A COMPUTER SIMULATION OF THE POPULATION DYNAMICS OF THE CAPE HAKES (*MERLUCCIUS CAPENSIS* AND *M. PARADOXUS*)

by

R. G. MERTENS

Sea Fisheries Branch and Zoology Department
University of Cape Town

Supervisors: Dr. J.G. Field (U.C.T.)
Dr. G.G. Newman (S.F.B.)

Thesis submitted for the Degree of Master of Science
at the University of Cape Town

December 1978

CONTENTS

ABSTRACT

Catch and effort statistics for the Cape hakes (*Merluccius capensis* and *M. paradoxus*) have indicated a substantial decrease in the stock size over the period 1955-74; consequently, a catch projection model was designed to investigate the hake population. Where appropriate, available data have been included in the model; however, some further research was required: 1. The monthly pattern of availability for 1974-76 was examined using South African data; it was found to be similar to that reported for earlier years, and the later figures were used. 2. Assuming that selection curves for different mesh sizes are identical except for their position on the X-axis, a method to calculate selection values for combinations of mesh size and fish length has been outlined, and used with data presented by Bohl *et al*. (1971). 3. An investigation was made of two methods of estimating natural mortality (M), utilizing the results of Virtual Population Analysis (V.P.A.). In both cases the criteria used to judge M were found to be insensitive, and therefore neither can be used. 4. The stock estimates obtained using V.P.A. were applied to two stock/recruit curves. The goodness of fit in both cases was poor, and nearly identical.

Initial runs of the catch projection model over the period 1964-74 drastically overestimated the catch of the younger age groups. This was probably due to no

allowance being made for discarded juvenile fish; when this was done, there was good agreement between observed and predicted catch.

The development of the model has underlined the need for further research to be made on natural mortality, stock/recruit relationships, and discard patterns. It has also stressed the need to examine age-related fishing patterns.

LIST OF TABLES AND FIGURES

1. INTRODUCTION

The hake stock off the Cape of Good Hope fishing ground (International Commission For Southeast Atlantic Fisheries, ICSEAF, Division 1.6), comprises two species, Merluccius capensis and M. paradoxus. They may be distinguished by their otolith morphology and gillraker colouration (van Eck, 1969). As there is no difference in their commercial value, no distinction is made between the two by the factories or skippers. Consequently most of the data available are for both species combined.

The hake fishery has been active since the beginning of the century. Apart from a few surveys prior to the Second World War, very little research was done until the 1960's, during which time foreign fishing increased considerably.

Hake data are collated and research planned at annual ICSEAF conferences. Two main types of data are presented to ICSEAF; these are data required from all countries (e.g. annual catch and effort statistics), and data provided from independent research in the member countries. This information and the studies which are briefly discussed below have facilitated some stock assessment research.

South African catch and effort statistics have been used by several authors, e.g. Roux (1949), Jones and van Eck (1967) to examine availability and changes in abundance.

A causal relationship between migration (using Botha's (1973) data) and availability will be discussed in Section 4.1.

Estimates of selection factors are essential for the calculation of stock size and prediction of catch. Consequently a series of experimental trawls was made by a joint German/South African team to obtain length/selection curves for different mesh sizes (Bohl _et al._, 1971).

Growth parameters for the Cape hakes have been investigated by several authors: Botha (1970, 1971), Elwertowski and Piotrowski (1975), Kolender (1975) and Draganik (1976b). From these, length-at-age may be calculated, and a selection factor may be obtained from the appropriate length/selection curve.

Since 1955 the catch has doubled while the effort has increased more than seven times (Table 1.1), which indicates a substantial decrease in the stock size. It is important, therefore, to examine these changes, to monitor, and if possible predict the long and short term effects of different fishing strategies. Various stock predictions have been made by fisheries biologists for ICSEAF, using equilibrium yield models: Newman _et al._ (1976), Draganik (1976b). However these models predict only the equilibrium catch (the catch of a cohort assuming a constant level of fishing mortality). There is a need for a catch projection

Years	Total catch	Total effort	c.p.u.e.
1940-47	26	1,831	14,20
1955	83	6,667	12,45
1956	85	7,556	11,25
1957	91	7,679	11,85
1958	94	8,034	11,70
1959	105	8,889	11,70
1960	115	9,237	12,45
1961	107	12,229	8,70
1962	107	10,490	10,20
1963	127	12,637	10,05
1964	123	11,714	10,50
1965	168	21,538	7,80
1966	156	20,392	7,65
1967	146	20,278	7,20
1968	109	15,139	7,20
1969	135	21,774	6,20
1970	124	23,846	5,20
1971	189	37,059	5,10
1972	195	48,750	4,00
1973	178	49,444	3,60
Mean for 1965-1969	143	19,824	7,21

Table 1.1 South African catch and effort data for the Cape hakes combined, off the Cape of Good Hope. (Newman *et al.*, 1976) (Catch: thousands of metric tons, Effort: standard trawler days.)

model which will predict yearly catches made under disequilibrium conditions. This will give management a guide on which to base its decisions. It must be emphasised that a model can be used only to indicate trends that may occur if the logic and parameters on which the model is based remain valid, and if the parameters (random and non-random), which cannot be included in the model, do not materially affect stock size and catch.

2. MODELS USED IN FISHERIES MANAGEMENT

The ultimate goal of fisheries management is to be able to predict stock size and yield of a fishery for particular levels of effort, under different management strategies, such as minimum mesh sizes or catch quotas. The long and short term effects must be predicted to allow the most efficient fishing strategy to be designed, which will invoke optimization procedures and prevent overfishing.

2.1 Equilibrium yield models

Generally the yield from a cohort is considered over a range of constant fishing mortalities. There are two types of equilibrium yield model, which are discussed below. In both cases the maximum sustainable yield is achieved at an intermediate level of effort.

2.1.1 Equilibrium yield can be calculated from a function which incorporates growth, mortality, and selection parameters. Ricker (1975) described three general types. In the first, Thompson and Bell (1934) compute mean abundance and weight per fish, which gives the available biomass. Estimates of the percentage stock mortality due to fishing (F), and natural mortality (M) are made, which allow the calculation of biomass harvested by fishing, and that lost naturally. Ricker (1975) has modified Thompson and Bell's method in that the biomass fished is calculated for each individual age and summed either arithmetically or geometrically depending on whether the change in stock weight is arithmetic or geometric.

The second equilibrium yield model described was developed by Baranov, who gives an expression for equilibrium yield using an average increase in length for each age. The weight is assumed to be proportional to the length cubed. The third model by Beverton and Holt (1957) improved upon the previous method by using the Brody-Bertalanffy growth relationship, which is more widely applicable than Baranov's method. Equilibrium yield models all calculate biomass fished over the life of a cohort, assuming values of natural and fishing mortality after recruitment to the fishery.

2.1.2 Stock production models relate yield directly to stock abundance or effort. Each describes a curve, usually parabolic, which implies that the maximum sustainable yield occurs at an intermediate level of abundance. Ricker (1975) discusses the validity of these models.

Schaefer (1954) developed a stock production model which gives maximum yield when the stock is exactly half its maximum size. Pella and Tomlinson (1969) improved upon Schaefer's method by using a modified Chapman-Richards curve which allows for possible skewness of the parabola.

Catch per unit effort (c.p.u.e.) on effort, developed by Gulland (1961) derives a relationship between c.p.u.e.

and the effort in several preceding years. Similarly the Gulland-Fox exponential model (Fox, 1970) derives a relationship between c.p.u.e. in numbers and the effort in several preceding years.

All stock production models are essentially the same, i.e. they represent change in yield associated with change in stock size or effort.

A number of models have been used to assess hake in ICSEAF Division 1.6. Draganik (1976b) employed the Beverton and Holt (1957) method to assess the effects of different mesh sizes on equilibrium yield. He concluded that an increase in mesh size from 75 mm to 110 mm would, on average, increase the yield by 45%.

Newman _et_ _al_. (1976) used three different models to investigate equilibrium yield: Pella and Tomlinson's (1969) stock production model, catch per unit effort on effort, and Thompson and Bell's (1934) model (yield per recruit analysis). All these methods indicate that a maximum sustainable yield of around 140 000 metric tons could be obtained, although the estimation of effort required differs - 10 000 units in the yield per recruit analysis, and about 20 000 units in the other two methods.

2.2 Catch projection models

The concepts underlying projection models are not new.

Usually the Beverton and Holt (1957) catch equation is used (equation 6.1). The manner in which the parameters in this equation are calculated varies according to the types of data available. Models tend to be designed for specific fisheries, e.g. Pope (1973) for the North Atlantic cod fishery, although several general ones have been written, e.g. Walters (1969).

The catch projection model developed in this thesis is specific to the Cape hakes; however it has been designed to allow easy modification of the various parameters used, and may therefore be applicable to other fish stocks.

It predicts the yearly catch under dis-equilibrium conditions. The effort and mesh size can be varied for each year. If effort and recruitment were held constant, the predicted catch curve would reach equilibrium when all ages of fish in the population had been fished with the same effort. If recruitment is dependent upon stock size, then the catch curve will be dictated by the stock/recruit curve used. An equilibrium catch will not necessarily be reached after only one generation.

3. CAPE HAKE DATA

3.1 Catch and effort statistics

South African catch and effort data are available from 1955 (Table 1.1); however, comprehensive figures for all countries are available from ICSEAF only for the years 1964-74. Newman *et al*. (1976) and Draganik (1976b) have derived catch-at-age values from the ICSEAF data. As Draganik's data include the year 1974 and Newman's do not, the former are used to calculate stock size, and are employed in the catch projection model.

3.2 Age estimates

In order to facilitate estimations of the stock size, the catch is converted into numbers caught at each age. This is achieved by means of length-frequency tables, length-at-age, and weight-at-age calculations.

Age is estimated from the state of the otoliths. Each otolith has a concentric pattern; each ring comprises a hyaline and an opaque band, which are thought to correspond to one year of growth. Botha (1971) describes the methods used to store and read Cape hake otoliths. There is some confusion concerning the standard manner of reading them (Elwertowski and Piotrowski, 1975). It is therefore important that the techniques of interpreting otoliths be standardized. They are read without reference to the fish, ensuring that age estimates are not biased by prior knowledge. The ages are then linked to the length of the hake from which the otolith was extracted, and the length-frequency distribution obtained is converted to an age-frequency distribution.

Where possible each participating country submits catch statistics to ICSEAF. If age composition or catch are not available then an estimate is made, based on the figures from the other countries.

3.3 Length-at-age calculations

The von Bertalanffy (1938) growth curve (equation 3.1) describes the growth of most types of fish. Values of its parameters for Cape hakes have been calculated by several authors: Elwertowski and Piotrowski (1975), Botha (1970, 1971) and Draganik (1976b).

$$L_t = L_\infty(1-e^{-K(t-t_o)}) \quad .... \text{ equation } 3.1$$

L_t = length at age t

L_∞ = maximum theoretical length which the fish can attain

K = coefficient of catabolism

t = age

t_o = time at which the fish would have been zero length

e = 2,71828

The values of the parameters obtained by various authors are presented in Table 1. of Elwertowski and Piotrowski (1975). These parameters differ considerably. This is probably due to differences in the interpretation of otoliths, and in the samples used to provide data to solve the growth equation. Probably for this reason, when catch projections (based on stock sizes obtained from Draganik's (1976a) catch data) were made using the different sets of parameters, Draganik's (1976b) parameters gave the best agreement between observed and predicted catch-at-age. These were consequently used in the model.

3.4 Length-weight relationships

Measurements of fish length and corresponding weight are taken and used to solve equation 3.2.

$$W = a.L^b \qquad \text{.......... equation 3.2}$$

W = weight in grammes

L = length of fish in centimetres

a and b are constants

The constants a and b can be found by the method of least squares. Values of a and b have been estimated by Newman (1974) and Draganik (1976b) using combined data for both species of Cape hake. Their results are almost identical and are used in the catch projection model. Kolender (1975) obtained similar values for *M. paradoxus*, but not for *M. capensis*, which is a less heavy species. His results could be used if the model were modified to simulate each species separately.

4. AVAILABILITY AND SELECTION

The availability of the hake at the time of trawling, and the selection due to mesh size, influence the size and composition of the catch. These two parameters are used in the catch projection model to calculate fishing mortality:

$$F = q.s.f.a \qquad \text{.......... equation 4.1}$$

q = catchability coefficient
s = selection
f = effort
a = availability

4.1 Availability

Average annual c.p.u.e. can be regarded as a measure of the stock size if the catch does not substantially reduce the stock during the period of one year. Catch and effort statistics are available on a monthly basis over the years 1974-76 from the various factories in the Cape. The catch figures are expressed in kilogrammes landed weight, i.e. beheaded. These have been changed to kilogrammes whole weight by using a factor of 1,46 (Chalmers, 1976). This conversion is standard for all hake catches.

The effort statistics are available in two forms:

1. Trawler hours, a measure of the time during which the trawl nets are down. 2. Trawler days, the number of days a trawler spends on a fishing ground. The latter takes no account of the number of trawls made per day or whether night trawling occurred. For this reason, trawler hours were used for the computation of c.p.u.e.. The figures for trawler hours had to be weighted to take account of the power of the trawlers. The factors used are: 2,00 for freezer-trawlers; 1,14 for wetfish-trawlers; and 0,53 for small vessels (Dalsen, pers. comm.).

Table 4.1 contains the corrected catch, effort, and c.p.u.e. for the years 1974-76. The availability is also presented for all years combined. It was obtained by dividing the monthly c.p.u.e. by the largest c.p.u.e.. Figure 4.1 is a graph of the monthly c.p.u.e. against time, for the years 1974-76, and their mean. There is one clearly defined peak, occurring in May-June. Roux (1949) has shown that for the years 1940-47 there were two peaks - one in May and a smaller one in December - and two minimum levels - September and January.

He suggested that these peaks might be due to a migration across the fishing grounds; inshore in spring and summer, offshore during autumn and winter. This hypothesis has been refuted by Botha (1973) who examined the distribution, migration and spawning behaviour of

	Catch	Effort	c.p.u.e.	Availability
1974				
Jan	1375553,60	2690,02	511,35	
Feb	978090,50	2921,21	334,82	
Mar	1166033,33	2217,44	525,85	
Apr	1597321,76	2751,97	580,43	
May	2022359,88	2760,94	732,49	
June	1741879,28	2253,97	772,80	
July	1812664,46	3570,12	507,73	
Aug	836620,88	1729,01	483,87	
Sep	945507,68	2081,90	454,16	
Oct	731400,14	1595,52	458,41	
Nov	384857,46	937,48	410,52	
Dec	531856,10	1235,93	430,33	
1975				
Jan	110884,08	203,77	544,16	
Feb	826720,62	1817,44	454,88	
Mar	1496451,82	2768,21	540,58	
Apr	1818876,76	3856,97	471,58	
May	2828139,72	5385,89	525,10	
June	4648348,00	7920,70	586,86	
July	2998619,54	6395,22	468,88	
Aug	2493262,44	6121,03	407,33	
Sep	2450839,22	6500,52	377,02	
Oct	2197158,38	5043,05	435,68	
Nov	2226416,78	4707,59	472,94	
Dec	2122089,56	6294,00	337,16	
1976				
Jan	2415482,40	5488,91	440,07	
Feb	2809279,44	6232,21	450,77	
Mar	3392981,60	7039,57	481,99	
Apr	3687711,80	6565,13	561,71	
May	7334026,76	10728,26	683,62	
June	5083800,30	8932,92	569,11	
July	5884419,04	10484,71	561,24	
Aug	4867974,34	8886,64	547,79	
Sep	4048622,28	7075,95	572,17	
Oct	2849830,94	5843,50	487,69	
Nov	3212423,40	5729,96	560,64	
Dec	3174356,82	6816,46	465,69	
Total				
Jan	3901920,08	8382,70	465,47	0,72
Feb	4614090,56	10970,86	420,58	0,65
Mar	6055466,80	12025,22	503,56	0,78
Apr	7103910,32	13174,07	539,23	0,84
May	12184526,36	18875,09	645,53	1,00
June	11474027,58	19107,59	600,50	0,93
July	10695703,04	20450,05	523,02	0,81
Aug	8197857,66	16736,68	489,81	0,76
Sep	7444969,18	15658,37	475,46	0,74
Oct	5778389,46	12482,07	462,94	0,72
Nov	5823697,64	11375,03	511,97	0,79
Dec	5828302,48	14346,39	406,26	0,63

Table 4.1 Catch and effort statistics for the years 1974-76.

The catch is in kilogrammes, the effort is in standard trawler hours.

Basic data from the South African Sea Fisheries Branch.

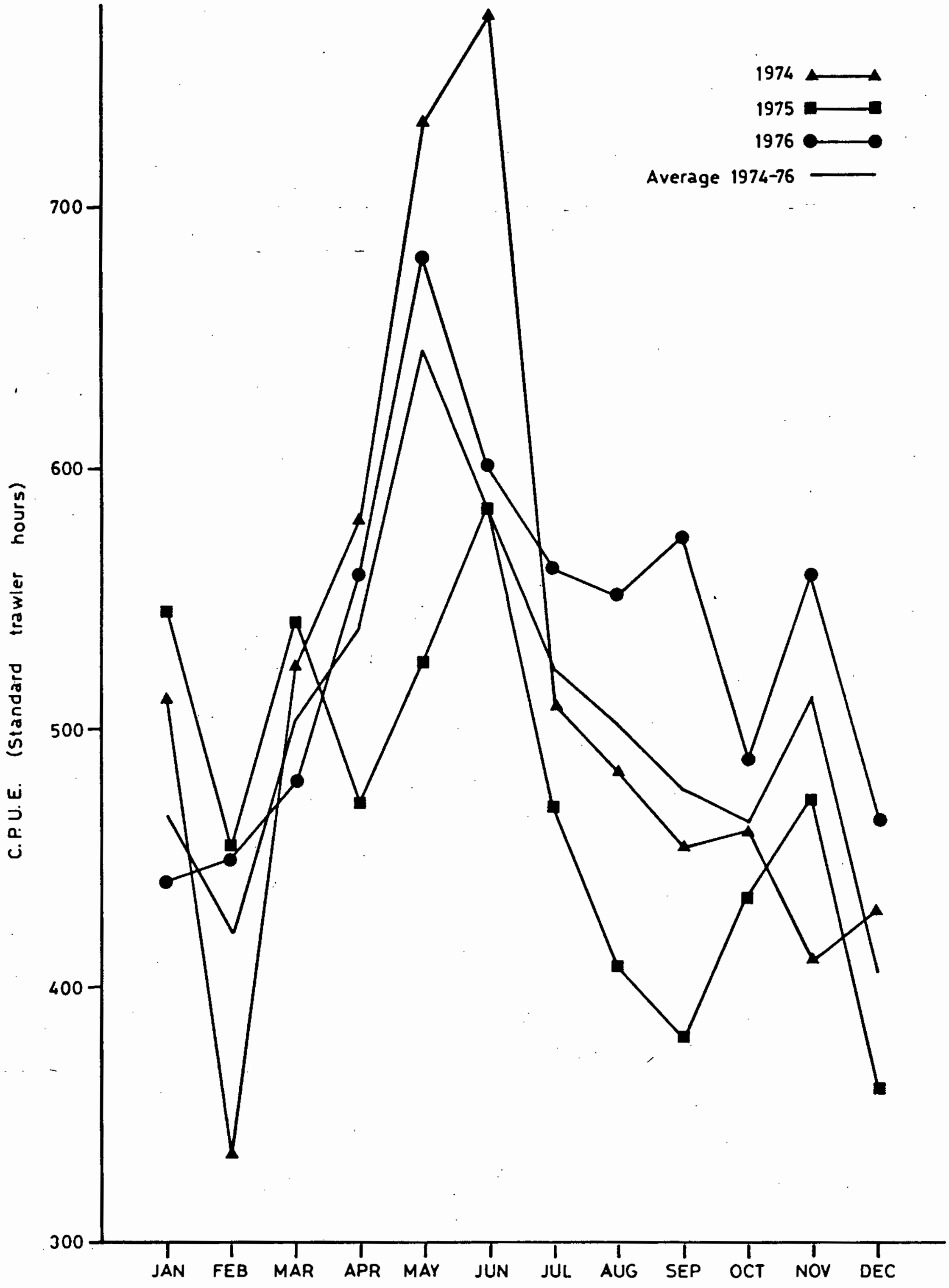

Figure 4.1 - Monthly c.p.u.e. of the Cape hakes for the years 1974-76.

the Cape hakes.

The two species vary in depth distribution, Merluccius capensis being a shallow water form, the optimum depth being between 145 and 440 metres, and M. paradoxus inhabiting fishing grounds of a depth between 220 and 640 metres (Botha, 1973).

Botha (1973) presents length frequency data for the Cape hakes sampled at six stations, situated at different depths. These data clearly show an increase in length with depth. By comparing length-frequency distributions during July and October (1972), Botha has shown that there is no seasonal inshore migration.

As hake are caught by bottom trawlers, the complete absence of actively spawning fish in either research or commercial trawls led Botha (1973) to conclude that the Cape hakes spawn in midwaters. The main spawning period is August-September which corresponds to a low level of c.p.u.e. and therefore availability. It is logical to conclude that availability is partially governed by behavioural patterns due to spawning.

The vertical migration pattern displayed by the Cape hakes is accommodated in the simulation model by using the monthly availability figures presented in Table 4.1. No account can be taken of the horizontal migration, consequently trawling is assumed to occur equally over all age groups.

4.2 Selection

The fish caught in a trawl net will in part be determined by the size of the mesh and by the size of the fish. Mesh selectivity experiments (the covered cod-end technique), have been conducted on the Cape hakes (Bohl et al., 1971). Using two research vessels, trawls were made with nets of five different mesh sizes (111,1 mm, 117,0 mm, 117,4 mm, 125,0 mm and 128,7 mm).

From the data collected, a graph of percentage retention against fish length was plotted for each of the five mesh sizes (Figure 4.2). The lowest percentage retained for even small size classes varies between 20% and 50%; this is due to the experimental technique. Thus for each selection curve a cutoff point was found, where there is no decrease in percentage retention for a decrease in fish length.

The data originally used by Bohl et al. (1971) in the construction of the selection curves are no longer obtainable. Hence the data points were read from the curves and then fitted by the method of least squares to two selection equations using the Biomedical Program package (described in Section 7). The two equations used were:

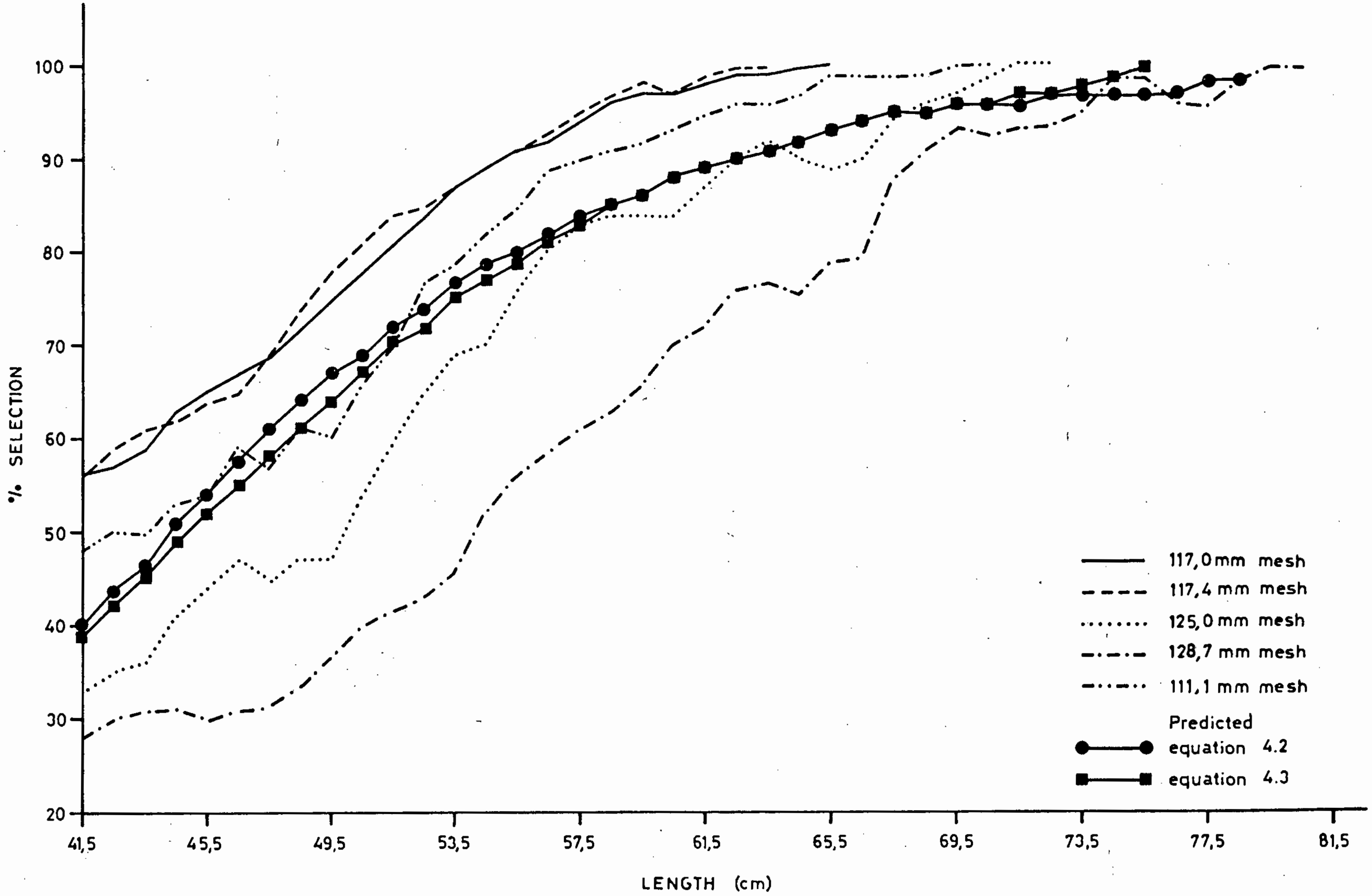

Figure 4.2 - Graph of the observed selection data for different mesh sizes, and their average predicted values against fish length. Observed data from Bohl et al. (1971). Predicted data from equations 4.2 and 4.3.

$Y = 100/(1+e^{(a-b.L)})$ .... equation 4.2

Y = percentage retention

L = length

a and b are two constants

from Draganik (1976b)

$Y = 100/(1+(K/L)^n)$ .... equation 4.3

K and n are two constants

(Jackson, pers. comm.)

The results obtained from these two equations are presented in Table 4.2. Both equations fit the data well, but in all cases better correlation, and a lower residual sum of squares are obtained using equation 4.2. It was therefore used in the catch projection model.

It was not until mid-1975 that a minimum mesh size of 110 mm was introduced by ICSEAF. The mesh sizes used prior to this differed from country to country; South African vessels used 102 mm mesh nets.

A method was therefore required which could use the selection data from Bohl et al. (1971) to calculate the percentage retention for any combination of fish length and mesh size. The method adopted assumes that the selection curves for the different mesh sizes are

Equation 4.2 $Y = 100/(1+e^{(a-b.L)})$

Mesh size mm	a	b	RSS	R	R^2
111,1	6,35	0,14	354,83	0,98	0,97
117,0	5,07	0,13	340,72	0,98	0,97
117,4	6,09	0,15	221,56	0,99	0,97
125,0	6,15	0,13	472,16	0,99	0,98
128,7	5,99	0,11	1216,77	0,98	0,96
Mean 119,84	5,69	0,13	22636,55	0,87	0,75

Equation 4.3 $Y = 100/(1+(K/L)^n)$

Mesh size mm	K	n	RSS	R	R^2
111,1	43,28	6,70	603,54	0,98	0,95
117,0	39,60	5,98	551,49	0,97	0,94
117,4	40,19	6,72	377,92	0,98	0,96
125,0	45,38	5,86	1288,79	0,98	0,96
128,7	49,34	5,25	3313,96	0,96	0,92
Mean 119,84	44,25	6,23	23772,83	0,86	0,74

Table 4.2 Parameters and statistics calculated using the Biomedical program package, for two selection curves and five different mesh sizes, and their means. Mean values obtained from all data combined. a, b, K, n are constants.

RSS = residual sum of squares

R = correlation coefficient

R^2 = coefficient of determination

identical, except for their positions with respect to the X-axis (Figure 4.2).

An average selection curve was obtained for all the selection data. The 50% retention length was found for each of the selection curves, and regressed against mesh size (Figure 4.3). From the regression, the 50% retention length can be found for any mesh size. To calculate the percentage retention for a given length and mesh size, a modified length is obtained from equation 4.4 and substituted in the average selection curve.

$$L_m = L_g + ({}_{50}L_a - {}_{50}L_c) \quad \text{.......... equation 4.4}$$

L_m = modified length

L_g = given length

${}_{50}L_a$ = 50% retention length for the average selection curve

${}_{50}L_c$ = 50% retention length for the average mesh size under consideration

This has the effect of shifting the average selection curve along the X-axis for each particular mesh size.

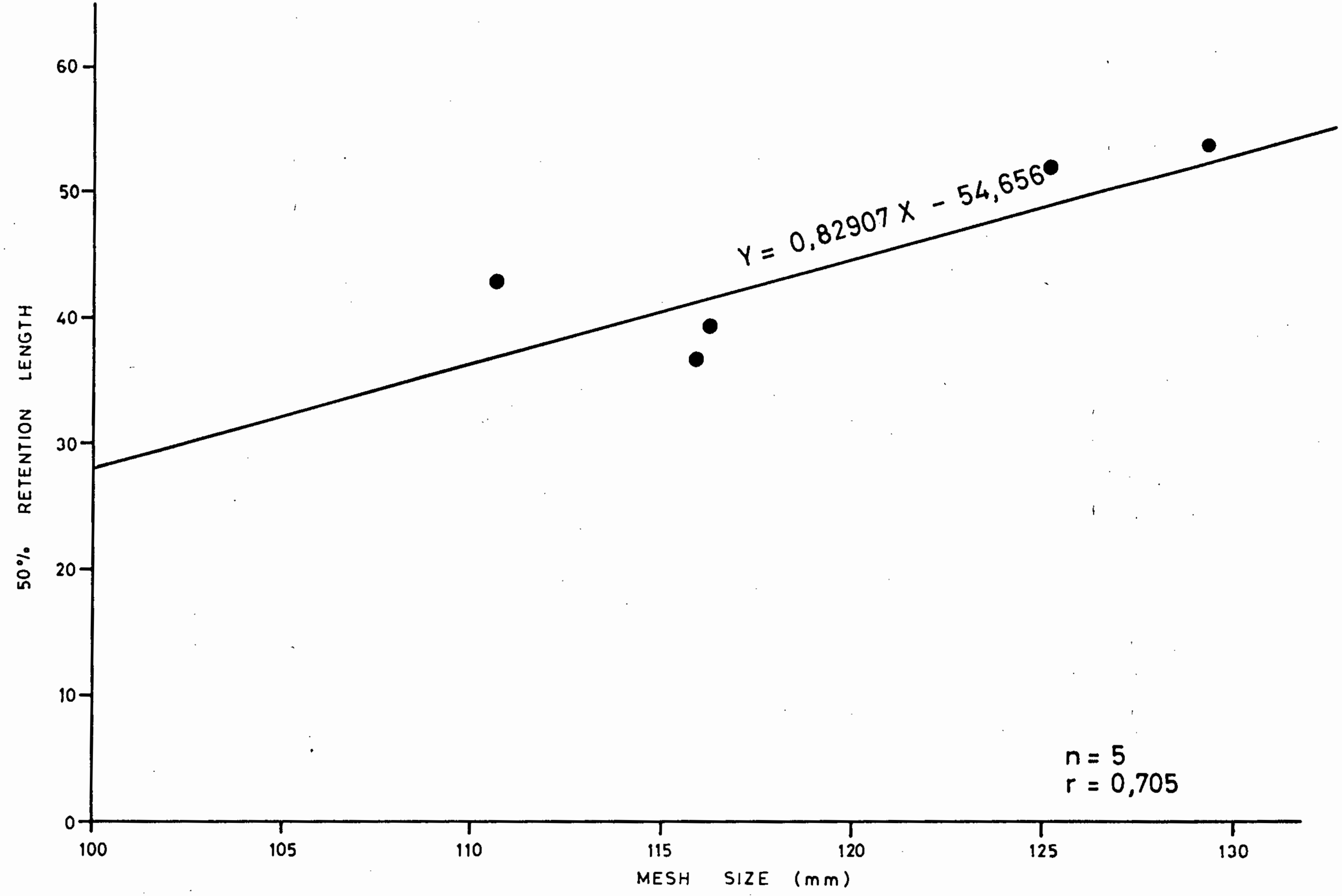

Figure 4.3 - Graph of the 50% retention lengths of the Cape hakes against mesh size.
Data from Bohl _et_ _al_. (1971).

5. NATURAL MORTALITY

Knowledge of the instantaneous coefficient of natural mortality (M) is essential in the calculation of stock size. Under- or over-estimation of M has a direct effect on the calculated stock size. It is a difficult parameter to compute. The age composition of an unfished population of the Cape hakes is not known, and tagging is impracticable, due to the poor condition of hake on arrival at the surface. Hence, values of M and fishing mortality (F) are obtained from catch and effort statistics. The methods employed to furnish these statistics have been described in Section 3.1.

5.1 Review of methods used to estimate M

Ricker (1975) details four methods (with worked examples) by which M may be calculated from catch and fishing effort in successive years:

5.1.1 Silliman's method requires data from two different periods in the fishery, where different constant levels of effort have prevailed. For each period, catch curves (semi-logarithmic plots of frequency against age) are made and total mortality (Z) (assumed to be the value of the slope of the catch curve) found. The proportion of the two fishing mortalities (assumed to be equal to the proportion of respective efforts over the same periods) is used to obtain M in terms of the two known values, F and Z.

5.1.2 Comparison of adjacent years differs from Silliman's method in the calculations of Z. This is obtained directly from the survival rate (S), which is equated to the proportion of the catch of the same cohorts during two consecutive years of constant effort.

5.1.3 Beverton and Holt's method is an extension of the previous one. It is used when effort varies continuously. It is valid if the following assumptions hold true: catch per unit effort (c.p.u.e.) is proportional to the mean population size, M is constant, and the catchability coefficient (q) does not vary with age after recruitment. The ratios of the c.p.u.e. of the same cohorts in two successive years provide an estimate of Z over a series of years. These are plotted as a linear function of effort, and M and q are respectively the intercept and the slope of the resultant line.

5.1.4 Paloheimo's method is a simplification of the previous method. The average total mortality (Z) is calculated from the ratio of the c.p.u.e.'s in two successive years and their corresponding efforts. This is repeated as many times as possible, and the resulting average total mortality in each year is regressed against the average effort during that year. The Y-axis intercept gives the total mortality for zero effort, which is natural mortality.

5.2 Estimates of Cape hake natural mortality

Wysokinski (1977) calculated the natural mortality of the Cape hakes in several ways: he used Silliman's method with catch and effort data extracted from Newman *et al.* (1976); two periods were regarded as each having constant effort: 1960-64, and 1965-70. The value of M calculated was 0,31.

The simplified Gulland method was also employed. This method is merely indicative of the range over which M may extend: $2K \leqq M \leqq 3K$

K = coefficient of catabolism

K is a parameter used in the von Bertalanffy growth equation, described in Botha (1971). It has been calculated by several authors. Wysokinski uses the value of K obtained when L_∞ (maximum attainable length) agrees best with actual measurements. His ranges for M are 0,26 - 0,39 for *M. capensis* and 0,28 - 0,42 for *M. paradoxus*.

Wysokinski also constructed catch curves for each of the year classes recruited during 1959-68, and from these he obtained a series of values for Z. A mean fishing mortality (F) was also calculated for each year class (over several years) and F was regressed against Z. M was read from the Y-axis intercept, and found to be 0,42. His calculations gave an unrealistically high total mortality for the year class of 1959. When this class was omitted he arrived at a lower mean value (M = 0,26).

Both Wysokinski (1977) and Draganik (1974) used the Paloheimo method. Draganik used his own data and obtained a value of M = 0,24 by extrapolating (by hand) a plot of Z against fishing effort (f). Using a regression analysis, Draganik calculated that M = 0,5 a value he considered too high. Using Newman's (1976) data, Wysokinski found M = 0,33.

From these different calculations, it appears that M lies between 0,2 and 0,4. The wide variation in results makes it impossible to judge accurately which is the most realistic.

6. VARIATION OF NATURAL MORTALITY WITH AGE

Natural mortality is unlikely to remain constant throughout the lifespan of most fish, including hake. Recognising that natural mortality can drastically affect estimates of stock size, a computer programme was developed to investigate natural mortality at each age. Virtual Population Analysis (V.P.A.), which was developed by Gulland (1965), is central to this investigation. In essence, it uses the Beverton and Holt (1957) catch equation (equation 6.1) in reverse, to calculate population-at-age and fishing mortality-at-age for a cohort.

$$ {}_xC_n = \frac{{}_xF_n \cdot {}_xN_n \cdot (1-e^{-{}_xZ_n})}{{}_xZ_n} \quad \text{..... equation 6.1} $$

$_xC_n$ = the number of fish of year class x caught of age n

$_xF_n$ = the fishing mortality on fish of year class x of age n

$_xN_n$ = the number of fish of year class x of age n

$_xZ_n$ = the total mortality on fish of year class x of age n

$= M_n + {}_xF_n$

M_n = natural mortality on fish of age n

The catch at age n ($_xC_n$) can be calculated as described by Newman <u>et al</u>. (1976). Estimates of the natural mortality at age n, and an initial estimate of fishing mortality for the oldest age group (terminal F) are required. From these, the population in numbers of age n (${}_xN_n$) can be calculated. The relationship between ${}_xN_{n+1}$ and ${}_xN_n$ is:

$$ {}_xN_{n+1} = {}_xN_n \cdot e^{-{}_xZ_n} \quad \text{.......... equation 6.2} $$

Substituting equation 6.2 in equation 6.1, we get:

$$ {}_xC_n = \frac{{}_xF_n}{{}_xZ_n} \cdot \frac{{}_xN_{n+1}}{e^{-{}_xZ_n}} \cdot (1-e^{-{}_xZ_n}) \quad \text{.... equation 6.3} $$

By substituting the population calculated (${}_xN_{n+1}$) and the known catch (${}_xC_n$) in equation 6.3, the fishing mortality (${}_xF_n$) may be found by iteration. The procedure is then repeated for the remaining age groups in the cohort. Centurier-Harris (1977) gives a more detailed description of V.P.A..

Fishing mortality is believed to be directly proportional to the effort expended (Newman *et al.*, 1976).

$$ F = q.f \quad \text{.......... equation 6.4} $$

F = fishing mortality

q = catchability coefficient

f = effort

The catchability coefficient (q) is accepted as being constant for an age group. Although it is not the same for all ages, it is probably very similar for those which are fully selected by trawl nets. A modified version of this equation is used in the catch projection model (equation 4.1). It allows for the effects of selection and availability.

Irrespective of the initial estimate of terminal F used in V.P.A., the values of F calculated for the preceding ages converge to a valid estimate (Ulltang, 1977), hence, if good effort data are available realistic estimates of q can be made. These can then be used to select a more realistic terminal F.

6.1 Investigation of M using V.P.A.

If the catchability coefficient were constant for all ages, and if the correct natural mortality-at-age, and the correct fishing mortality for the oldest age group were used in the V.P.A. equations, the calculated fishing mortalities for particular age groups should have a linear relationship with the appropriate effort values. This line should pass through the origin. Ulltang (1977) has however claimed that the regression of F values (calculated by V.P.A. using the true M) against effort, will not generally result in a Y-axis intercept which is appreciably closer to the origin than that obtained if wrong M values are used, i.e. this is not a reliable method of investigating M.

A computer programme has been developed to test Ulltang's hypothesis. It uses the Beverton and Holt (1957) catch equation (6.1) to generate stock and catch size at each age. The V.P.A. technique is then used to calculate the population and fishing mortality-at-age for different estimates of natural mortality-at-age.

Two sets of data were used: the first set used a value of q which remained constant for all ages. In the second set q was increased with age. The natural mortalities-at-age used to generate the test data are included in Tables 6.1 and 6.2. Fishing mortality values of each age of a cohort were obtained by V.P.A. for different patterns of natural mortality-at-age. These mortality values were regressed against effort. The results for the two sets of data are presented in Tables 6.1 and 6.2. The test data with a constant catchability coefficient all give Y-axis intercepts closer to zero, and higher correlation coefficients than the corresponding test data in the second set. In both cases the variation in the Y-axis intercepts is small for comparatively large changes in natural mortality, which is in accordance with Ulltang's (1977) hypothesis.

The test data comprise accurate catch statistics, whereas the real data do not. Hence, applications of this method would probably lead to the choice of a poor estimate of the natural mortality for each age. Cohort Analysis (Pope, 1972) is similar to V.P.A., but it has the advantage that iteration is not necessary. Results from the two analyses are very similar and any criticisms of V.P.A. may apply

Simulation number	Average M	Values of M-at-age (years) 3	4	5	6	7	8	9	Regression coefficients Intercept	Slope x 10^{-4}	Correlation coefficient
1	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	-0,16	0,81	0,93
2	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	-0,16	0,72	0,95
3	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	-0,15	0,63	0,96
4	0,20	0,05	0,10	0,15	0,20	0,25	0,30	0,35	-0,11	0,76	0,94
5	0,20	0,10	0,10	0,10	0,20	0,30	0,30	0,30	-0,10	0,75	0,94
6	0,20	0,15	0,15	0,15	0,20	0,25	0,25	0,25	-0,12	0,78	0,94
7	0,40	0,10	0,20	0,30	0,40	0,50	0,60	0,70	-0,07	0,63	0,97
8	0,40	0,25	0,30	0,35	0,40	0,45	0,50	0,55	-0,12	0,68	0,96
9	0,40	0,20	0,20	0,20	0,40	0,60	0,60	0,60	-0,05	0,61	0,97
10	0,40	0,30	0,30	0,30	0,40	0,50	0,50	0,50	-0,10	0,67	0,96
11	0,60	0,30	0,40	0,50	0,60	0,70	0,80	0,90	-0,08	0,55	0,98
12	0,60	0,45	0,50	0,55	0,60	0,65	0,70	0,75	-0,11	0,59	0,97
13	0,60	0,30	0,30	0,30	0,60	0,90	0,90	0,90	0,00	0,48	0,99
14	0,60	0,40	0,40	0,40	0,60	0,80	0,80	0,80	-0,05	0,53	0,99
15	0,20	0,35	0,30	0,25	0,20	0,15	0,10	0,05	-0,20	0,86	0,93
16	0,20	0,30	0,30	0,30	0,20	0,10	0,10	0,10	-0,21	0,87	0,93
17	0,20	0,25	0,25	0,25	0,20	0,15	0,15	0,15	-0,19	0,84	0,93
18	0,40	0,70	0,60	0,50	0,40	0,30	0,20	0,10	-0,23	0,81	0,93
19	0,40	0,55	0,50	0,45	0,40	0,35	0,30	0,25	-0,20	0,77	0,94
20	0,40	0,60	0,60	0,60	0,40	0,20	0,20	0,20	-0,26	0,83	0,92
21	0,40	0,50	0,50	0,50	0,40	0,30	0,30	0,30	-0,21	0,78	0,93
22	0,60	0,90	0,80	0,70	0,60	0,50	0,40	0,30	-0,22	0,72	0,93
23	0,60	0,75	0,70	0,65	0,60	0,55	0,50	0,45	-0,19	0,68	0,95
24	0,60	0,90	0,90	0,90	0,60	0,30	0,30	0,30	-0,29	0,79	0,91
25	0,60	0,80	0,80	0,80	0,60	0,40	0,40	0,40	-0,25	0,74	0,93
26	0,40	0,40	0,41	0,36	0,31	0,36	0,41	0,46	-0,15	0,73	0,95
27	0,40	0,53	0,43	0,33	0,23	0,33	0,43	0,53	-0,15	0,74	0,95
28	0,60	0,66	0,61	0,56	0,51	0,56	0,61	0,66	-0,15	0,64	0,96
29	0,60	0,73	0,63	0,53	0,43	0,53	0,63	0,73	-0,14	0,64	0,97

Table 6.1 Results of the regression of fishing mortality of a cohort (generated by V.P.A., using different values of natural mortality (M)-at-age) against effort. The pattern of M in simulation 13 was used to generate the test data; the catchability coefficient (q) was kept constant.

Simulation number	Average M	Values of M-at-age (years) 3	4	5	6	7	8	9	Regression coefficients Intercept	Slope $x\ 10^{-4}$	Correlation coefficient
1	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	-0,32	0,83	0,90
2	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	-0,30	0,73	0,90
3	0,60	0,60	0,60	0,60	0,60	0,60	0,60	0,60	-0,26	0,64	0,89
4	0,20	0,05	0,10	0,15	0,20	0,25	0,30	0,35	-0,29	0,79	0,92
5	0,20	0,10	0,10	0,10	0,20	0,30	0,30	0,30	-0,28	0,78	0,92
6	0,20	0,15	0,15	0,15	0,20	0,25	0,25	0,25	-0,30	0,80	0,91
7	0,40	0,10	0,20	0,30	0,40	0,50	0,60	0,70	-0,23	0,65	0,93
8	0,40	0,25	0,30	0,35	0,40	0,45	0,50	0,55	-0,27	0,69	0,92
9	0,40	0,20	0,20	0,20	0,40	0,60	0,60	0,60	-0,21	0,63	0,93
10	0,40	0,30	0,30	0,30	0,40	0,50	0,50	0,50	-0,25	0,68	0,92
11	0,60	0,30	0,40	0,50	0,60	0,70	0,80	0,90	-0,20	0,56	0,92
12	0,60	0,45	0,50	0,55	0,60	0,65	0,70	0,75	-0,23	0,60	0,91
13	0,60	0,30	0,30	0,30	0,60	0,90	0,90	0,90	-0,15	0,50	0,94
14	0,60	0,40	0,40	0,40	0,60	0,80	0,80	0,80	-0,19	0,54	0,92
15	0,20	0,35	0,30	0,25	0,20	0,15	0,10	0,05	-0,36	0,87	0,89
16	0,20	0,30	0,30	0,30	0,20	0,10	0,10	0,10	-0,37	0,88	0,89
17	0,20	0,25	0,25	0,25	0,20	0,15	0,15	0,15	-0,35	0,86	0,89
18	0,40	0,70	0,60	0,50	0,40	0,30	0,20	0,10	-0,35	0,81	0,87
19	0,40	0,55	0,50	0,45	0,40	0,35	0,30	0,25	-0,33	0,77	0,89
20	0,40	0,60	0,60	0,60	0,40	0,20	0,20	0,20	-0,38	0,83	0,87
21	0,40	0,50	0,50	0,50	0,40	0,30	0,30	0,30	-0,34	0,78	0,89
22	0,60	0,90	0,80	0,70	0,60	0,50	0,40	0,30	-0,32	0,71	0,87
23	0,60	0,75	0,70	0,65	0,60	0,55	0,50	0,45	-0,29	0,67	0,77
24	0,60	0,90	0,90	0,90	0,60	0,30	0,30	0,30	-0,38	0,78	0,89
25	0,60	0,80	0,80	0,80	0,60	0,40	0,40	0,40	-0,34	0,73	0,87
26	0,40	0,40	0,41	0,36	0,31	0,36	0,41	0,46	-0,30	0,74	0,91
27	0,40	0,53	0,43	0,33	0,23	0,33	0,43	0,53	-0,29	0,74	0,92
28	0,60	0,66	0,61	0,56	0,51	0,56	0,61	0,66	-0,26	0,64	0,90
29	0,60	0,73	0,63	0,53	0,43	0,53	0,63	0,73	-0,26	0,65	0,91

Table 6.2 Results of the regression of fishing mortality of a cohort (generated by V.P.A., using different values of natural mortality (M)-at-age) against effort. The pattern of M in simulation 13 was used to generate the test data; the catchability coefficient (q) was increased with age.

equally to Cohort Analysis.

6.2 Further investigations of V.P.A.

Draganik (1978) used Cohort Analysis to calculate fishing mortality-at-age for the years 1965-75. He averaged the fishing mortalities for each year and regressed these values against effort; as the resultant Y-axis intercept was close to zero, he concluded that the estimate of M was good.

It would appear from the previous section that this method is unlikely to be very reliable. It was therefore tested with hypothetical data, obtained using the Beverton and Holt (1957) catch equation. The results are presented in Table 6.3.

As in the previous method (Section 6.1), the Y-axis intercept is relatively insensitive to M. The pattern of M-at-age used to generate the test data should give the smallest Y-axis intercept and the highest correlation coefficient. In this case it did not. This is probably due to the extreme sensitivity of M to error, introduced when the test catch data were rounded up to the nearest 100 metric tons.

6.3 Modified Virtual Population Analysis

V.P.A. and Cohort Analysis can be used to calculate a series of fishing mortalities for each age over a period of years. Estimates, independent of V.P.A., must be made of terminal

Simulation number	Natural mortality	Regression coefficients Intercept	Slope x 10^{-4}	Correlation coefficient
1	0,05	0,14	0,18	0,96
2	0,10	0,12	0,17	0,96
3	0,15	0,10	0,17	0,97
4	0,20	0,08	0,16	0,98
5	0,25	0,07	0,15	0,98
6	0,30	0,05	0,15	0,99
7	0,35	0,04	0,14	0,99
8	0,40	0,03	0,13	1,00
9	0,45	0,02	0,12	1,00
10	0,50	0,01	0,12	1,00
11	0,55	0,00	0,11	1,00
12	0,60	-0,01	0,10	1,00
13	0,65	-0,01	0,09	0,99
14	0,70	-0,02	0,09	0,99
15	0,75	-0,02	0,08	0,99
16	0,80	-0,02	0,07	0,99
17	0,85	-0,02	0,07	0,98
18	0,90	-0,02	0,06	0,98
19	0,95	-0,02	0,05	0,97

Table 6.3 Results of the regression of fishing mortality (averaged for all age groups) against effort. The value of M in simulation 12 was used to generate the test data; M was kept constant for all ages.

F, and F for the last year of each age group. If good effort data are available, the latter can be found by using the regression of F (for each age group) against effort (f) (equation 6.4).

If the Y-axis intercept from this regression were sensitive to natural mortality-at-age (M), using the criterion that the true value of M-at-age should yield a Y-axis intercept which passes through the origin, M-at-age could be found by iteration.

Although V.P.A. cannot be used to find M, it does supply estimates of stock size, which can then be used in the catch projection model.

6.4 General conclusions

The modified Virtual Population Analysis (described in Section 6.3) can be used to calculate fishing mortality (F) and stock size-at-age each year, from the catch-at-age, effort (f), estimates of M-at-age, and q. It differs from the usual method (Gulland, 1965) in that, for all ages except the oldest, the values of F in the final year under consideration are found by regressing F at each age against f, and solving the subsequent regression equation (equation 6.4). This is applicable only when F is linearly related to f, i.e. q is constant.

Ulltang (1977) has shown that the Y-axis intercept from the regression of F (from a year class) against effort varies insignificantly for large changes in M. This has been confirmed in the present study. It has also been shown to apply when fishing mortalities are averaged for each year.

If stock sizes are to be estimated using the principles underlying V.P.A. or Cohort Analysis, then a realistic value of M at each age must be obtained. The methods investigated here have been shown to be inadequate; it is necessary therefore that an alternative approach is found.

7. STOCK/RECRUITMENT RELATIONSHIPS

Recruitment may be regarded as the process in which juvenile fish join the fishable stock. In Section 4.1 it is mentioned that small hake are generally found in shallow water, and migrate into deeper water with age (Botha, 1973). It is therefore logical to postulate that when the pelagic juvenile hake join the demersal adult stock they will do so at the shallower end of their depth distribution range.

Recruitment to the fishable stock may therefore be governed not only by the age at which the Cape hakes migrate to the bottom, but also by the minimum depth at which the trawlers operate, the mesh size, and the particular requirements of the fishery.

7.1 Types of recruitment

Ricker (1975) describes three general types of recruitment:

7.1.1 Continuous recruitment: in which there is a gradual increase in vulnerability of the members of a year class over a period of years, due to an increase in size, or a change in distribution or behaviour.

7.1.2 Recruitment by platoons: where the vulnerability of a year class increases gradually over a period of two or more years, but during any fishing season individual fish are either catchable or non-catchable.

7.1.3 Knife edge recruitment: in which all fish of a given age become vulnerable at a particular time in a given year, their vulnerability remaining the same throughout their lives. Gulland's (1965) definition differs: it states that this situation occurs if the average length of recruits migrating into a fishing area subjects them to selection above the 0,5 level.

7.2 Stock size and recruitment

A catch projection model requires a method of estimating the annual recruitment. A relationship must be found which utilises available data to calculate the number of recruits in a given year. It is usual to define a relationship between stock density and recruitment. However, year-to-year fluctuations in the environment may cause changes in recruitment as large as those caused by stock density, in which case a predictive recruitment model is not realistic.

Ricker (1975) states that to obtain a significant correlation between recruitment and environmental factors, data for a period of between 15 and 25 years should be available. No such data are available. Despite this lack of long term information, two types of stock/recruit curves were fitted to the existing data for South African hake.

7.3 Stock/recruit curves

The two commonly used stock/recruit curves, the Beverton and Holt curve and the Ricker curve, were tested to ascertain which was more applicable to the Cape hakes.

The Beverton and Holt stock/recruit curve (equation 7.1) is more suitable when there is a ceiling to the abundance, caused by a limit to the available food or a predator-prey relationship (Ricker, 1975).

$$R_c = \frac{1}{a + b/P} \qquad \text{.......... equation 7.1}$$

R_c = biomass of the recruits

P = biomass of the parent stock

a and b are constants

The Ricker stock/recruit curve (equation 7.2) applies when cannibalism of the young by the adults is an important regulatory mechanism (Ricker, 1975). Cannibalism is known to be prevalent in the Cape hakes (Jones and van Eck, 1967), so this model may be appropriate.

$$R_c = a.P.e^{-b.P} \qquad \text{.......... equation 7.2}$$

7.4 Method to calculate the stock/recruit parameters

To calculate the parameters in the two stock/recruit equations a computer package was used: Biomedical Computer Programs, edited by Dixon (1975). The two non-linear equations were solved by programme BMDP3R, which requires the user to include a subroutine which defines the stock/recruit equations and their partial derivatives. The constants a and b are solved by means of Gauss-Newton iterations.

Output from this package is comprehensive. It includes the residual sum of squares, observed and predicted values for the dependent variable (recruitment), and the observed independent variable (stock) and a graph of these, if required. It also allows for a comparison of different equations using the same data in the same run.

The modified Virtual Population Analysis programme, discussed in Section 6, was used to calculate the stock size, and the resulting recruits, from Draganik's (1976a) catch data. An allowance was made for discards (discussed in the next section). The parameters of the stock/recruit curves were then estimated using the BMDP package. Additional statistics were calculated from the observed and predicted recruits, and the results are summarized in Table 7.1.

	a	b	RSS	R	R^2
Ricker	0,603286	0,000597	54390	0,246	0,060
Beverton and Holt	0,001167	1,642353	54428	0,243	0,059

Table 7.1 Parameters and statistics from the Ricker and Beverton and Holt stock/recruit curves.

RSS = residual sum of squares
R = correlation coefficient
R^2 = coefficient of determination

a and b are constants in the stock/recruit curves.

The predicted recruits obtained from the two stock/recruit curves are virtually identical (Figure 7.1). Both give a poor fit to the observed data, due to the short time series, and the irregular nature of the data. As mentioned, the Ricker curve is more likely to be appropriate for the Cape hakes; provision has therefore been made for its use in the catch projection model.

7.5 Recruitment in the catch projection model

Recruitment may be calculated in two ways:

1. No relationship is assumed between the stock size and recruitment. The latter is allowed to fluctuate according to the pattern of variability observed around the mean.
2. The validity of the Ricker stock/recruit curve is accepted and used to generate recruitment, taking into account the variance observed around the relationship.

Provision was made in the catch projection model for the use of either method of calculating recruitment.

The distribution of the variability around the predicted recruitment appears to be rectangular for both methods of

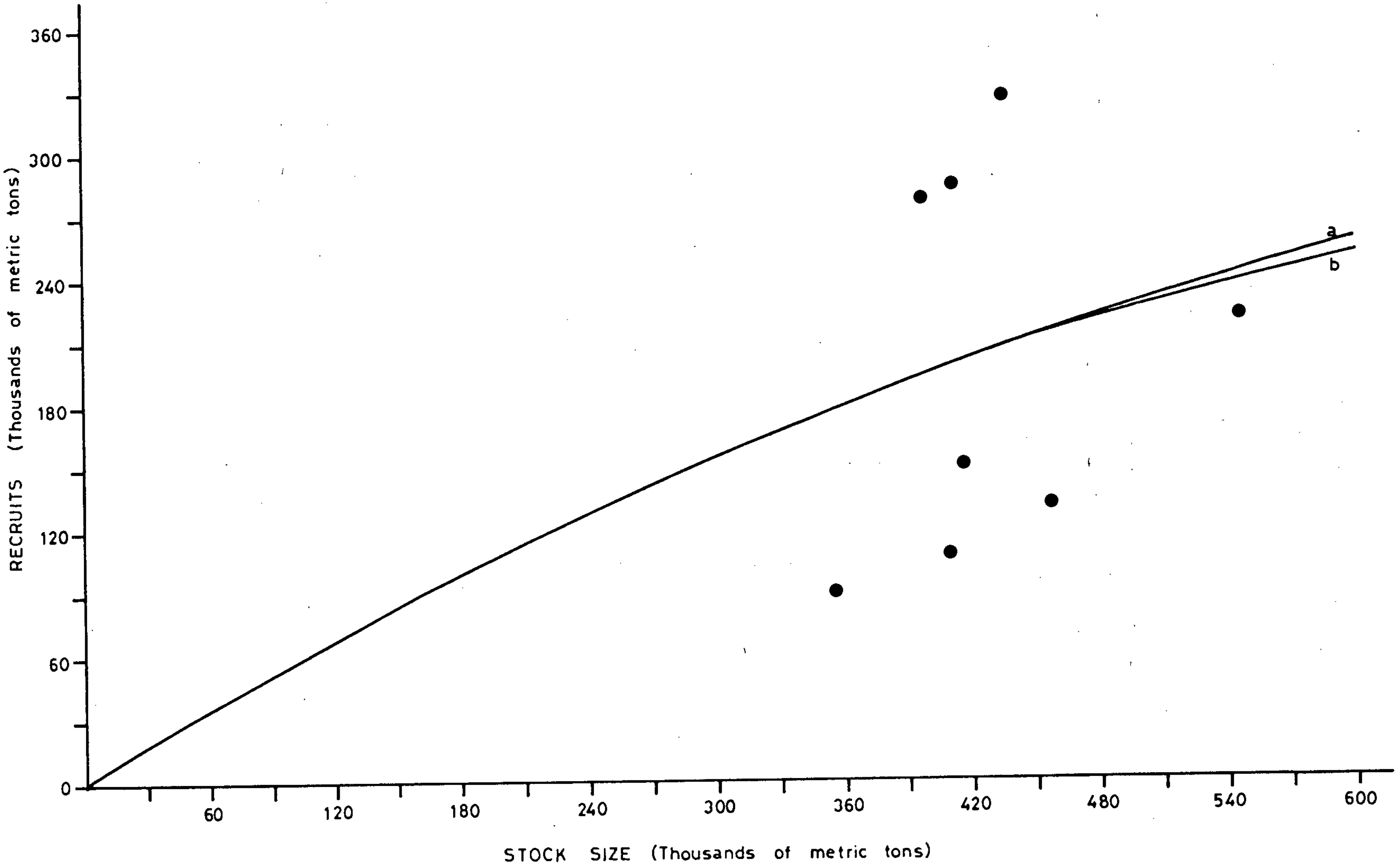

Figure 7.1 - Two stock/recruit curves fitted to the Cape hake data.
a = Beverton and Holt stock/recruit curve; b = Ricker stock/recruit curve.
● = observed data.

predicting recruitment; however, this could be due to the few data used. As no data for a recruitment curve are available, all the recruits are added to the stock at the beginning of the year, i.e. knife edge recruitment is assumed. The catch is estimated on a monthly basis using the appropriate selection curve, and recalculating length for each age.

8. CATCH PROJECTION MODEL

The catch projection model has been designed using the concept of modular programming. This entails each biological function being in a separate subprogramme. If any of these functions require modification for the particular stock being used, then changes to the relevant subprogramme alone need be made. This serves to localise any problems in coding which may occur. The derivations of the biological parameters used in the model are described in the relevant sections below.

8.1 Data input

The data inputs are represented in Figure 8.1. They can be broadly classified into three divisions:

8.1.1 Initial values; these are changed during a run, e.g. the stock size is entered, and then updated on a monthly basis.

8.1.2 Constant parameters; values which remain unaltered during a run, e.g. natural mortality-at-age, availability, oldest and youngest age, first year, number of years to be projected, monthly availability, average mesh size, mesh selection parameters, growth parameters, weight/length parameters, monthly tables flag, stock/recruit parameters, stock/recruit deviation limits, catchability coefficient.

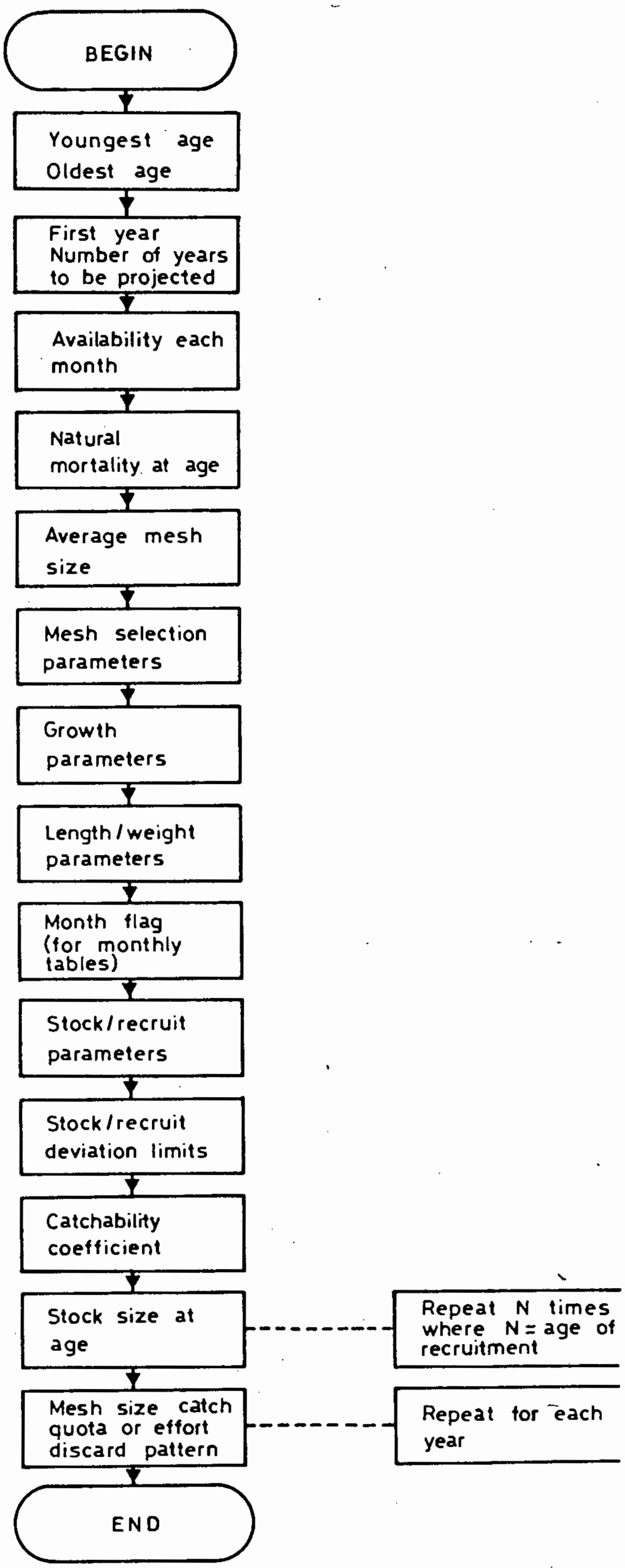

Figure 8.1 - Catch projection model data input.

8.1.3 Yearly input; data which remain constant for a year, e.g. catch quota or effort, mesh size, discard rate.

8.2 Inter-relationships between the parameters used in the model

The inter-relationships between the various parameters used are shown in a highly simplified flow diagram, Figure 8.2. Fish loss in numbers due to fishing and to total mortality is calculated monthly for each age from the Beverton and Holt (1957) catch equation (6.1). This utilises the relationship between stock size, natural mortality (M) and fishing mortality (F). Natural mortality (M) is set as a constant for each age group, whereas F is recalculated each month (equation 4.1) from four parameters:

1. Catchability coefficient; assumed constant for all ages.
2. Availability; given a value for each month (Section 4.1).
3. Effort; entered each year, and divided by 12 to give a monthly value.
4. Selection must be found for each age group, each month, from equation 4.2. It is dependent on the length of the fish half way through each month. This length is obtained from the von Bertalanffy growth equation (3.1).

The catch is converted to weight, by substituting the calculated length into the length/weight equation (3.2).

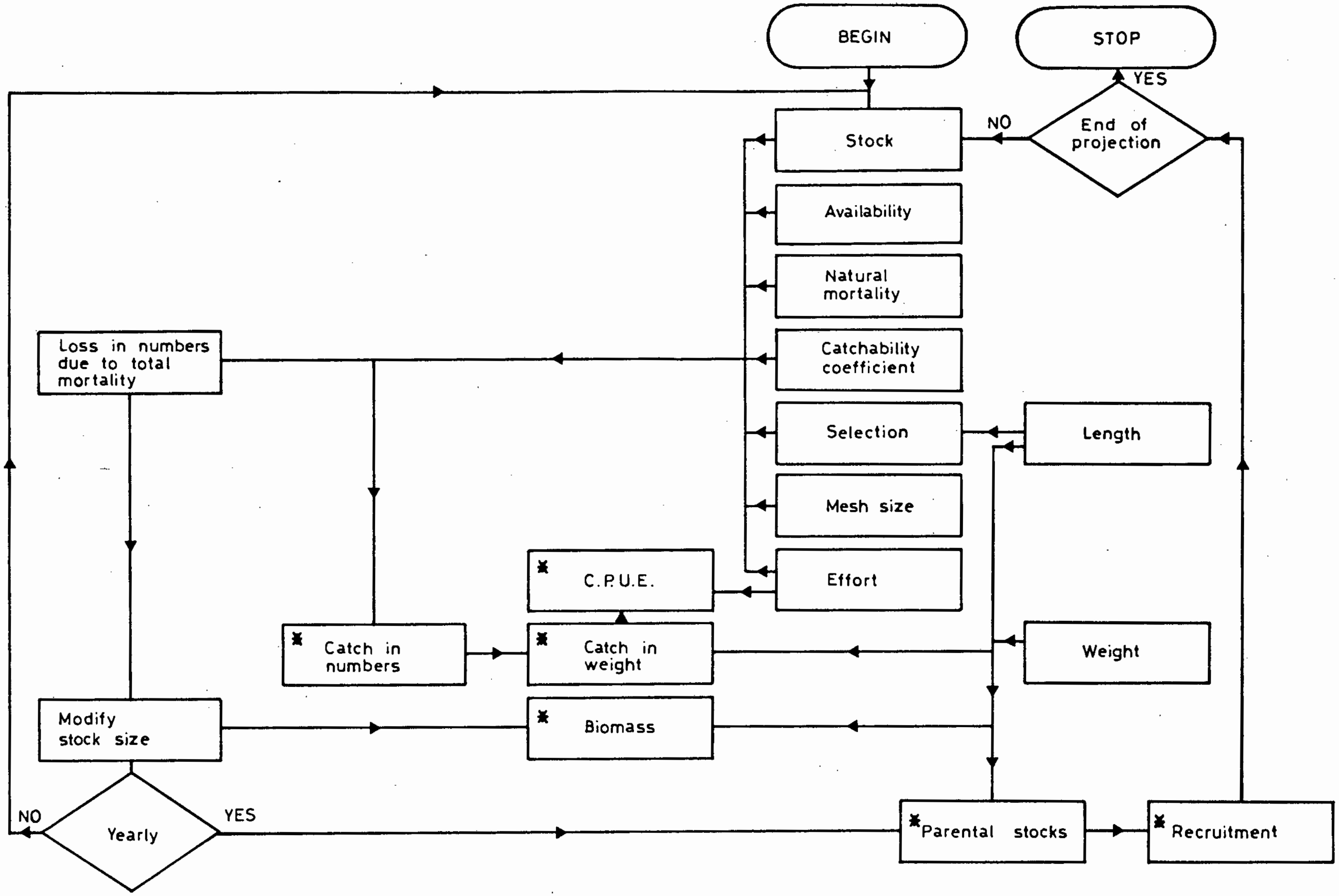

Figure 8.2 - Simplified flow diagram of the catch projection model.
* indicates output.

Catch per unit effort can now be found. The number of fish lost to total mortality is used to modify the stock accordingly. Recruits are calculated using the Ricker stock/recruit curve or a random number generator, and the stock updated annually. The parental biomass is then calculated and stored to predict the recruitment three years later.

8.3 Historical validation

The stock sizes in weight and number were calculated by the mortality model (Section 6) using Draganik's (1976a) data. The average weights used were obtained from the age/length and length/weight equations. The natural mortality used was 0,24, from Draganik (1974).

Catch was predicted from each of the stock estimates for the years 1964-74. Predicted catches were much higher than the observed catch for ages three to five in all the years (Tables 8.1 and 8.2). This discrepancy could be caused by the catch-at-age data having been calculated from the landed catch, which takes no account of the discarding of smaller hake. Newman (1974) presents two possible discard patterns (Table 8.3), both of which were used to adjust the catch.

					Age				
Year		3	4	5	6	7	8	9	Total
64	OBS	3	6	10	14	4	6	3	52
	PRD(1)	57	40	27	16	9	5	1	155
	PRD(2)	30	30	27	16	9	5	1	118
	PRD(3)	16	21	27	16	9	5	1	95
65	OBS	4	8	15	19	16	8	4	73
	PRD(1)	98	79	48	30	14	6	4	278
	PRD(2)	53	60	48	30	14	6	4	214
	PRD(3)	31	42	48	30	14	6	4	174
66	OBS	16	32	48	31	19	6	1	154
	PRD(1)	99	81	59	30	14	4	1	288
	PRD(2)	57	65	59	30	14	4	1	231
	PRD(3)	36	49	59	30	14	4	1	194
67	OBS	22	41	43	24	13	3	1	146
	PRD(1)	87	80	52	26	11	3	0	259
	PRD(2)	52	65	52	26	11	3	0	209
	PRD(3)	35	50	52	26	11	3	0	177
68	OBS	21	35	35	19	11	4	1	124
	PRD(1)	76	54	39	19	8	3	1	200
	PRD(2)	46	44	39	19	8	3	1	160
	PRD(3)	31	34	39	19	8	3	1	135
69	OBS	55	56	29	22	12	4	1	180
	PRD(1)	102	79	42	24	11	4	1	262
	PRD(2)	70	67	42	24	11	4	1	218
	PRD(3)	53	55	42	24	11	4	1	189
70	OBS	54	51	28	18	10	4	1	165
	PRD(1)	124	70	41	21	10	3	1	270
	PRD(2)	84	59	41	21	10	3	1	220
	PRD(3)	64	49	41	21	10	3	1	190
71	OBS	148	76	25	19	9	4	1	284
	PRD(1)	236	107	42	26	10	4	1	426
	PRD(2)	133	94	42	26	10	4	1	311
	PRD(3)	156	81	42	26	10	4	1	320
72	OBS	205	99	27	14	7	2	1	354
	PRD(1)	294	129	46	20	9	2	1	501
	PRD(2)	195	117	46	20	9	2	1	391
	PRD(3)	211	105	46	20	9	2	1	394
73	OBS	180	112	24	8	4	2	1	293
	PRD(1)	260	100	38	18	6	3	1	439
	PRD(2)	229	88	38	18	6	3	1	396
	PRD(3)	185	59	38	18	6	3	1	336
74	OBS	117	59	21	8	6	3	1	214
	PRD(1)	193	87	35	13	8	2	1	339
	PRD(2)	162	77	35	13	8	2	1	297
	PRD(3)	127	66	35	13	8	2	1	251

Table 8.1 Observed and predicted catch in numbers (millions) for the years 1964-74.

OBS = observed catch

PRD(1) = predicted catch, no allowance for discards

PRD(2) = predicted catch, 50% three year olds and 25% four year olds discarded

PRD(3) = predicted catch, 75% three year olds and 50% four year olds discarded

					Age				
Year		3	4	5	6	7	8	9	**Total**
64	OBS	1	4	10	20	22	13	9	79
	PRD(1)	22	26	27	23	17	11	4	130
	PRD(2)	11	20	27	23	17	11	4	114
	PRD(3)	6	14	27	23	17	11	4	102
65	OBS	1	5	16	28	30	19	12	110
	PRD(1)	37	52	48	42	26	13	11	229
	PRD(2)	20	39	48	42	26	13	11	198
	PRD(3)	12	27	48	42	26	13	11	179
66	OBS	6	22	50	45	37	14	4	177
	PRD(1)	37	53	59	43	27	9	3	232
	PRD(2)	22	42	59	43	27	9	3	205
	PRD(3)	14	32	59	43	27	9	3	187
67	OBS	9	27	44	34	24	8	2	149
	PRD(1)	33	52	52	37	20	7	1	203
	PRD(2)	20	42	52	37	20	7	1	180
	PRD(3)	13	33	52	37	20	7	1	163
68	OBS	8	24	36	27	21	9	3	127
	PRD(1)	29	35	39	27	16	7	2	155
	PRD(2)	18	29	39	27	16	7	2	137
	PRD(3)	12	23	39	27	16	7	2	125
69	OBS	21	38	30	32	23	10	4	159
	PRD(1)	38	51	42	34	20	9	3	197
	PRD(2)	26	43	42	34	20	9	3	178
	PRD(3)	20	36	42	34	20	9	3	164
70	OBS	21	34	28	26	19	9	4	141
	PRD(1)	46	45	41	30	18	8	3	192
	PRD(2)	32	38	41	30	18	8	3	170
	PRD(3)	24	32	41	30	18	8	3	157
71	OBS	58	51	26	28	18	10	4	195
	PRD(1)	87	68	41	36	19	10	4	265
	PRD(2)	49	60	41	36	19	10	4	220
	PRD(3)	57	52	41	36	19	10	4	220
72	OBS	79	66	28	21	13	5	2	216
	PRD(1)	106	81	44	28	17	6	2	285
	PRD(2)	71	74	44	28	17	6	2	242
	PRD(3)	76	66	44	28	17	6	2	240
73	OBS	70	51	24	11	8	5	2	171
	PRD(1)	94	70	37	25	12	7	2	248
	PRD(2)	83	63	37	25	12	7	2	229
	PRD(3)	67	55	37	25	12	7	2	198
74	OBS	46	39	22	12	12	4	3	138
	PRD(1)	71	56	35	18	14	5	2	201
	PRD(2)	59	49	35	18	14	5	2	182
	PRD(3)	46	42	35	18	14	5	2	163

Table 8.2 Observed and predicted catch by weight (thousands of metric tons) for the years 1964-74.

OBS = observed catch

PRD(1) = predicted catch, no allowance for discards

PRD(2) = predicted catch, 50% three year olds and 25% four year olds discarded

PRD(3) = predicted catch, 75% three year olds and 50% four year olds discarded

Pattern	Age						
	3	4	5	6	7	8	9
1	50	25	0	0	0	0	0
2	75	50	0	0	0	0	0

Table 8.3 Possible discard patterns, expressed as a percentage of the catch at each age.

The new catch estimates were used to recalculate the stock sizes, which were then used in the catch projection model. The results are displayed in Tables 8.1 and 8.2. Those obtained using the higher discard rate agree best with the observed data. There is however, an overestimation of the catch of the younger age groups for the years 1964-67. This could be due to trawling not taking place equally over all areas within which specific age groups occur. This is possible as there appears to be an age/depth distribution pattern (Section 4.1) and Botha (pers. comm.) has confirmed that the fishing grounds have been extended both inshore and offshore since 1964.

The new estimates of stock size, which include adjustments for discard rates, were fitted to the two stock/recruit curves as has been described in Section 7. Several runs were made of the model for 1968-74, based on the observed stock in 1968. Recruitment was introduced using the two sources outlined in Section 7.5, namely the Ricker stock/recruit curve and the mean weight of recruits applied irrespective of stock size.

The results are presented in Tables 8.4 and 8.5. Generally there is good agreement between the observed and predicted catch, irrespective of the source of recruitment. However, discrepancies do arise from the irregular nature of recruitment, and the lack of accurate information on discard rates.

The validity of the model seems better if discards are taken into account, judging by simulation of the past history of the fishery. Consequently it may be used to predict future catches under different fishing strategies.

Certain precautions must be adhered to when using the model. Recruitment must be maintained within observed levels, otherwise unrealistically high or low levels of stock size and therefore catch may be predicted. Similarly, the predicted stock size must be maintained within observed bounds, as the effects of very high or very low levels are unknown. If a stock/recruit curve is used, great caution must be exercised, particularly if there is a time lag between spawning and recruitment to the fishable stock. Trends could appear in the stock size which are merely artifacts of the stock/recruit curve.

As new catch data and revisions to existing catch data become available they should be used to recalculate stock size estimates, and stock/recruit curve parameters. Catch projections should now be repeated using these data.

					Age				
Year		3	4	5	6	7	8	9	Total
68	OBS	21	35	35	19	11	4	1	124
	PRD(1)	31	34	39	19	8	3	1	135
	PRD(2)	31	34	39	19	8	3	1	135
69	OBS	55	56	29	22	12	4	1	180
	PRD(1)	52	45	42	23	11	5	2	179
	PRD(2)	73	45	42	23	11	5	2	199
70	OBS	54	51	28	18	10	4	1	165
	PRD(1)	76	50	36	16	8	4	2	191
	PRD(2)	86	68	36	16	8	4	2	220
71	OBS	148	76	25	19	9	4	1	284
	PRD(1)	121	81	44	15	6	3	2	272
	PRD(2)	114	93	61	15	6	3	2	293
72	OBS	205	99	27	14	7	2	1	354
	PRD(1)	187	74	39	10	3	1	1	315
	PRD(2)	193	70	45	13	3	1	1	326
73	OBS	180	75	24	8	4	2	1	293
	PRD(1)	175	70	21	5	1	0	0	272
	PRD(2)	123	72	20	6	2	0	0	223
74	OBS	117	59	21	8	6	2	1	214
	PRD(1)	68	56	17	2	1	0	0	145
	PRD(2)	83	40	18	2	1	0	0	143
68	OBS	8	24	36	27	21	9	3	127
	PRD(1)	12	22	39	27	16	7	2	125
	PRD(2)	12	22	39	27	16	7	2	125
69	OBS	21	38	30	32	23	10	4	159
	PRD(1)	20	29	42	32	20	11	5	159
	PRD(2)	27	29	42	32	20	11	5	167
70	OBS	21	34	28	26	19	9	4	141
	PRD(1)	29	32	36	22	15	9	5	148
	PRD(2)	32	44	36	22	15	9	5	164
71	OBS	58	51	26	28	18	10	4	195
	PRD(1)	44	52	43	21	12	8	4	184
	PRD(2)	42	59	60	21	12	8	4	205
72	OBS	79	66	28	21	13	5	2	216
	PRD(1)	68	46	38	13	6	3	2	176
	PRD(2)	70	44	43	18	6	3	2	186
73	OBS	70	51	24	11	8	5	2	171
	PRD(1)	63	44	20	7	2	1	0	137
	PRD(2)	43	45	19	8	3	1	0	121
74	OBS	46	39	22	12	12	4	3	138
	PRD(1)	25	36	17	3	10	0	0	82
	PRD(2)	30	25	17	3	11	0	0	78

Table 8.4 Observed and predicted catch in numbers (millions) (above) and by weight (thousands of metric tons) (below) for the years 1968-74, (from a catch projection based on the stock in 1968).

Recruitment is predicted from the Ricker stock/recruit curve.

OBS = observed catch

PRD(1) and PRD(2) = predicted catch (variation in recruitment introduced from a random number generator).

					Age				
Year		3	4	5	6	7	8	9	Total
68	OBS	21	35	35	19	11	4	1	124
	PRD(1)	31	34	39	19	8	3	1	135
	PRD(2)	31	34	39	19	8	3	1	135
69	OBS	55	56	29	22	12	4	1	180
	PRD(1)	41	45	42	23	11	5	2	168
	PRD(2)	64	45	42	23	11	5	2	191
70	OBS	54	51	28	18	10	4	1	165
	PRD(1)	73	39	36	16	8	4	2	178
	PRD(2)	85	60	36	16	8	4	2	210
71	OBS	148	76	25	19	9	4	1	284
	PRD(1)	123	79	35	15	6	3	2	262
	PRD(2)	115	91	53	15	6	3	2	285
72	OBS	205	99	27	14	7	2	1	354
	PRD(1)	190	75	38	8	3	1	1	315
	PRD(2)	184	70	44	12	3	1	1	315
73	OBS	180	75	24	8	4	2	1	293
	PRD(1)	175	71	21	5	1	0	0	273
	PRD(2)	103	69	20	6	1	0	0	199
74	OBS	117	59	21	8	6	2	1	214
	PRD(1)	53	56	17	2	1	0	0	129
	PRD(2)	63	33	17	2	1	0	0	116
68	OBS	8	24	36	27	21	9	3	127
	PRD(1)	12	22	39	27	16	7	2	125
	PRD(2)	12	22	39	27	16	7	2	125
69	OBS	21	38	30	32	23	10	4	159
	PRD(1)	16	29	42	32	20	11	5	155
	PRD(2)	24	29	42	32	20	11	5	164
70	OBS	21	34	28	26	19	9	4	141
	PRD(1)	28	25	36	22	15	9	5	140
	PRD(2)	32	39	36	22	15	9	5	158
71	OBS	58	51	26	28	18	10	4	195
	PRD(1)	45	50	34	21	12	8	4	174
	PRD(2)	42	58	52	21	12	8	4	197
72	OBS	79	66	28	21	13	5	2	216
	PRD(1)	69	47	37	11	6	3	2	174
	PRD(2)	67	44	43	16	6	3	2	180
73	OBS	70	51	24	11	8	5	2	171
	PRD(1)	63	44	20	7	2	1	0	137
	PRD(2)	37	43	19	8	3	1	0	111
74	OBS	46	39	22	12	12	4	3	138
	PRD(1)	19	36	17	3	1	0	0	77
	PRD(2)	23	21	16	3	1	0	0	65

Table 8.5 Observed and predicted catch in numbers (millions) (above) and by weight (thousands of metric tons) (below) for the years 1968-74, (from a catch projection based on the stock in 1968).

Recruitment is equated to the mean weight of observed recruits.

OBS = observed catch

PRD(1) and PRD(2) = predicted catch (variation in recruitment introduced from a random number generator).

9. DISCUSSION AND CONCLUSION

A catch projection model has been designed to simulate the Cape hake population. All available data have been examined, and where appropriate, included in the simulation model. One of the outcomes has been an evaluation of those areas where further research is required.

Although the model has been written specifically for the Cape hake fishery, its design allows easy modifications for other fisheries. In this respect, sections dealing with specific biological functions can be altered, deleted, or incorporated with minimal effort.

For the purpose of the study, the two species of Cape hake have been regarded as comprising the same population. Newman _et_ _al_. (1976) have suggested that the similarity in the growth rates of the two species lends some validity to this approach. At present, insufficient data prevent the two species from being treated separately. The model has therefore been considerably simplified as it involves only one population.

South African catch and effort statistics have been used to calculate the monthly pattern of availability during the years 1974-76. Results very similar to those of earlier authors (Roux, 1949; Jones and van Eck, 1967) were obtained, justifying the inclusion of seasonal availability within the model. Although effort tends to be greatest when the availability is high, effort has been assumed to be evenly expended throughout the year. This could be modified, and the effects of varying the monthly effort - e.g. closed fishing season - could thus be examined.

The sources of error in the data (used to construct the catch projection model) will in part determine the model's validity. They are therefore referred to in the ensuing discussion.

Yearly catch-at-age has been estimated by Draganik (1976b) and Newman _et al_. (1976) using data presented to ICSEAF. These catch estimates are subject to error from various sources, which include non-standardization of age determination techniques, and not accounting for discards. Methods which rely upon accurate catch statistics would therefore be invalidated.

Stock assessments were made using V.P.A., and equations underlying this analysis assume that the catch-at-age represents the stock-at-age. Consequently, inaccuracies in the catch estimates will manifest themselves in the stock estimates.

Methods of calculating natural mortality (M) are discussed in Section 5. Values obtained suggest a range of between 0,2 and 0,4, and the differences in the stock size estimates obtained using these figures in V.P.A. are very large. It is therefore important to determine the true value of M. An investigation was made of two methods which utilize the results of V.P.A. to determine the value of M. Unfortunately it was found that the criteria used to judge M were insensitive, and therefore neither method could be employed.

The assumption that fishing effort is expended equally over all age groups is used in the catch projection model. This need not be the case. In more recent years, the catch of nine-year-olds has decreased, while the catch of one-and two-year-olds has risen dramatically. This is probably due to a change in fishing areas. To simplify this, the stock has been regarded as comprising of three-to nine-year-olds. Also, the estimation of stock-at-age for the latest year using V.P.A. requires the estimation of fishing mortality for each age of that year. This must reflect the catchability and selectivity.

The age/length and length/weight relationships in the Cape hakes have been well documented. Elwertowski and Piotrowski (1975) present a summary of the results. Generally there is good accord; the discrepancies that do occur are probably due to the differences in ageing the fish.

The work on selection by Bohl _et al_. (1971) has been used to provide selection values for combinations of mesh size and fish length. As the imposition of a minimum mesh size is a very valuable management tool, it would be beneficial to repeat the mesh/selectivity experiments for a greater number of different mesh sizes, and also extend trials to cover different fish densities.

When the catch projection model was initially used to predict the catch over a period of one year, it was found that there was good agreement between the observed and predicted catches for the older age groups. However, for the younger ages the predicted catch was far higher than the observed catch. One possible reason could be that discard rates had not been accounted for. Using discard patterns presented by Newman (1974), a far closer fit was obtained. The discard patterns adopted in this analysis therefore affect estimates of the actual catch (landed catch remains the same), and stock size. It would therefore seem necessary to examine discard patterns in greater detail, possibly using age composition from research cruises, and revising stock estimates.

Recruitment is determined by a combination of the stock size and environmental factors. As no measure of the latter is available, attempts were made to link recruits to stock size, using the Beverton and Holt and the Ricker stock/recruit curves. Both give a poor fit to the data, and are almost identical over the observed range. Variation in the predicted recruits can be introduced by using random numbers; it should be normally distributed around the predicted value.

An alternative method of generating recruitment is to use random numbers, distributed according to the observed pattern around the mean. This can, however, give unrealistic values at very low or high levels of stock size, because clearly recruitment/stock relationships must have a parabolic character.

Further research into recruitment in the Cape hakes is necessary. Hopefully, a longer series of data, better estimates of stock size, and environmental data should give a sounder basis for predicting recruits.

The catch data used in this thesis cover the years 1964-74, and age groups three to nine. Data for the years 1975-78 are currently being assembled. It would appear that over these four years, the catch rates for ages eight and nine have become very low, whereas the catch of the one and two-year-olds has risen considerably. A change in the pattern of discarding fish, an increase in inshore trawling or increasing fishing effort, or a combination of these factors could be responsible for the higher catch of young hake.

Consequently, the research presented here is at present being extended to include ages one and two, and the years 1974-78. When this has been completed, meaningful catch predictions may be made.

The catch projection model has been able to simulate the history of the hake fishery, in spite of the deficiencies discussed. Its development has illuminated the need for further information on mortality rates, and stock/recruit relationships. It has also demonstrated the importance of incorporating discard patterns into stock assessment and has stressed the need to understand changes in fishing which could direct effort towards fish of a specific size.

ACKNOWLEDGEMENTS

I should like to thank my supervisors, Dr. John Field of the University of Cape Town, and Dr. Garth Newman of the Sea Fisheries Branch, Cape Town, for their help in developing the model and in critically appraising the manuscript.

In particular I should like to thank Ms. Penny Barnett, who constructively criticised my grammar, and who ended up typing this thesis.

REFERENCES

BEVERTON, R.J.H. and S.J. HOLT 1957 On the dynamics of exploited fish populations. *U.K. Min. Agric. Fish. Invest. (Ser. 2)*, *19*:533 pages.

BOHL, H., L. BOTHA and T.H. van ECK 1971 Selection of Cape hake (*Merluccius merluccius capensis* Castelnau and *Merluccius merluccius paradoxus* Franca) by bottom-trawl cod-ends. *J. Cons. int. Explor. Mer.*, *33*(*3*): 438-471.

BOTHA, L. 1970 The growth of the Cape hake, *Merluccius capensis*. *Investl Rep. Div. Sea Fish. S. Afr.*, *82*:1-9.

1971 Growth and otolith morphology of the Cape hakes *Merluccius capensis* Cast. and *M. paradoxus* Franca. *Investl Rep. Div. Sea Fish. S. Afr.*, *97*:1-32.

1973 Migrations and spawning behaviour of the Cape hakes. *S. Afr. Shipp. News and Fishing Ind. Rev.*, *28*(*4*): 62-67.

CENTURIER-HARRIS, O. 1977 Estimates of size and interaction of the South African anchovy and pilchard populations. M. Sc. thesis: University of Cape Town.

CHALMERS, D.S. 1976 Weight conversion factors, length/weight relationship and annual landings of some South African trawl-caught fish. *Fish. Bull. S. Afr.*, *8*:1-4.

DIXON, W.J. (Ed.) 1975 *B.M.D.* *Biomedical Computer Programs*. University of California Press: Los Angeles.

DRAGANIK, B. 1974 Hake stocks exploited in the ICSEAF convention area. *ICSEAF/W.G./74/Inf. Doc/1.*

1976a Fishing mortality of hake stocks exploited in Subarea 1 of the ICSEAF convention area. *ICSEAF Collection of Scientific papers*, *3*:59-84.

1976b An attempt to apply Beverton and Holt's model in assessing the South African hake yield at different levels of fishing intensity. *ICSEAF Collection of Scientific papers*, *3*:85-90.

1978 Equilibrium catch curves for hake fished in division 1.5. *ICSEAF Collection of Scientific papers*, *5*:71-80.

ELWERTOWSKI, J. and A. PIOTROWSKI 1975 An attempt to assess the parameters of hake stocks by means of computer programs. *ICSEAF Collection of Scientific papers*, *2*:44-53.

FOX, W.W. 1970 An exponential yield model for optimizing exploited fish populations. *Trans. Am. Fish. Soc.*, *99*:80-88.

GULLAND, J.A. 1961 Fishing and the stocks of fish at Iceland. *U.K. Min. Agric. Fish. Invest. (Ser. 2)*, *23*(*4*): 52 pages.

1965 Estimation of mortality rates. *Annex to Rep. Arctic Fish. Working Group, Int. Counc. Explor. Sea C.M.*, *1965*(*3*): 9 pages.

JONES, B.W. and T.H. van ECK 1967 The Cape hake: its biology and the fishery. *S. Afr. Shipp. News and Fishing Ind. Rev.*, *22*(*11*):90-97.

KOLENDER, E. 1975 Age and growth rates of hakes in the ICSEAF area. *ICSEAF Collection of Scientific papers*, *2*:70-76.

NEWMAN, G.G. 1974 Changes in hake yield with increased mesh size. *ICSEAF Collection of Scientific papers*, *1*:212-219.

NEWMAN, G.G., R.J.M. CRAWFORD and O.M. CENTURIER-HARRIS 1976 Stock assessment of the hake (*Merluccius capensis* and *Merluccius paradoxus*) on the Cape of Good Hope fishing grounds (ICSEAF Division 1.6). *ICSEAF Collection of Scientific papers*, *3*:141-150.

PELLA, J.J. and P.K. TOMLINSON 1969 A generalized stock production model. *Bull. Inter-Am. Trop. Tuna Comm.*, *13*:419-496.

POPE, J.G. 1972 An investigation of the accuracy of Virtual Population Analysis using Cohort Analysis. *Int. Comm. Northwest Atl. Fish. Res. Bull.*, *9*:65-74.

1973 An investigation into the effects of variable rates of the exploitation of fishery resources. The mathematical theory of the dynamics of biological populations:23-34. Based on a conference organized by the Institute of Mathematics and its applications in association with the Institute of Biology. Edited by M.S. BARTLETT and R.W. HIORNS. Academic Press: London.

RICKER, W.E. 1975 Computation and interpretation of biological statistics of fish populations. *Fish. Res. Board of Canada Bull.*, *191*: 1-382.

ROUX, E.R. 1949 Migrations of the Cape hake or stockfish (*Merluccius capensis* Cast.) on the west coast of South Africa. *Trans. R. Soc. S. Afr.*, *32*(*2*):217-231.

SCHAEFER, M.B. 1954 Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Bull. Inter-Am. Trop. Tuna Comm.*, 1(2):27-56.

THOMPSON, W.F. and F.H. BELL 1934 Biological statistics of the Pacific halibut fishery. 2. Effect of changes in intensity upon total yield and yield per unit of gear. *Rep. Int. Fish. (Pacific Halibut) Comm.*, 6:108-pages.

ULLTANG, O. 1977 Sources of error in and limitations of Virtual Population Analysis (Cohort Analysis). *J. Cons. int. Explor. Mer.*, 37(3): 249-260.

van ECK, T.H. 1969 The South African hake: '*Merluccius capensis*' or '*Merluccius paradoxus*'. *S. Afr. Shipp. News and Fishing Ind. Rev.*, 24(5):95-97.

von BERTALANFFY, L. 1938 A quantitative theory of organic growth. *Hum.Biol.*, 10:181-213.

WALTERS, C.J. 1969 A generalized computer simulation model for fish population studies. *Trans. Amer. Fish. Soc.*, 98(3):505-512.

WYSOKINSKI, A. 1977 Natural mortality in hakes with particular consideration of the South African stock. ICSEAF/SAC/77/S.P./11.