimation of the size of fish stock, the determination of optimum levels of harvest and its corresponding maximum sustainable yield. The complexity of the fish populations makes it difficult for stock assessment scientists to produce accurate estimates of the size of fish stock and allowable levels of harvest (Brown and Patil 1986). Hence, the stock assessment results are usually presented to the fishery managers along with some ranges of uncertainty. Expressing these uncertainties in terms of confidence intervals or the use of graphs which show the likely outcomes of various management strategies under different scenarios have not made it easier for the managers (Francis 1991; Brown and Patil 1986).

Another method which may be more useful is to express the uncertainty using the term risk to the fishery (Francis 1991; Brown and Patil 1986). Using risk analysis, the fisheries scientists may be able to quantify their assessment advice in a more understandable manner which will reflect the likely outcomes and consequences of different strategies to the managers (Peterson and Smith 1982; Linder and Patil 1987; Brown and Patil 1986; Francis 1991,1992).

5.2 DEFINITION OF RISK

It is reasonable to assume that the introduction of a fishery to any fish stock might causes a decline in its breeding stock. So, it is more important to find out the extent of the reduction in the breeding stock than it is to detect its occurrence.

Most management strategies are designed to conserve fish stocks, especially the spawning stock and juvenile fish. This is based on the assumption that spawning stock is related to recruitment, and maintaining the stock size above a minimum level should ensure the continuity of the stock provided that the minimum level is sufficient. Hence, it is advisable to maintain some desired fraction of the virgin biomass, B_0 , to decrease the likelihood of serious damage to the fish stock (Peterson and Smith 1982; Francis 1991).

In the western rock lobster fishery, where the annual exploitation rate is in excess of 60% and the overall exploitation rate through the entire life after

recruitment to the fishery is greater than 80% (Brown, Caputi and Hall, in press; Phillips and Brown, 1989; Bowen and Hancock, 1989), only a small proportion of that annual stock will be available for future exploitation after each season. Since the future of this valuable fishery depends significantly on the number of new recruits, it is advisable to maintain some level of spawning stock to ensure the continuity of this valuable fishery.

The term risk to the western rock lobster fishery will be defined as the percentage of time "something bad" will happen to the fish stock within a given time period. In this thesis, "something bad" would have happened if the biomass of the spawning stock falls below 20% of the virgin biomass, B_0 in the 1991/92 to 1995/96 seasons (Francis 1991). With risk analysis, management would be able to effectively evaluate different fishing strategies after taking into consideration both the economic and political consequences.

5.3 SENSITIVITY ANALYSIS

The evaluation process from section 4.4 suggests that the delay-difference models are the preferred models for use in the risk analysis of the western rock lobster.

To carry out a risk analysis on the western rock lobster, the first step involves estimating the parameters by fitting the catch and effort for 1950/51 to 1990/91 to the delay-difference models by assuming a

Beverton-Holt recruitment function (please refer to Section 4.3.2 for the procedures). Given the growth parameters K , W_k , W_{k+1} , and the survival parameter, M , the estimates for catchability, q , and the two recruitment parameters, α and β obtained using NLIN, from SAS (please refer to Appendix A for the SAS program and Appendix B for the result) are:

$$q = 0.031,$$

$$\alpha = 26.697,$$

$$\beta = 0.903,$$

with $SSE = 0.527$.

To evaluate the effects of variations in the model parameters on the $Catch_{1990/91}$ and the ratio of $B_{1990/91}/B_1$ using the delay-difference models, a sensitivity analysis was carried out using *Solver* in Excel. Table 5.1 shows the percentage changes in the $Catch_{1990/91}$ and the ratio of $B_{90/91}/B_1$ with changes in the model parameters W_k , W_{k+1} , K , and M .

Table 5.1: Percentage changes in the estimated catch for 1990/91 and the ratio of $B_{90/91}/B_1$ using Deriso-Schnute Difference Models with the Beverton-Holt Recruitment Function. Changes are rounded to one decimal place and the signs indicate the direction of the change.

Parameters	Catch for 1990/91 %	$B_{90/91}/B_1$ %
$W_k + 25\%$	-0.4	-0.3
$W_k - 25\%$	+0.6	+0.4
$W_{k-1} + 25\%$	+0.6	+0.4
$W_{k-1} - 25\%$	-0.4	-0.3
$K + 25\%$	+0.1	+0.2
$K - 25\%$	-0.2	-0.2
$M + 25\%$	+0.4	-0.1
$M - 25\%$	-0.1	+0.2
$M + 25\%; K + 25\%$	+0.4	-0.1
$M - 25\%; K + 25\%$	-0.1	+0.3
$M - 25\%; K - 25\%$	-0.1	+0.3
$M + 25\%; K - 25\%$	+0.4	-0.1
$M + 25\%; p + 25\%$	+0.1	-0.3
$M - 25\%; p + 25\%$	-0.7	-0.5
$M - 25\%; p - 25\%$	+0.3	+0.8
$M + 25\%; p - 25\%$	+0.5	+0.1

From table 5.1, it can be concluded that the estimates of both the catch_{90/91} and the ratio $B_{90/91}/B_1$ are robust because variations (even greater than 25%) in the model parameters do not significantly affect them.

5.4 EQUILIBRIUM ANALYSIS AND SIMULATION

This section deals with the equilibrium relationship between stock size and the annual fishing effort; it is assumed that the fish stock will reach an equilibrium state if the annual fishing effort can be held at a constant value for a sufficient number of years. This relationship may help to identify the optimum level of fishing effort, E_{MSY} that could produce the maximum sustainable yield, MSY.

5.4.1 FORM OF THE EQUILIBRIUM RELATIONSHIP

DELAY-DIFFERENCE MODEL (BEVERTON-HOLT RECRUITMENT)

Under the assumption of equilibrium (by dropping the subscripts off all the variables), the delay-difference model (3.29) will become

$$B = (1+p)sB - ps^2B + W_k R - psW_{k-1}R \quad (5.1)$$

By substituting $C = hB$, where h is the annual harvest rate, into equation (3.31) and after some algebraic manipulations, the equilibrium biomass and catch under the Beverton-Holt stock-recruitment function will be given by

$$B_e = \frac{\alpha}{D} - \frac{\beta}{(1-h)} \quad (5.2a)$$

$$C_e = hB_e \quad (5.2b)$$

where D and h are the growth-survival function and annual harvest rate respectively, expressed as

$$D = \frac{1 - (1+p)s + ps^2}{W_k - spW_{k-1}} \quad (5.3)$$

$$h = 1 - \exp(-qE) \quad (5.4)$$

NOTE: The expression for D in Zheng and Walters (1988) on page 225 is not correct due to an error in the third term of equation (8). For confirmation, please see Hilborn and Walters (1992) page 339, equation (9.3.2).

BIOMASS DYNAMICS MODELS

Under the assumption of equilibrium, the Schaefer model (equation 3.7a) becomes

$$B = (1+r)B - \frac{rB^2}{B_m} - C$$

Using $C = hB$, the equilibrium biomass, B_e , and equilibrium catch, C_e , is given by

$$B_e = \frac{B_m(r-h)}{r} \quad (5.5a)$$

$$C_e = hB_e \quad (5.5b)$$

Similarly, the expression for Pella and Tomlinson model may be given by

$$B_e = \{B_\infty (r - h)/r\}^{m-1} \quad (5.6a)$$

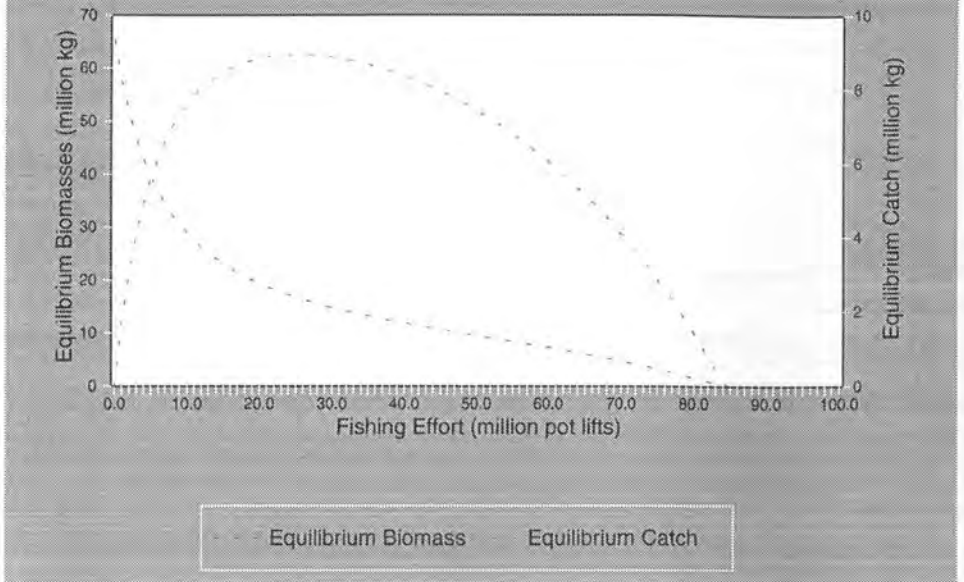
$$C_e = hB_e \quad (5.6b)$$

Given the values of all the parameters and the harvest rate, $h = 1 - \exp(-qE)$ the equilibrium biomass and yields can all be expressed as a function of effective fishing effort, E , i.e. $B_e = g(E)$ and $C_e = t(E)$.

5.4.2 EQUILIBRIUM BEHAVIOUR IN RELATION TO TIME LAGS

Using the estimates obtained in section 5.3, and plotting the predicted biomass equations 5.2a and the yield equations 5.2b against effective fishing effort, E , the delay-difference model with a Beverton-Holt recruitment relationship produces the equilibrium catch with fishing effort as in Figure 5.1. The estimated equilibrium virgin biomass ≈ 66.9 million kg, and the predicted maximum sustainable yield ≈ 8.8 million kg which corresponds to a biomass ≈ 18.0 million kg. However, the estimated optimum annual effective fishing effort of 22.6 million pot lifts is well beyond the current maximum levels of effective fishing effort.

Figure 5.1: Delay-Difference Model
(Beverton-Holt Recruitment)



However, fitting the Schaefer model and the Pella and Tomlinson model using the 1945/46 to 1990/91 seasons data (see section 4.3.2.2) gives the following estimates:

Schaefer Model: $q = 0.024$;
 $k = 68.687$;
 $r = 0.552$;

with $SSE = 1.121$.

Pella and Tomlinson Model:

$$q = 0.024;$$

$$k = 65.301;$$

$$r = 0.556;$$

$$m = 1.988;$$

with SSE = 1.118.

Using the estimates and plotting equations 5.5 and 5.6 against the effective fishing effort, E , results in Figure 5.2 and Figure 5.3.

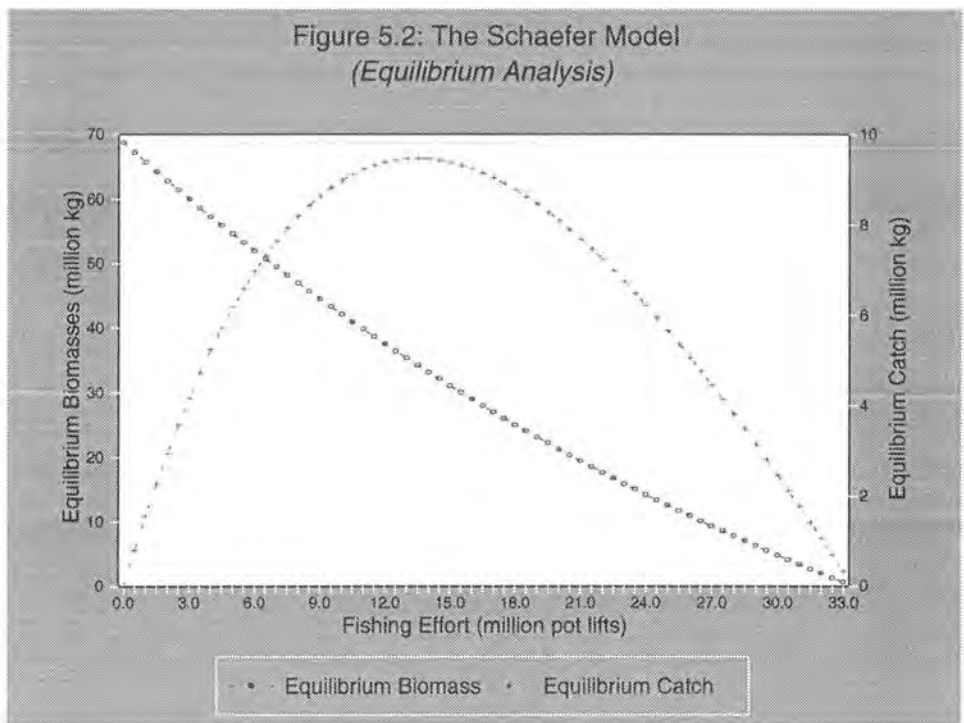


Figure 5.3: The Pella & Tomlinson Mode
(Equilibrium Analysis)

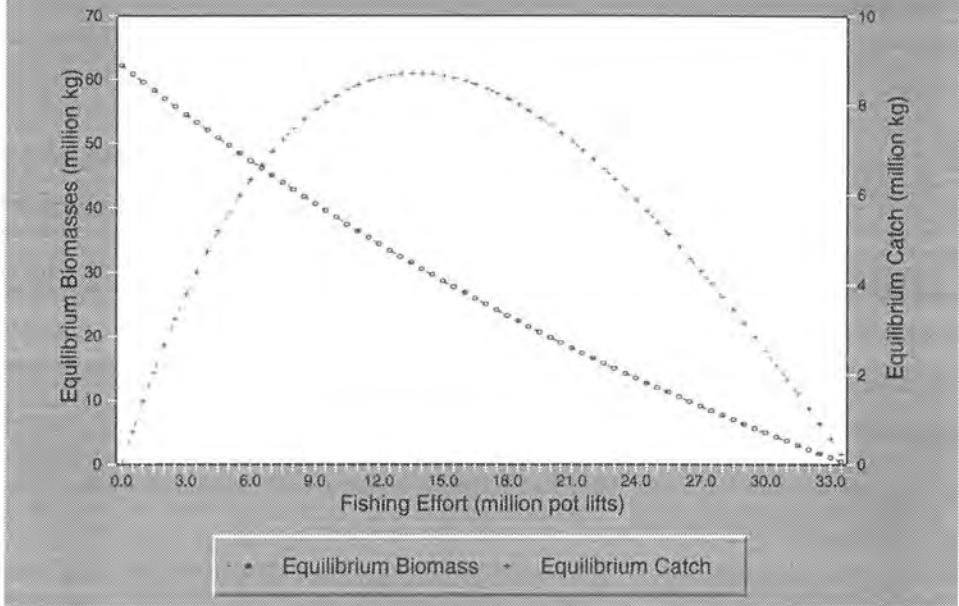


Table 5.2 summarises the results (MSY and E_{MSY}) of the simulations for the biomass dynamics models. In this paper the optimum fishing effort is taken as 13.5 million pot lifts.

Table 5.2: Summary of MSY and E_{MSY} of the biomass dynamics models

Model	MSY	E_{MSY}
Deriso-Schnute	8.80	22.60
Schaefer	9.48	13.50
Pella and Tomlinson	8.71	13.70

5.5 RISK ANALYSIS AND SIMULATION

Phillips (1986) noted that existing high level of effective fishing effort and a low level of puerulus settlement may cause the size of breeding stock to fall below the critical level which may lead to recruitment failure. To ensure the survival of this fishery, different hypothetical management strategies of effective fishing effort reduction which may reduce the biological risk to a more acceptable level are investigated. The evaluation of these strategies should be carried out after considering the other different and sometimes conflicting objectives of the management: economic, recreational and social. In this thesis, the relative frequency of catch for the year 1991/92 to 1995/96 exceeding the maximum sustainable yield is considered together with the biological risk for a better evaluation of the proposed management strategies.

Since achieving the maximum sustainable yield is one of the objectives, the proposed fishing effort for future years is set close to the optimum

fishing effort of 13.5 million pot lifts (see section 5.4.2). The following hypothetical scenarios for reducing effective fishing effort (Table 5.3) are used for the risk analysis.

Table 5.3. Fishing efforts (millions of pot lifts) for the 1991/92 to 1995/96 seasons.

Scenario Number	Fishing Season				
	1991/2	1992/3	1993/4	1994/5	1995/6
1	15.5	16.0	16.0	16.0	16.5
2	14.0	14.0	14.0	13.5	313.5
3	13.5	13.5	13.5	13.5	13.5
4	12.5	12.5	12.5	13.5	13.5
5	10.0	10.0	12.0	12.0	13.5
6	0.0	0.0	13.5	13.5	13.5

Following the work of Zheng and Walters (1988), the assumptions for the simulations are:

- due to the environmental effects, the recruitments are assumed to be log-normally distributed. If the average recruitment is represented by γ , the chosen variance has 0.5γ and 2γ as the 90% confidence intervals; and

- the parameter of catchability, q is assumed to be normally distributed with the estimated mean and variance.

The procedure for the simulation is as follows:

- (1) The biomass for the 1948/49 and 1949/50 seasons are assumed to correspond to B_1 and B_2 . Using the model, the fishery is simulated from B_1 and B_2 up to and including the 1990/91 season using the estimated parameters.
- (2) Simulations from the 1991/92 season up to and including the 1995/96 season are carried out with random catchability, random recruitment, and the suggested effective fishing efforts (see Table 5.3).
- (3) For each of the simulated biomass from the 1991/92 to 1995/96 seasons, the catch for each year is calculated using $1 - \exp(-qE)B_t$.
- (4) Steps 2 and 3 are then repeated 5000 times. The biological risk was calculated as the percentage of these 5000 runs when the biomass in any one of the seasons falls below 20% of the virgin biomass (please refer to Figure 5.4). For the purpose of evaluating the strategies, the biological risk (refer to Figure 5.5) and the relative frequency of the catch exceeding the maximum sustainable yield (assumed to be 9.0 million kg) (refer to Figure 5.6) for each season (1991/92 to 1995/96) are calculated.

Figure 5.4: Risk Analysis
(Deriso-Schnute Delay-Difference Model)

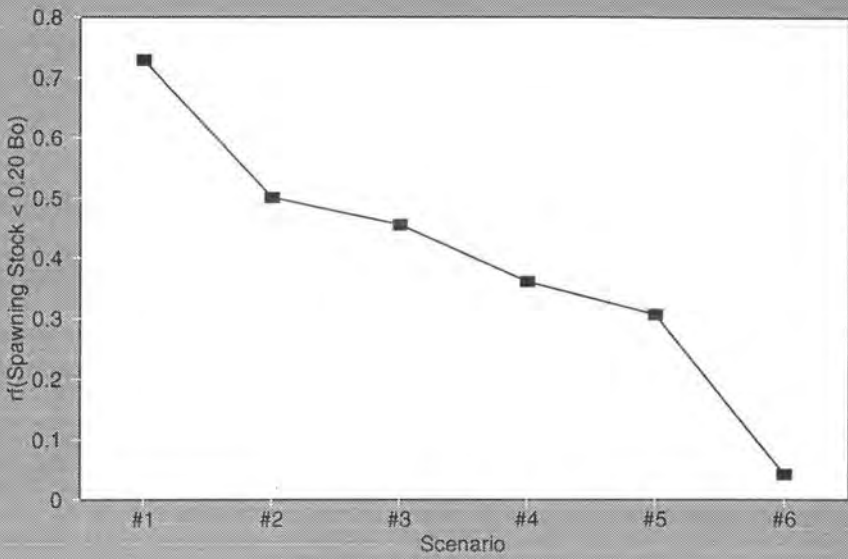


FIGURE 5.5: Risk Analysis
(Delay-Difference Model)

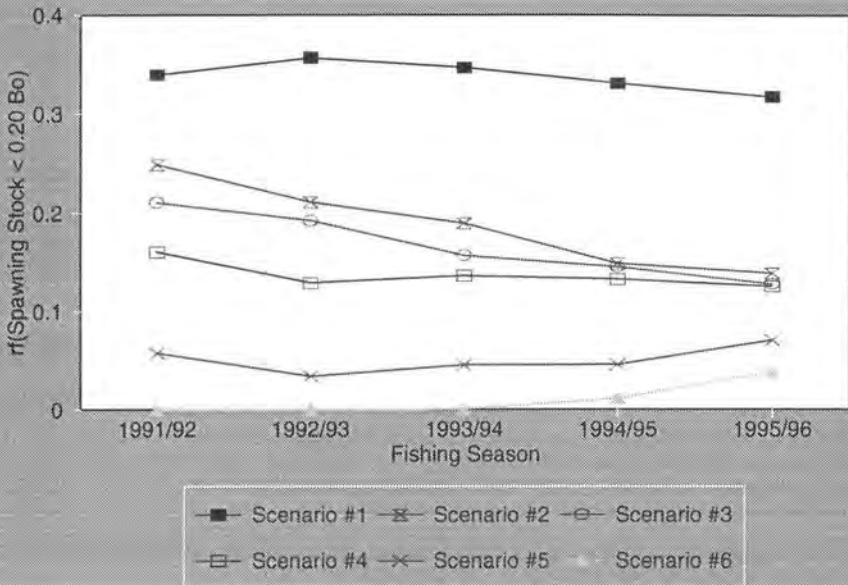
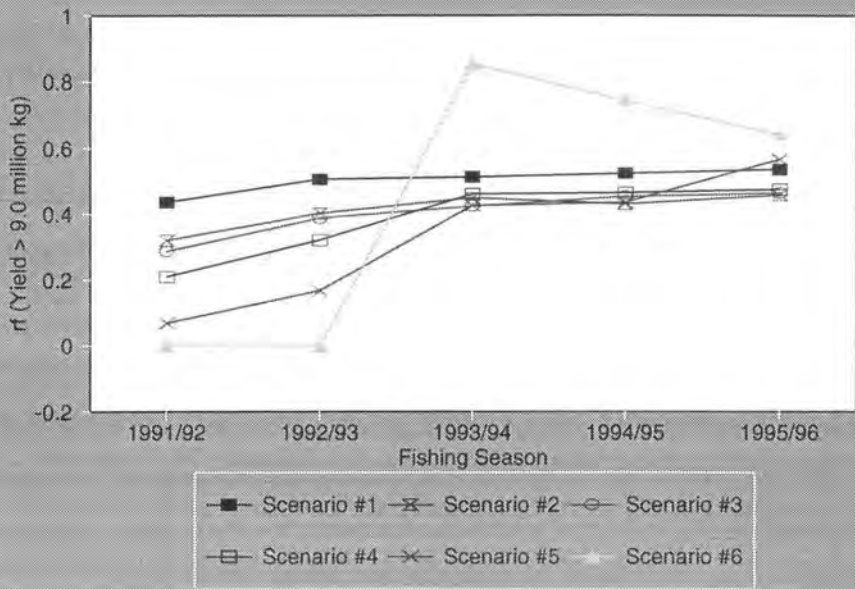


FIGURE 5.6: MSY Analysis
(Delay-Difference Model)



5.6 RESULTS AND DISCUSSION

The results are represented by Figure 5.4 and Figure 5.5 using the Deriso-Schnute delay-difference model which assumed a Beverton-Holt stock-recruitment relationship and existing life history parameters (W_k , W_{k-1} , p , M). Both figures illustrate how the risk of recruitment failure will change under different effort reduction strategies.

By assuming the effective fishing effort in the 1995/96 season ≈ 16.5 million pot lifts and using the simulation method described later in this section, the percentage of time the spawning stock biomass would fall below 20% of the virgin biomass is a staggering 73%.

As is evident from Figure 5.4, the risk of the spawning stock biomass falling below 20% of the virgin biomass within the next 5 years decreases sharply from 73% for all the proposed effort reduction strategies. Notice that scenario 5 and scenario 6 caused the risk of recruitment failure within the next 5 years to drop from 73% to 31% and 4% respectively. However, to achieve such a significant drop in the risk of recruitment failure requires drastic reduction in the fishing effort for the first two years as illustrated in Figure 5.6. Hence it is not practical to implement either scenario as it would have too great an effect on both the fishermen and the fishing industry.

Figure 5.5 suggests that if recruitment failure is going to happen within the next 5 years then it is likely to occur in 1991/92 and 1992/93 rather

than later. This suggests that scenario 3 and 4 which registered a much lower risk of recruitment failure for 1991/92 and 1992/93 are the preferred scenarios. Scenario 1 with higher fishing efforts displayed a fairly uniform high risk of recruitment failure.

From section 5.3, the model has been found to be rather insensitive to the assumed growth parameter, p , the natural mortality, M , the recruited weight, W_k , and the pre-recruit weight, W_{k-1} . However, the results and subsequently the above discussions on the effort reduction strategies must be treated with caution. It is very likely that all the risks to the fishery have not been included and the true risks to the fishery have not been taken into consideration. Lastly, the analysis is carried out under the assumption that the Deriso-Schnute delay-difference model accurately model the western rock lobster fishery.

APPENDIX A

TITLE 'Delay-Difference Model (Beverton-Holt Recruitment);
* Biomass at Year 1948 and 1949 taken as B1 and B2;

DM 'log; clear'; * Clear the log screen;
DM 'output; clear'; * Clear the output screen;
OPTIONS Pagesize=50 Linesize=78;

DATA Lobster;
INPUT Season Catch Effort Cpue;
IF Catch=. THEN Delete;

CARDS:

1944	0.2769	0.2400	1.15391
1945	0.5560	0.3800	1.46312
1946	0.9214	0.5700	1.61645
1947	1.0625	0.6800	1.56247
1948	2.4145	1.2200	1.97912
1949	3.0632	1.7800	1.72089
1950	3.3959	1.8600	1.82577
1951	4.1141	2.3200	1.77331
1952	3.6486	2.4600	1.48319
1953	4.4552	3.0000	1.48508
1954	5.2934	3.4300	1.54327
1955	5.0986	3.5900	1.42023
1956	5.2471	4.1100	1.27667
1957	6.4349	4.3300	1.48612
1958	8.4872	5.4000	1.57170
1959	9.1885	6.6300	1.38589
1960	8.2029	6.3100	1.29998
1961	8.9308	8.5100	1.04944
1962	10.0104	11.9519	0.83755
1963	8.9495	8.9072	1.00475
1964	8.2204	8.2761	0.99327
1965	8.9181	8.7316	1.02136
1966	9.7793	9.2599	1.05610
1967	11.1113	9.2973	1.19511
1968	9.1266	10.1195	0.90187
1969	7.7731	9.0216	0.86161
1970	8.9773	10.0392	0.89423
1971	9.1252	10.3675	0.88018

1972 7.6262 9.4779 0.80463
 1973 7.6463 10.3264 0.74047
 1974 9.3566 10.7577 0.86975
 1975 9.4742 10.8280 0.87498
 1976 9.5187 11.6695 0.81569
 1977 10.7071 11.5205 0.92939
 1978 12.1893 11.9330 1.02147
 1979 11.0896 11.9463 0.92829
 1980 10.3696 12.2859 0.84403
 1981 11.0939 12.8448 0.86369
 1982 12.9228 13.4285 0.96235
 1983 11.3828 13.1084 0.86836
 1984 9.6912 13.7300 0.70584
 1985 8.1662 13.0260 0.62692
 1986 8.5291 13.8720 0.61484
 1987 12.0661 16.0149 0.75343
 1988 12.3118 15.5942 0.78951
 1989 10.2985 15.5901 0.66058
 1990 9.2205 15.7897 0.58395

;

RUN;

PROC NLIN DATA=lobster METHOD=DUD;

PARMS q=0.01 TO 0.04 BY 0.01

Alpha=5 TO 30 BY 5

Beta=0.0 TO 1 BY 0.2;

BOUNDS Alpha > 0, Beta > 0, q > 0;

K = 0.565; * Brody's growth coefficient;
 p = exp(-K); * Ford's growth coefficient;
 w4 = 0.301; * Weight at age 4;
 w5 = 0.412; * Weight at age 5;
 m = 0.226; * Natural Mortality Rate;
 sigma = exp(-m); * Survival from natural mortality;

RETAIN B BLag1 BLag2 ELag1 ELag2;

* Get the lagged data;

ELag2 = lag2(effort); * Effort: 2 years ago;

ELag1 = lag(effort); * Effort: 1 year ago;

* It is different because of "RETAIN" statement;

BLag2 = lag(B); * Biomass: 2 years ago;

BLag1 = B; * Biomass: 1 year ago;

BLag4 = lag3(B); * Biomass: 4 years ago;

BLag5 = lag4(B); * Biomass: 5 years ago;

```

CLag4 = lag4(Catch);      * Catch: 4 years ago;
CLag5 = lag5(Catch);      * Catch: 5 years ago;

S = BLag4-CLag4;          * S(t-w)=S(t-4);
SLag1 = BLag5-CLag5;      * S(t-1-w)=S(t-5);

phi = EXP(-q*effort);     * Survival from Fishing;

if _obs_LT 7 then do;     * Observations from Yr 1944-1949;
  B = catch / (1 - phi); * used to determine Bo and B1;
end;                       * Actually Bo is from Yr 1948 while;
                           * B1 is from Yr 1949;

else do;
if _obs_LE 47 then
  t1=sigma*exp(-q*ELag1); * Survival from both Natural and;
  t2=sigma*exp(-q*ELag2); * Fishing Mortality;
  B = (1+p)*t1*BLag1
    - p*t1*t2*BLag2
    + w5*(alpha*S)/(Beta+S)
    - p*t1*w4*(alpha*SLag1)/(Beta+SLag1);
end;

* Use observations from year 1950/51 to year 1990/91;

if _obs_GT 47 then
  _obs_ = 1;              * Reset after each iteration;

if _obs_LT 7 then do;
  PCPUE = .;
end;
else do;
  PCPUE = q*B;
end;

MODEL CPUE=PCPUE;

OUTPUT OUT=LOBSTER2 P=CPUEHAT R=CRESID
PARMS=QFINAL PARMS=RCFINAL;
RUN;

```

APPENDIX B

Delay-Difference Model (Beverton-Holt Recruitment)
9:04 Thursday, January 6, 1994

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Non-Linear Least Squares Iterative Phase
Dependent Variable CPUE Method: DUD

Iter	Q	ALPHA	BETA	Sum of Squares
1	0.030478	26.672990	0.861836	0.526547
2	0.030461	26.691403	0.887015	0.526526
3	0.030568	26.633843	0.878111	0.526525
4	0.030538	26.654708	0.883763	0.526524
5	0.030482	26.693091	0.900162	0.526523
6	0.030478	26.696310	0.901740	0.526523
7	0.030478	26.697383	0.902784	0.526523

NOTE: Convergence criterion met.

Non-Linear Least Squares Summary Statistics Dependent Variable CPUE

Source	DF	Sum of Squares	Mean Square
Regression	3	47.718896407	15.906298802
Residual	38	0.526523238	0.013855875
Uncorrected Total	41	48.245419645	
(Corrected Total)	40	4.180486145	

Parameter	Estimate	Asymptotic Std. Error	Asymptotic 95 % Confidence Interval	
			Lower	Upper
Q	0.03047810	0.0088530056	0.012556215	0.048399977
ALPHA	26.69738312	6.0872431797	14.374466582	39.020299654
BETA	0.90278409	2.4758125880	-4.109210830	5.914779005

Asymptotic Correlation Matrix

Corr	Q	ALPHA	BETA
Q	1	-0.9758253	-0.840265941
ALPHA	-0.9758253	1	0.9301613981
BETA	-0.840265941	0.9301613981	1

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