Exploring management procedures for controlling bycatch of Hooker's sea lions in the SQU 6T fishery

NIWA Client Report: WLG2004/97
December 2004

NIWA Project: DOC05303

Exploring management procedures for controlling bycatch of Hooker's sea lions in the SQU 6T fishery

Authors
Ms Susan W. Kim
Mr David J. Gilbert
Dr Paul A. Breen

Prepared for

Department of Conservation

NIWA Client Report: WLG2004/97
December 2004

NIWA Project: DOC05303

National Institute of Water & Atmospheric Research Ltd
301 Evans Bay Parade, Greta Point, Wellington
Private Bag 14901, Kilbirnie, Wellington, New Zealand
Phone +64-4-386 0300, Fax +64-4-386 0574
www.niwa.co.nz

Contents

Executive Summary ii

1. INTRODUCTION 1
   1.1. Specific work required 1

2. Fitting the model to new data 1
   2.1. Bycatch and fishing effort 2
   2.2. Population data 3
      2.2.1. Annual pup birth estimates 3
      2.2.2. Catch-at-age 5
      2.2.3. Age structure of breeding females 6
      2.2.4. Re-sightings of tagged female pups 7
      2.2.5. Re-sightings of branded females 8
      2.2.6. Pups from branded females 9
      2.2.7. Pup mortality data 9
   2.3 Estimation procedures 10
   2.4. Results 10

3. POPULATION CRITERION 19
   3.1. Management goal 19
   3.2. Simple criterion 20
   3.3. A second criterion 20

4. EVALUATING ALTERNATIVE BYCATCH CONTROL RULES 21
   4.1. Bycatch control rules 21
   4.2. Projection procedures 23
   4.3. Indicators 23
   4.4. Results 23

5. DISCUSSION 26

6. REFERENCES 27

Reviewed by: *Approved for release by:*

Alistair Dunn **Dr Rosie Hurst**

Executive Summary

This study extends the approach of Breen & Kim (2004) to modelling the sea lion population at the Auckland Islands, and to evaluating the likely effects of different alternative bycatch control rules.

The study first updated the catch, effort and population data sets with new or revised information provided by DoC. Then the study explored two alternative criteria for evaluating whether a rule would result in a ‘net reduction” in the sea lion population. Although quite different in approach, the two criteria performed similarly in simple simulations, so the simpler was chosen.

The study used the same bycatch control rules used by Breen & Kim (2004). We present results for these rules in terms of the new criterion and we present other indicators as well.

This report is highly constrained by the limited time available, and it should be read in conjunction with the report of Breen & Kim (2004), which describes the model and procedures fully.

1. INTRODUCTION

In late November 2004, NIWA was asked by the Department of Conservation (DoC) to conduct some modelling work on the Hooker's (or New Zealand) sea lion (*Phocarctos hookeri*) population at the Auckland Islands.

This work was a modification and extension of work conducted by Breen & Kim (2004; submitted) for MFish. The former report should be consulted for a discussion of the background to the problem. In brief,

- sea lions are classified as threatened,
- some sea lions are accidentally killed in squid trawls near the Auckland Islands (area SQU 6T),
- MFish currently manages the bycatch under the Fisheries Act, using a management procedure that was tested by the Breen & Kim (2004) work,
- DoC wishes to develop a Population Management Plan under the Marine Mammal Protection Act (MMPA),
- as part of that process DoC required further model runs to address the criteria specified by the MMPA.

1.1. Specific work required

The work asked of NIWA involved three phases:

1. fitting the Breen-Kim model to new data that had been obtained by DoC in the 2003-04 research season, using the same model and assumptions used in the earlier modelling done for MFish,
2. in consultation with DoC, translating the MMPA criteria into an operational criterion that could be used to evaluate model results, and
3. running the model with a set of "bycatch control rules" and evaluating the results with the criterion agreed upon in step 2.

This report will be structured around these three phases.

2. Fitting the model to new data

The Breen-Kim model is fully described in Breen & Kim (2004). It uses the observed bycatch and effort data from the fishery, and is fitted to seven biological data sets. Catch and effort data were available from one additional fishing season (2004) and biological data sets had been extended after the MFish modelling work was completed in mid-2003.

The fishery, breeding activities and research all occur in the austral summer and span parts of two calendar years. We name all such seasons by the January year, *viz.* the 2003-2004 fishing season occurred in February through June 2004 and is called "2004".

2.1. Bycatch and fishing effort

The vector of bycatch and fishing effort data is shown in Table 1. Actual fishing effort is used to calculate the catchability coefficient each year from the estimated bycatch and the model's estimate of vulnerable sea lions. The table also shows the bycatch limit (Fisheries related mortality limit, FRML) imposed each year, the date of fishery closure when applicable, and the 'extrapolated effort" or effort that would have been expended, assuming a 13-week season, had the fishery not been closed early. This is used to estimate the mean and standard deviation of annual attempted effort (the effort that would have been expended had the fishery not been closed early), which in turn was used to estimate the effect of alternative bycatch control rules on the fishery.

Table 1: The annual fishing effort (tows) for the SQU 6T squid fishery, bycatch limits (FRML), estimated sea lion bycatch, dates of closing and extrapolated effort assuming a 13-week season for years when the season was closed. Numbers are taken from the MFish IPP 2004.

Year	Effort (tows)	FRML	Bycatch	Closure date	Extrapolated effort
1988	1737		33	-	1737
1989	3711		141	-	3711
1990	5318		117	-	5318
1991	3500		21	-	3500
1992	2216	32	82	-	2216
1993	654	63	17	-	654
1994	4571	63	32	-	4571
1995	3759	69	109	-	3759
1996	4160	73	104	4-May	4160
1997	3353	79	114	28-Mar	5449
1998	1413	63	63	27-Mar	2296
1999	395	64	12	-	395
2000	1206	65	70	8-Mar	3136
2001	580	75	64	7-Mar	1508
2002	1653	79	84	13-Apr	2149
2003	1383	70	39* (70)	-	1383
2004	2555	124	118		2555
Mean	2480		72		2853

*The final estimate for 2003 was 39 (Suze Baird, NIWA, pers. comm.), but the preliminary estimate of 70 was used in this study and the discrepancy discovered very late in the work. This will have no effect on the estimation, and should have almost no effect on the projections.

2.2. Population data

Population data used by the model in this study were of several kinds, with some overlap among datasets. All new and updated data used in the study were supplied by Louise Chilvers of DoC.

2.2.1. Annual pup birth estimates

Pup births have been estimated annually at each of the four Auckland Islands rookeries since the 1995 breeding season. Before that, from 1943 to 1993, pup birth estimates were sporadic in time; Sandy Bay was always counted in these earlier years; birth estimates at other rookeries were sporadic. Earlier pup birth estimates are considered to be less reliable than the more recent birth estimates (Ian Wilkinson, DoC, pers. comm.).

The estimates are estimated total births including those that died. Pup mortalities are estimated separately (see below). DoC developed a reliability code for each estimate (Table 2) ranging from 1 (a reliable estimate from mark-recapture) to 4 (low reliability). For the earlier study (Breen & Kim 2004) the MFish Aquatic Environment Working Group (AEWG) agreed that only estimates with codes 1 or 2 should be used.

The pup birth estimates are the model's only source of population size information.

Table 2: **Annual estimated pup births and their reliability codes for the four Auckland Islands sea lion rookeries (Ian Wilkinson and Louise Chilvers, DoC, unpublished data). Only reliability codes 1 or 2 were used in the fitting.**

January	Sandy Bay		Dundas Island		Figure of Eight		Southeast Point	
Year	Estimate	Reliability	Estimate	Reliability	Estimate	Reliability	Estimate	Reliability
1943	350	4						
1966	465	2						
1973	525	2	1000	4	29	3		
1975	420	2						
1976	481	2						
1977	428	2						
1978	434	2	2077	2				
1980	193	4						
1981	471	2	2468	3	51	3		
1982	523	2					21	3
1983	142	4						
1984	458	2						
1985	500	2	253	4	47	4		
1986	452	2	1344	2				
1987	473	2	1386	4	105	1		
1990	434	2			120	1		
1991	429	2	1132	4				
1992	489	2	1934	2				
1993	432	1	2086	2	74	1	63	3
1995	464	1	1837	1	132	1	71	1
1996	455	1	2017	1	144	1	69	1
1997	509	1	2259	1	143	1	63	1
1998	477	1	2373	1	120	1	51	1
1999	513	1	2186	1	109	1	59	1
2000	506	1	2163	1	137	1	50	1
2001	562	1	2148	1	94	1	54	1
2002	403	1	1756	1	96	1	27	1
2003	489	1	1891	1	94	1	43	1
2004	507	1	1869	1	87	1	52	1

Methodology for the birth estimates varies from single counts at one time through multiple counts in a single day to mark-recapture estimates in the most recent years. Earlier counts have been corrected by DoC to account for the time of year at which the count was made or for under-counting, but exact methods have not yet been formally described. The short name for this dataset is "pups."

2.2.2. Catch-at-age

Some sea lions caught by the squid fishery are preserved and delivered to DoC, who have organised autopsies since 1997 (Dickie 1999; Gibbs et al. 2002; 2003; Louise Chilvers, DoC, pers. comm.). Part of the autopsy procedure includes estimating the age from rings in the tooth (see Gibbs et al. 2003 for details of the procedure).

Ages compiled from the autopsy reports made available to us are shown in Table 3. In some years we had a choice between "growth layer groups" and "root ridges" as the basis for the age; we chose the former in light of discussions in Gibbs et al. (2003). Where the age was given as a range we used the midpoint; where it was given as a non-integer or as a two-year range we used the integer or lower value, respectively.

This dataset contains information about vulnerability-at-age to the squid fishery: pups are apparently not vulnerable and vulnerability of 1- and 2-yr-olds is low. These data also contain information, in the slope of the decline in catch with increasing age, about survival-at-age.

The short name for this dataset is "Auto".

Table 3: Frequency of ages in autopsied sea lions ("Auto", from Dickie 1999; Gibbs et al. 2002; 2003; 2004; Louise Childers, pers. comm.) and age structure of breeding female sea lions at Sandy Bay ("Popn"; section 2.2.3).

Age	Auto	Popn
0	0	0
1	3	0
2	2	0
3	18	0
4	12	13
5	23	45
6	22	76
7	15	117
8	11	151
9	9	143
10	11	121
11	7	76
12	5	51
13	1	41
14	3	26
15	0	18
16	0	13
17	0	7
18	0	4
19	0	2
20	0	0
21	1	0

2.2.3. Age structure of breeding females

As part of a larger study of the population dynamics of sea lions, DoC biologists estimated the ages of lactating females at the Sandy Bay rookery. In each of 1999, 2000 and 2001, females were captured and sedated with gas, and a post-canine tooth was removed (Simon Childerhouse, DoC, pers. comm.). The estimated ages of 822 animals from the three years were combined for this study (Table 3). A separate study (Childerhouse et al. 2004) compared the known and estimated ages for some previously tagged animals and concluded that ageing error was small.

Because all the animals under "Popn" in Table 3 were breeding, these data comprise the model's main source of information about maturity-at-age. In the slope of declining numbers with increasing age, they also contain information about survival-at-age. In theory this could be confounded with declining fecundity at age, but that would have a similar effect on model results apart from slight changes in the number of vulnerable sea lions relative to the number of pup births.

The short name for this dataset is "Popn". These data remain the same as those used by Breen and Kim (2004).

2.2.4. Re-sightings of tagged female pups

DoC biologists tagged female pups in 1987 and 1990 through 1993. Searches were made for tagged animals in subsequent years, especially in 1999 and later years, and the re-sighting histories of tagged animals were made available (Louise Chilvers, DoC, unpublished data) (Table 4). These data were re-extracted from DoC's database, and differ somewhat, especially for the 2003 re-sightings, from the data used by Breen & Kim (2004) (compare Tables 4a and 4b). The new extract was considered to be best available information.

Table 4a: Numbers of pups tagged in each year (bold) and the number re-sighted in each subsequent year (Louise Chilvers, DoC, pers. comm.).

				Tagged in		Total
Re-sighted	1987	1990	1991	1992	1993	re-sighted
1987	**101**					
1988	0					0
1989	0					0
1990	0	**156**				0
1991	0	3	**193**			3
1992	2	11	8	**241**		22
1993	0	0	0	1	**214**	1
1994	0	0	0	1	0	1
1995	0	0	0	1	0	1
1996	0	9	11	7	13	40
1997	0	1	0	1	0	2
1998	0	2	5	5	1	13
1999	1	24	37	62	60	184
2000	3	23	47	63	68	204
2001	3	21	38	58	54	174
2002	3	14	25	65	57	164
2003	2	15	30	51	51	149
2004	1	12	27	45	48	133

Table 4b: Numbers of pups tagged in each year (bold) and the number re-sighted in each subsequent year, as used in 2003 modelling (Ian Wilkinson, DoC, pers. comm.).

				Tagged in		Total
Re-sighted	1987	1990	1991	1992	1993	re-sighted
1987	**101**					
1988	0					0
1989	0					0
1990	0	**156**				0
1991	0	3	**193**			3
1992	2	12	8	**235**		22
1993	0	0	0	1	**205**	1
1994	0	0	0	1	0	1
1995	0	0	0	1	0	1
1996	0	8	10	6	14	38
1997	0	1	0	2	0	3
1998	0	2	6	4	1	13
1999	1	25	38	61	59	184
2000	3	24	48	62	70	207
2001	3	23	39	58	54	177
2002	3	16	27	66	58	170
2003	2	15	10	40	16	83

This dataset obviously contains information about survival-at-age. The data would have contained good information about immature survival, but re-sighting effort was low in the first five years after tagging for each cohort.

The short name for this dataset is “tags”.

2.2.5. Re-sightings of branded females

In 2000, 135 females with pups at Sandy Bay were branded with a unique number, and these females were recorded again if they returned to the rookery in 2001, 2002, 2003, or 2004. The raw numbers of females observed in each year were 116, 107, 94 and 82 (Ian Wilkinson and Louise Chilvers, DoC, unpublished data). This data set was simply updated by adding the 2004 estimate. Some females were absent in one year and re-sighted in a subsequent year, but we used only the raw re-sightings data.

Some females in this sample had been tagged as pups and thus their ages were known; the mean age of the 49 such animals available to us in 2003 was 8.6 years in 2000. This small dataset contains information about survival of mature females, and hence about survival-at-age. The short name for this dataset is “BF”.

2.2.6. Pups from branded females

The females branded in 2000 were all breeding females. On subsequent observations in later years they were scored as to whether they had a pup or not (Ian Wilkinson and Louise Chilvers, DoC, unpublished data). This was done in two categories: "pupped" or "probably pupped": we added all the former to half the latter. The pups observed in 2001 to 04 were 99, 69, 77 and 66 respectively. This data set was simply updated by adding the 2004 estimate. There is no evidence to suggest that additional pup births from these females occur at any of the other three Auckland Islands rookeries (Ian Wilkinson, DoC, pers. comm.).

This small dataset contains information about the current pupping rates and hence the shape of the density-dependent sub-model; indirectly they have a large effect on the survival parameters. The short name for this dataset is "BFpups".

2.2.7. Pup mortality data

DoC biologists recorded the known pup mortalities through mid-January for each rookery and each year from 1993 to 2003 (Ian Wilkinson and Louise Chilvers, DoC, unpublished data) (Table 5). This data set was simply updated by adding the 2004 estimate. Further data collected past mid-January in recent years were unavailable for this study.

This small dataset (the total mortalities from each year) was the model's main source of information about early pup survival. The short name for this dataset was "pupmort".

Table 5: Total numbers of estimated pup births, deaths by mid-January, and the percentage mortality at all four Auckland Islands rookeries (Louise Chilvers, DoC, pers. comm.).

Year	Total	Alive	Dead	%Mort
1993	2389	2304	85	3.6
1995	2518	2206	312	12.4
1996	2685	2389	296	11.0
1997	2975	2729	246	8.3
1998	3021	2350	671	22.2
1999	2867	2572	295	10.3
2000	2856	2689	167	5.8
2001	2859	2468	391	13.7
2002	2282	1826	456	20.0
2003	2518	2078	438	17.4
2004	2515	2347	168	6.7

2.3 Estimation procedures

The 2003 estimation model was used with exactly the same fixed values, assumptions, priors, phases and initial values used by Breen & Kim (2004). As in 2003, we generated a single long chain of 30 million Markov chain - Monte Carlo (McMC) simulations started from the mode of the joint posterior distribution (MPD), and we saved 5000 regularly spaced samples. Diagnostics reported by Breen & Kim (2004) were not repeated, but the traces were inspected.

2.4. Results

MPD results are shown in Table 6 and compared with Breen & Kim's (2004) results. Table 6 also summarises the posterior distributions of estimated and derived parameters between the two studies. When all the normalised residuals are combined (Figure 1) their distribution follows the normal distribution within plus and minus 2 standard deviations.

The objective function (total negative log-likelihood) increased (the model was fitting to more data). There were no large changes in parameters or in the model's estimate of the state of the population relative to *K* except for the re-sighting probability for 2003, w_{03}^{r}, which increased, perhaps as a result of the revised data.

Table 6: **MPD estimates and summaries of posterior distributions from the 2003 and 2004 fits of the model. Dataset names are as defined in the text. Parameters are defined in Breen & Kim (2004). The last two indicators, N^{mat}/K and N_0/N^{mat} (mature numbers as a proportion of carrying capacity, and pups per mature female) were based on 2003 numbers in the earlier study, and 2004 numbers in this study.**

	2003		2004			
	MPD	**Median**	**MPD**	**5%**	**Median**	**95%**
Negative log-likelihoods						
Total	2797.7	2815.1	3399.3	3411.2	3417.7	3426.6
Pups	310.3	314.7	327.1	331.4	334.2	338.8
Auto	-45.2	-43.1	-46.1	-46.8	-44.1	-38.0
Popn	-51.8	-48.1	-50.1	-51.2	-47.7	-42.7
Tags	2362.7	2369.8	2851.5	2851.6	2858.0	2865.7
BFpups	12.3	11.9	17.3	14.4	15.5	18.1
BF	213.5	213.2	304.2	300.8	304.9	310.7
Pupmort	-6.8	-8.3	-8.1	-12.4	-8.9	-4.0
Parameters						
$\tilde{\sigma}$	0.103	0.112	0.109	0.098	0.114	0.137
K	7393	7376	7701	6735	7288	7978
N1	2137	1959	1188	1362	1945	2851
R0	0.500	0.495	0.500	0.484	0.497	0.500
z	3.085	3.065	4.91	1.88	3.03	5.04
S0	0.866	0.867	0.872	0.858	0.873	0.888
S1	0.084	0.080	0.071	0.063	0.087	0.116
S2	1.000	0.983	1.000	0.977	0.987	0.997
S3	0.018	0.016	0.017	0.014	0.016	0.018
Mat50	6.018	5.645	6.310	5.003	5.780	6.393
Mat95-50	1.821	2.069	1.563	0.847	1.956	3.409
v_{50}	2.86	2.60	2.69	1.89	2.79	4.45
v_{95-50}	0.18	1.21	0.57	0.22	1.93	8.24
σ_1	885	871	841	637	854	1161
σ_2	5555	5067	4431	3724	5019	5889
σ_3	622	644	578	442	636	991
σ_4	375	407	333	247	373	616

Table 6 (Cont): MPD estimates and summaries of posterior distributions from the 2003 and 2004 fits of the model. Dataset names are as defined in the text. Parameters are defined in Breen & Kim (2004).

	2003		2004			
	MPD	**Median**	**MPD**	**5%**	**Median**	**95%**
Q_1	0.177	0.178	0.180	0.172	0.179	0.187
Q_2	0.760	0.760	0.757	0.748	0.759	0.769
Q_3	0.042	0.042	0.042	0.037	0.042	0.047
Q_4	0.020	0.020	0.020	0.017	0.020	0.023
w_{91}^r	0.014	0.017	0.014	0.007	0.018	0.037
w_{92}^r	0.059	0.062	0.055	0.042	0.060	0.083
w_{93}^r	0.002	0.003	0.002	0.001	0.003	0.009
w_{94}^r	0.001	0.003	0.001	0.001	0.003	0.007
w_{95}^r	0.002	0.003	0.001	0.001	0.003	0.008
w_{96}^r	0.066	0.071	0.063	0.056	0.074	0.097
w_{97}^r	0.006	0.008	0.003	0.002	0.006	0.013
w_{98}^r	0.027	0.031	0.024	0.019	0.031	0.048
w_{99}^r	0.440	0.485	0.388	0.401	0.480	0.576
w_{00}^r	0.569	0.630	0.487	0.508	0.611	0.731
w_{01}^r	0.541	0.601	0.481	0.502	0.609	0.731
w_{02}^r	0.663	0.734	0.543	0.566	0.686	0.824
w_{03}^r	0.393	0.434	0.597	0.621	0.755	0.905
w_{04}^r	–	–	0.661	0.682	0.835	0.975
λ	3.3%	3.2%	4.2%	2.1%	3.0%	4.2%
N^{mat}/K	96.2%	95.6%	98.0%	90.4%	95.2%	97.6%
N_0/N^{mat}	37.9%	38.3%	34.6%	34.8%	38.7%	42.1%

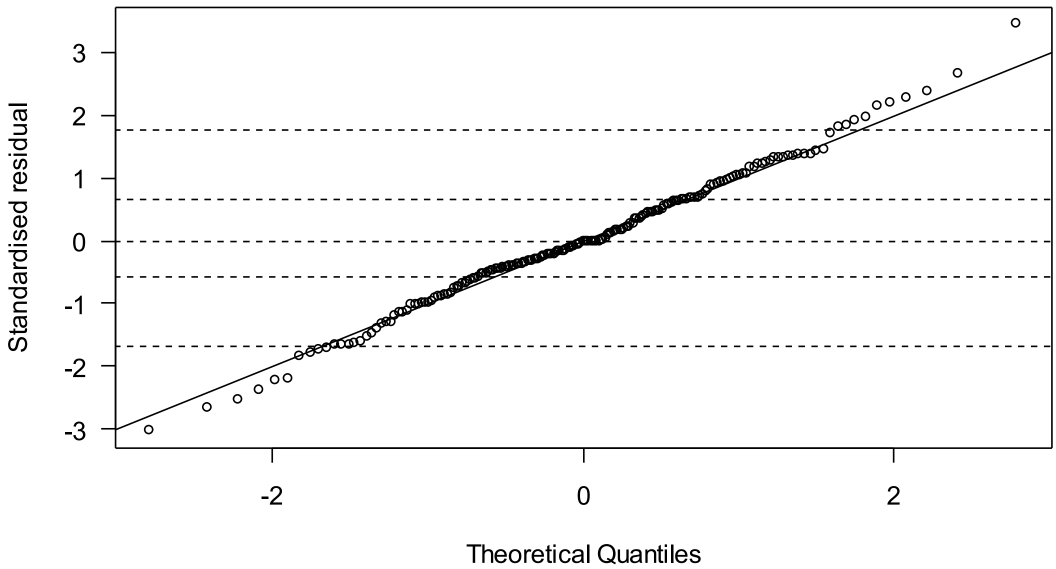

Figure 1: Q-Q plot of all normalised residuals (excluding those from the fits to tag-re-sighting data) from the base case MPD. The dotted lines show the median and 5th, 25th, 75th and 95th percentiles.

The model's fit to the data (Figure 2 to Figure 6) was much the same as it had been in 2003. The fit to pup birth estimates is very flat (Figure 2), reflecting the model's reconstruction of a stable population. Fits to the tag re-sighting data (Figure 3) were quite good except for the first tagged cohort, from 1987. Fits to the two -at-age data sets "Auto" and "Popn" (Figure 4 and Figure 5) were generally reasonable and showed the same patterns discussed by Breen & Kim (2004). The model had a tendency to under-estimate the number of pups from branded females ("BFpups") in the past two years (Figure 6).

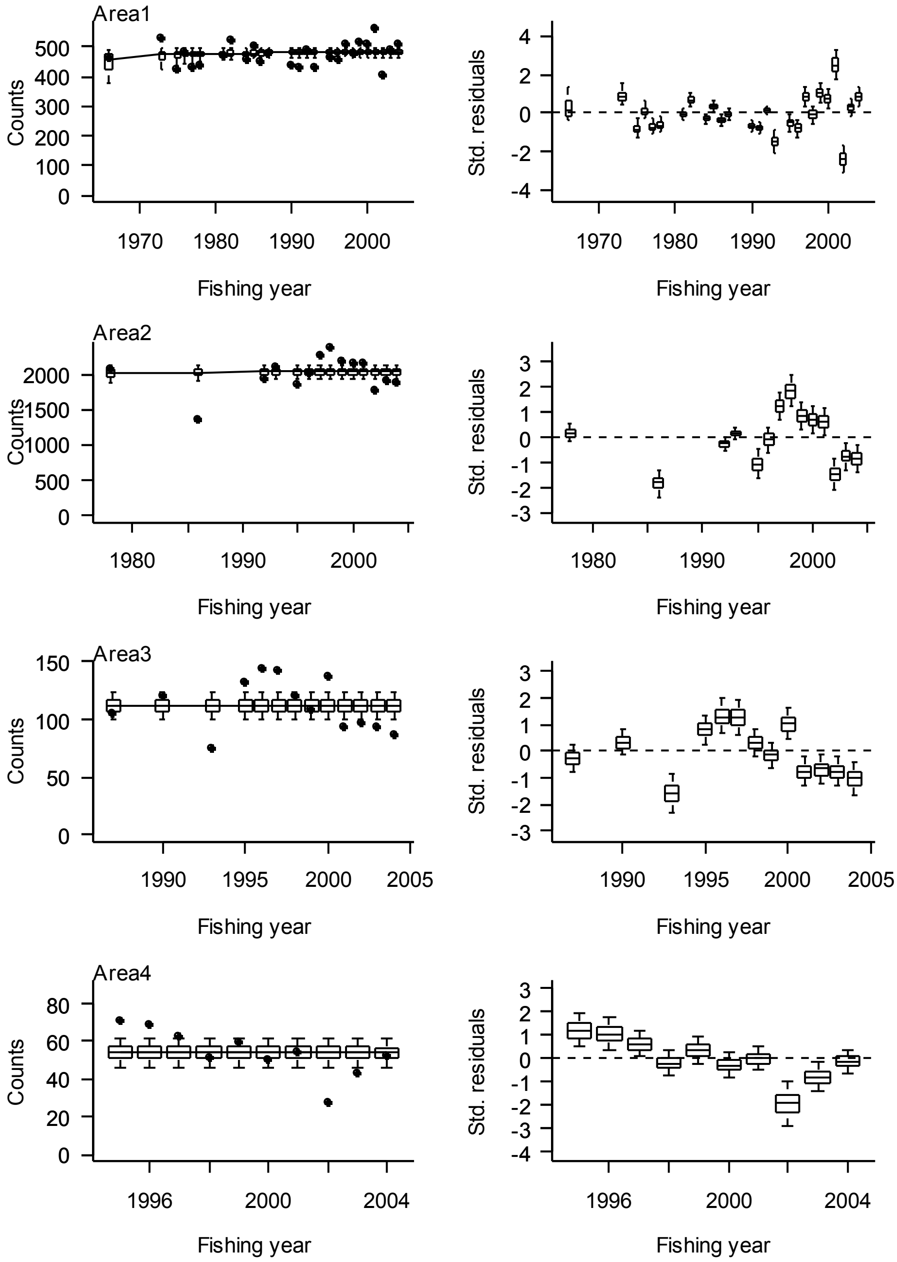

Figure 2: **Fits to pup birth estimates (left) and normalised residuals (right) for (from the top) Sandy Bay, Dundas, Figure of Eight and SE Point. The box plots summarise posterior distributions: median, 25th and 75th percentiles (box) and the 5th and 95th percentiles (whiskers). Dots on the left-hand plots are the observed values.**

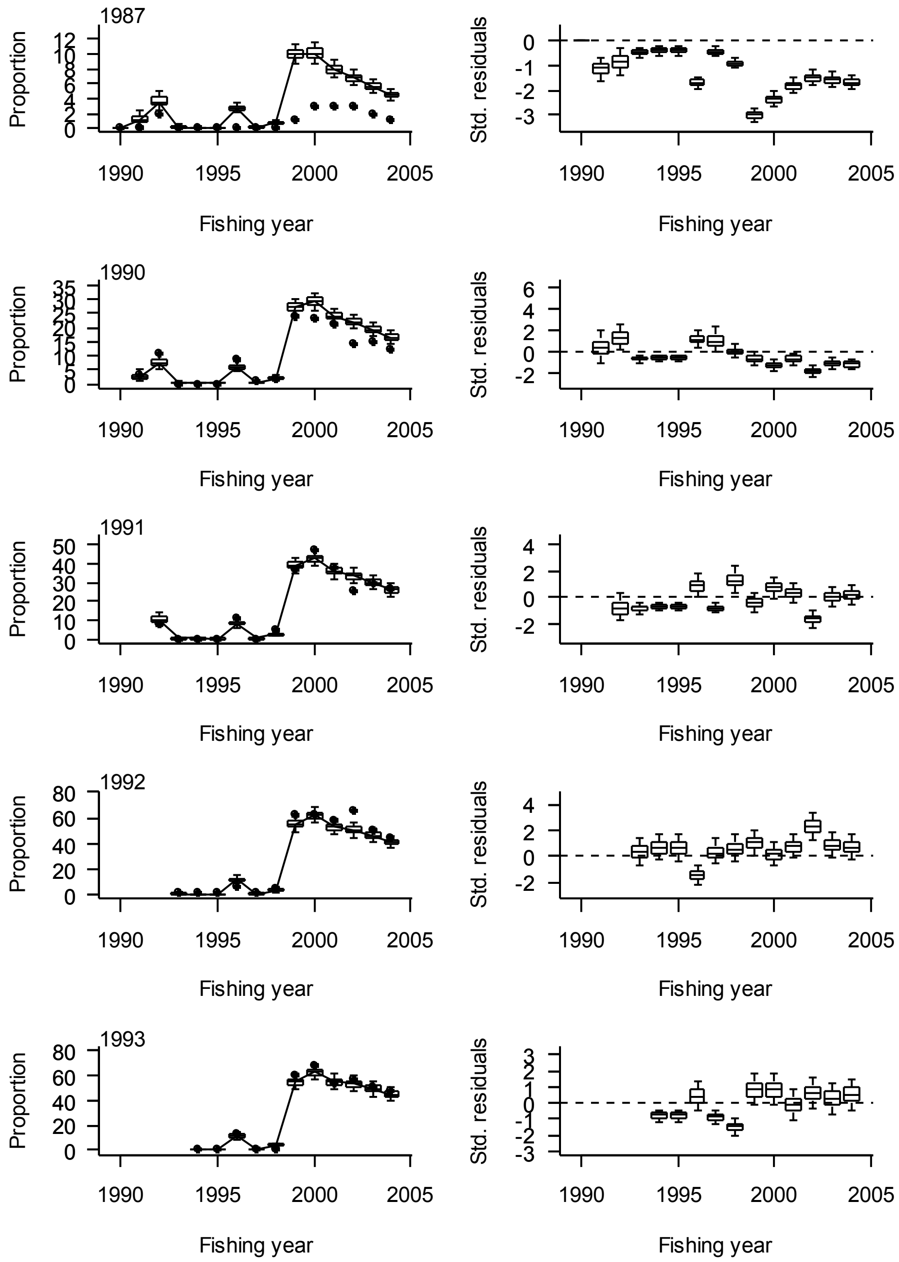

Figure 3: Fits and residuals to the tagged pup re-sighting data. The year of tagging is given at the top left for each fit plot.

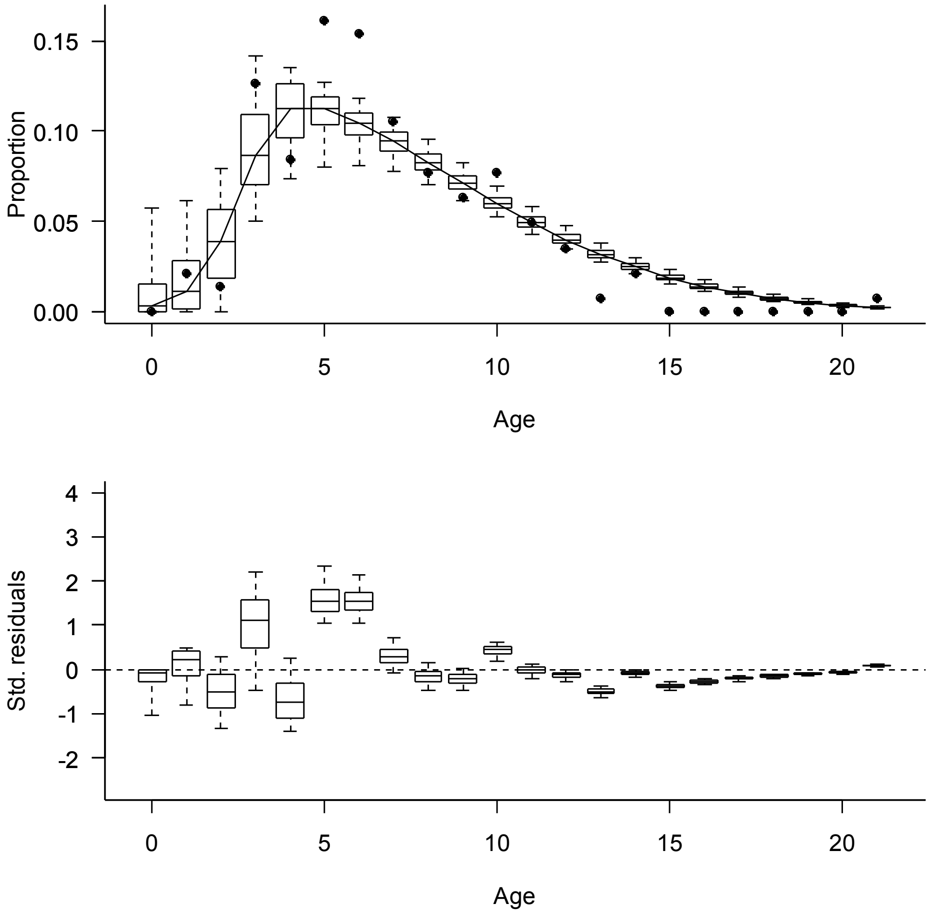

Figure 4: The fit (upper) and residuals for the catch-at-age data.

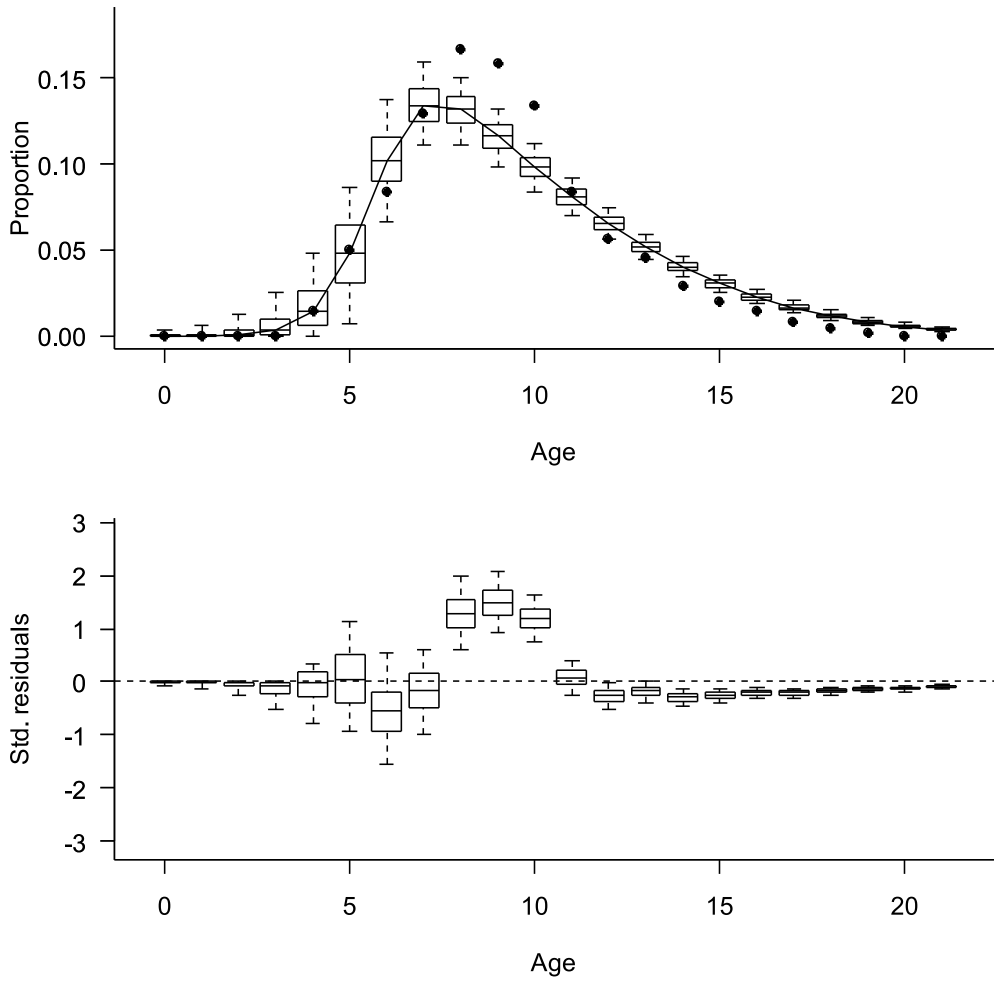

Figure 5: The fits and residuals for the breeding female age data.

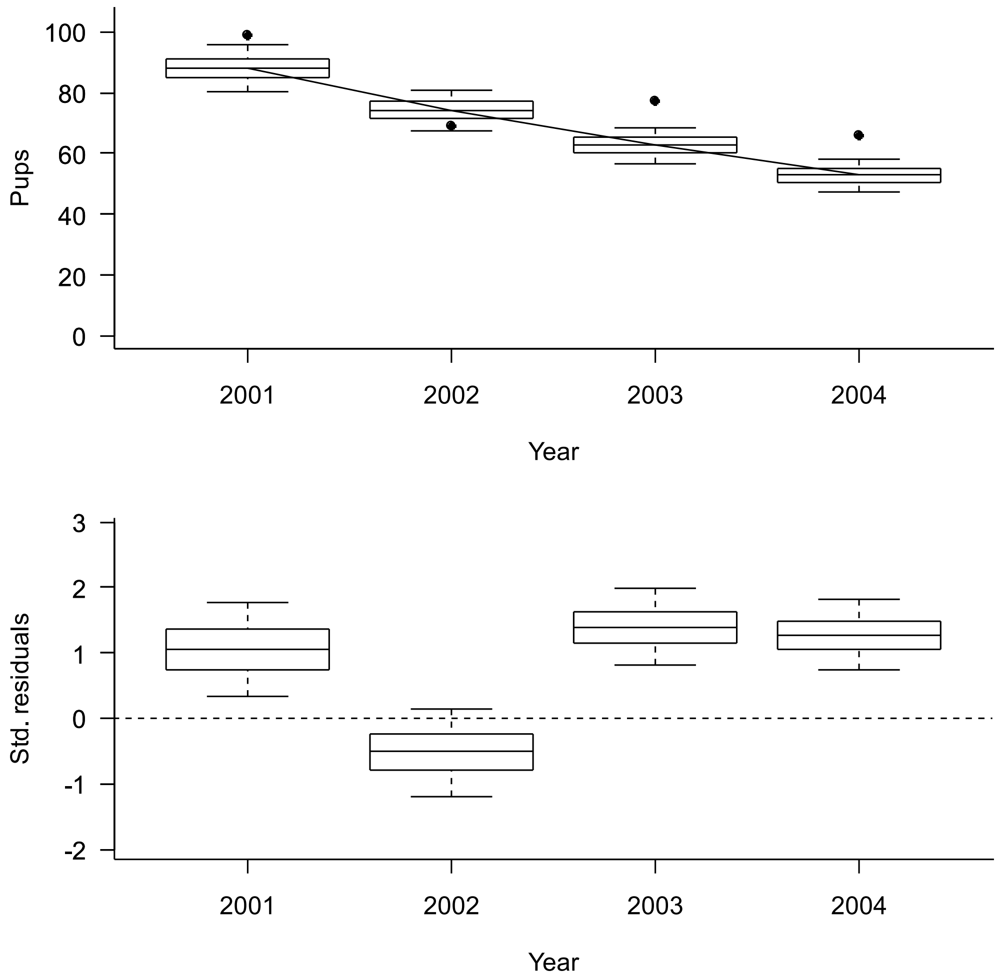

Figure 6: The fits and residuals for the observed pups from branded females.

3. POPULATION CRITERION

3.1. Management goal

The goal addressed by Breen & Kim (2004), that had been developed and agreed by the AEWG, was

> *To ensure the sea lion population remained above 90% of its carrying capacity, K, or else remained above 90% of the level it would obtain in the absence of fishery bycatch, 90% of the time in 20-year and 100-year runs.*

Under the relevant legislation, DoC requested NIWA to address the following alternative goal:

> *Fishing related mortality should neither cause a net reduction in the size of the population nor seriously threaten the reproductive capacity of that population.*

It was determined by DoC or agreed in discussions that:

- "the population" refers to the population that is discrete and occurring within the boundaries of the fisheries management or quota management area during the breeding season (December – February) for which an area-based "Maximum allowable fisheries related mortality (MALFiRM) is to be established, in this study the Auckland Islands population;
- "size of the population" refers to the number of sexually mature individuals in 2004, estimated in this study by the posterior distribution;
- the period over which modelling would assess "net reduction" was 20 years, and the study would be based on a comparison of numbers in 2024 with 2004; and
- the "no net reduction" criterion was considered a stricter test in this situation than the "seriously threaten the reproductive capacity" criterion, so the latter would automatically be satisfied if the "no net reduction" criterion were satisfied, and only the former was tested.

We explored, in discussion with DoC, two alternative criteria for assessing the results of model runs with respect to "no net reduction". In the model, sets of runs are made from the 5000 samples of the joint posterior distribution obtained from the McMC. In a set, the initial population in 2004 is different for each of the 5000 runs. In addition, random error is added to survival and pupping, and random observation error is added to the estimated pup births, influencing the operation of the bycatch control rules.

3.2. Simple criterion

In a set of runs, 5000 runs are made, all starting from different initial values and fluctuating stochastically. In these runs, some populations increase and some decrease over the 20 years. The first criterion considered was therefore

$$P'^{\mathrm{X}} = \frac{\mathrm{count}\left[N_{20,i}^{\mathrm{X}} < N_{0,i} \right]}{5000}$$

where P'^{X} is the probability obtained by counting the runs that satisfy the inequality, under bycatch control rule X, that the population will decrease in the *i*th run, $N_{20,i}^{\mathrm{X}}$ is the mature population size in the *i*th run after 20 years (in 2024) and $N_{0,i}$ is the mature population size in the *i*th run initially (in 2004). An interpretation of the "no net reduction" criterion was that this would be achieved when some rule, Rule X, produced $P'^{\mathrm{X}} = 0.50$. That is, if the chance of increase and decrease are equal, when integrated over the estimation and process uncertainty, the median expectation for the population is "no net reduction".

3.3. A second criterion

The criterion above does not examine the scale of fluctuation caused by stochastic changes in population processes. A second criterion was considered that did so:

$$P^{\mathrm{X}} = \frac{\mathrm{count}\left[N_{20,i}^{\mathrm{X}} < \gamma \times \frac{1}{5000} \sum_{i=1}^{5000} N_{0,i} \right]}{5000}$$

The parameter γ is related to the scale of variation in N_{20}^{X}, and is

$$\gamma = \frac{p^{10}\left(N_{20}^{\mathrm{X}}\right)}{\frac{1}{5000} \sum_{i=1}^{5000} N_{20,1}^{\mathrm{X}}}$$

where $p^{10}\left(N_{20}^{\mathrm{X}}\right)$ denotes the 10th percentile of the distribution of numbers after 20 years. Simple simulations suggested that, in the absence of any change in mean or median population size, the value of P^{X} is 0.10 if the 10th percentile is used to calculate γ, 0.05 if the 5th percentile is used and so on. In simple simulations, $P'^{\mathrm{X}}=0.50$ and $P^{\mathrm{X}}=0.10$ when distributions were compared that had no mean change.

Thus either criterion, the simple or the second alternative, could be used to assess "no net reduction" in the sets of model runs. Both appeared to be robust to skewness in the distributions in the absence of any real change in mean or median population size. The precision of the second criterion was slightly higher, but precision could be increased by making more model runs, with different random numbers, from the same bycatch control rule.

After discussions with DoC, on the basis that these criteria appeared equivalent, the simpler one, P'^{X} =0.50, was chosen to assess whether rule *X* produced "no net reduction".

4. EVALUATING ALTERNATIVE BYCATCH CONTROL RULES

In this part of the study, we explored a family of bycatch control rules to find the one that produced "no net reduction", or P'^{X} =0.50.

4.1. Bycatch control rules

DoC requested that we use the family of bycatch control rules described by Breen & Kim (2004). The basis for this family is the approach taken by MFish before 2004, based on the work of Wade (1998). Each year, a bycatch limit or FRML was calculated from the previous two years' estimates of vulnerable sea lions:

$$C_y^{FRML} = 0.5\left(\frac{N_{y-1}^{vuln} + N_{y-2}^{vuln}}{2}\right)\lambda F_r$$

where N_y^{vuln} is a conservative estimate of the number of sea lions vulnerable to being caught in year y, which includes some immature animals, λ (called $R_{\max}$ in Wade 1998) is the maximum rate of population increase and F_r is a "recovery factor". The central term is the mean, over two years, of conservative estimates of the number of sea lions vulnerable to being caught.

N_y^{vuln} was taken as the lower 20th percentile of the population estimate obtained from the Gales and Fletcher (1996) model, as calculated each year by DoC. The inputs were estimated pup births in year *y* from Campbell Island and the Auckland Islands combined, and a set of assumed distributions of population parameters. There was a one-year lag because of the need to consult on bycatch management: for instance, the 2001 pup birth estimates were first used in the calculations for the alternative FRML limits for the 2002 fishing season. Wade (1998) suggested that λ = 0.12 would be a suitable default value for pinnipeds, but λ = 0.08 was adopted in New Zealand. F_r was set at 0.15.

The modelling work of Breen & Kim (2004) explored simple variants of the Wade rule used in New Zealand. In that work, the Wade rule was simplified so that it could be evaluated within the model without reference to the Gales and Fletcher model. In this version, the empirical relation between estimated pup births (at the Auckland Islands only) $N_{0,y}$ and vulnerable numbers N_y^{vuln} was estimated, then this was combined with the λ and F_r constants into a single constant:

$$C_y^{FRML[310]} = 0.02577\left(\frac{N_{0,y-1} + N_{0,y-2}}{2}\right)$$

where $N_{0,y}$ is the estimated number of pup births, at the Auckland Islands rookeries only, in year y.

In the modelling work, this rule was named Rule 310, where "3" denoted the Wade rule family and "10" denoted 1.0 times the New Zealand version of the Wade rule. Two other variants were explored by Breen & Kim (2004): Rule 305, which gave exactly half the bycatch limit of Rule 310, and Rule 320, which gave twice the bycatch limit of Rule 310. These are members of a general family of rules described by the equation below. In Rule 305, $n = 0.5$; in Rule 310, $n = 1$; in Rule 320, $n = 2$.

$$C_y^{FRML[3n]} = n\left[0.02577\left(\frac{N_{0,y-1} + N_{0,y-2}}{2}\right)\right]$$

Further variants, with n up to 11, were explored in further (Breen & Kim, submitted). One rule, with n = 9.23, was called the "cusp rule" because it only just satisfied the criteria identified by the AEWG.

For this work we used rules in this family from Rule 300 (no fishing) (=Rule 0) to the cusp rule (Rule 392), and one that had no limitation on fishing (Rule 1). This rule does not limit fishing, but assumes a mean effort of 2910 tows with a specified standard deviation, based on the fishery history. The "adaptive" Rule 4 of Breen & Kim (2004) was also used:

$$C_y^{FRML[4]} = 102\left(\frac{N_{0,y-1} + N_{0,y-2}}{2\bar{N}}\right)^2 + 32\left(\frac{N_{0,y-1} + N_{0,y-2}}{2\bar{N}}\right)^4$$

where $\bar{N}$ is the mean number of pup births observed from 2000 through 2004.

4.2. Projection procedures

Projection procedures were described in Breen and Kim (2004). To increase the precision of estimating P'^{X} we made sets of 25,000 runs each, i.e. making 5 runs from each sample of the joint posterior distribution, using different random number sequences.

One small change from previous practice was as follows.

During the projection, the model calculates an average catchability parameter, *lnmeanq*, from the bycatch, number of tows and vulnerable sea lion numbers each year. In this study, the 2003 and 2004 estimates of bycatch were not used in this calculation because MFish changed its procedures: no independent estimates of bycatch were made, as in previous years. Instead, MFish adopted a fixed "strike rate" and estimated bycatch from the product of this strike rate and the number of tows.

4.3. Indicators

As well as the criterion P'^{X} described above, we agreed in discussions with DoC to estimate the following indicators used by Breen & Kim (2004):

- *"effortlost"*: the median (of the 5000 runs) of the mean (over the 100 years in each run) of tows lost through the operation of the bycatch control rule during the run, as a measure of cost to the fishing industry,
- *"%closed*": the median percentage of seasons closed early through the operation of the bycatch control rule during the run.
- "*maxcatch*": the median of maximum annual bycatch in each run,
- "*meancatch*": the median of mean annual bycatch in each run,
- "*pupmin*": the median of minimum pup birth estimates in each run, and
- "*pupmax*": the median of maximum pup birth estimates in each run,.

The specific equations for calculating these were provided by Breen & Kim (2004).

4.4. Results

The results are shown in Table 7. The rule that comes closest to $P'^{X} = 0.50$ was Rule 314 (Figure 7), i.e. the rule that sets limits that are 1.4 times those set by Rule 310. This rule had a median of mean annual catch of 64 animals (over 20 years), and a median maximum bycatch of 114 animals.

The rule would close the fishery early in a median of 38% of seasons and cause a median loss of 622 tows out of a mean attempted 2910 tows (21%). These estimates are made assuming that the bycatch is estimated each year and that there is no carry-over of 'unused' bycatch from previous years. The model does not attempt to simulate the recent practice of assuming a strike rate and estimating bycatch from the product of effort and strike rate.

Table 7: Results from various bycatch control rules. The first column is the percentage of runs in which numbers after 20 years were less than the initial numbers. Other indicators are described above, and the values shown are the medians of posterior distributions. Rule 300 has no fishing, other rules in the 300 series are as described in the text, Rule 392 is the so-called cusp rule, Rule 1 has no bycatch control rule, Rule 4 is the adaptive rule described in the text.

Rule	P'^{X}	*effortlost*	*%closure*	*maxcatch*	*meancatch*	*pupmin*	*pupmax*
Rule 300	0.3179	2910	100%	0	0	1775	3851
Rule 305	0.3976	1622	77%	43	31	1775	3847
Rule 310	0.4607	931	52%	83	52	1773	3842
Rule 312	0.4805	758	45%	99	59	1773	3841
Rule 314	0.4991	622	38%	114	64	1772	3840
Rule 315	0.5068	565	35%	121	67	1772	3839
Rule 316	0.5144	515	33%	128	69	1772	3838
Rule 318	0.5259	429	28%	142	73	1772	3837
Rule 320	0.5389	360	24%	156	76	1771	3836
Rule 330	0.5750	164	12%	217	88	1769	3832
Rule 350	0.6046	46	4%	304	97	1767	3829
Rule 370	0.6143	17	2%	349	100	1767	3828
Rule 392	0.6187	6	1%	373	101	1766	3827
Rule 1	0.6223	0	0%	397	102	1766	3826
Rule 4	0.5386	378	25%	188	76	1770	3836

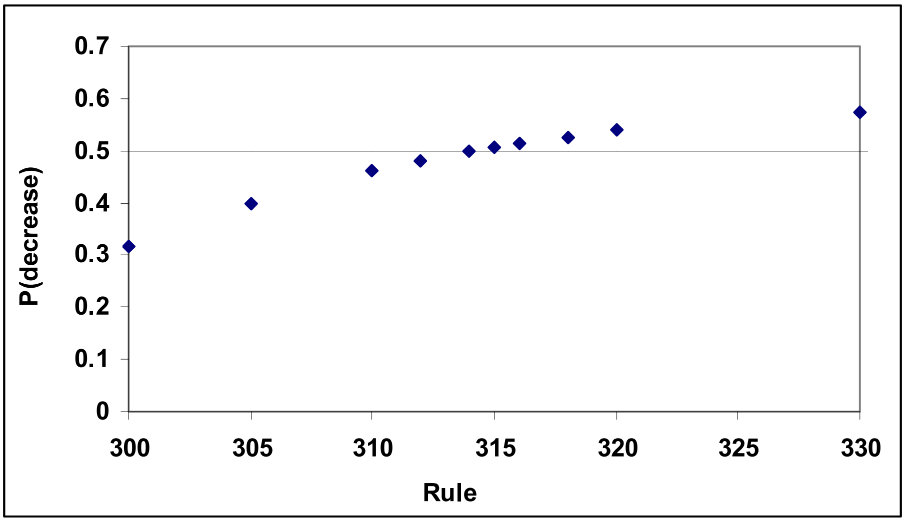

Figure 7: Showing the main criterion P'^{X} for each rule in the 300 series up to Rule 330. The horizontal line shows P'^{X} = 0.50.

The average bycatch does not increase indefinitely as the rules increase, but has an asymptote near 100 animals (Figure 8). Maximum bycatch also reaches an asymptote (Table 7).

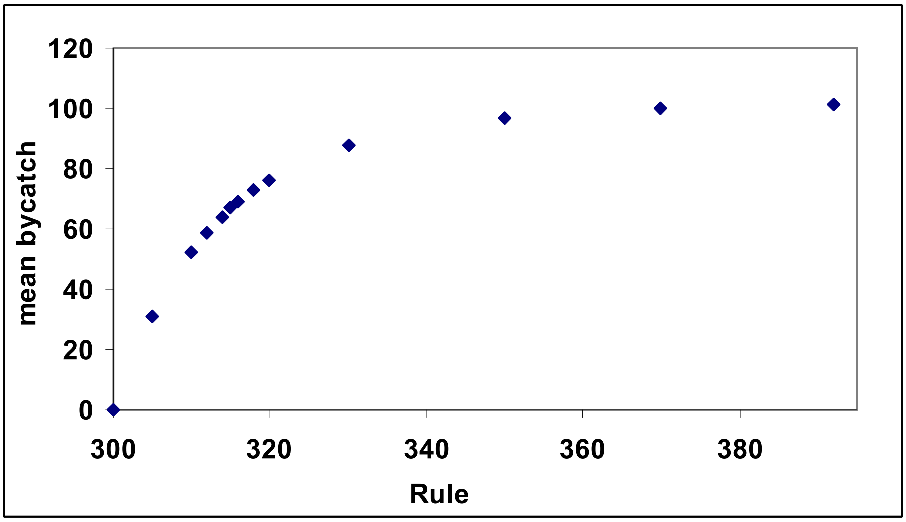

Figure 8: Mean bycatch for each rule.

The various bycatch control rules have little effect on the pup indicators: both minimum and maximum pup births decrease by about 0.5% between Rules 300 (no fishing) and Rule 1 (no bycatch control).

5. DISCUSSION

This study was seriously limited by the time available. The approach taken was to replicate the 2003 procedures except for updating the various data sets used, incorporating the new criterion required by DoC, and a small change to calculating catchability to avoid using bycatch estimates that were not real estimates. Changes to the model suggested by Breen & Kim (2004) could not be made, and at least one data set, not available in 2003, was not used because doing so would have involved new coding.

Breen & Kim's (2004) discussion of model fitting should be read in conjunction with this report.

The model's parameter and population estimates were similar to those from 2003 (Breen & Kim 2004). This suggests that sensitivity trials and other diagnostics would also have similar results to those reported by Breen & Kim (2004).

Results suggest that Rule 314 is closest to the rule that controls bycatch to prevent any "net reduction" in the expected mature sea lion population. The study used 20 years as the period to over which to examine change, but a rule that produces no net reduction over 20 years should produce no expected reduction over any period.

When rules are compared, the differences between rules in the 312 to 316 range are small (Figure 7, Table 1). The relation between P'^{X} and the rules crosses the 50% line at a shallow angle (Figure 7), so probably the exact place at crossing is sensitive to small changes in modelling choices, i.e. the precision of the rule multiplier is probably not very high. The choice of rule in this area does not affect P'^{X} much (Table 7) but has greater effects on the fishery indicators.

The model results are made under the assumption that a bycatch control rule would be implemented as a management procedure (Butterworth & Punt 1999), and that the same rule would automatically generate bycatch limits for some period. In the model, populations fluctuate widely for any rule. In reality, the sea lion population will also fluctuate naturally at any bycatch limit or under any rule, through the agencies of disease, parasites, food supply fluctuations, predation and other influences on population processes. As well as this variability, the pup birth estimates themselves are subject to process and observation error. All parties should therefore be aware that if a management procedure is adopted, an increase or decrease in the pup birth estimate over a short period could not be taken as evidence that the bycatch control rule was succeeding or failing in its purpose.

At the same time, a management procedure such as Rule 314 should be implemented with a review date, perhaps five years after implementation. By then, more and perhaps better data would be available, and modelling technology would also have improved.

6. REFERENCES

Breen, P.A.; Kim, S.W. (2004). Exploring alternative management procedures for controlling bycatch of New Zealand or Hooker's sea lion in the SQU 6T arrow or Wellington flying squid fishery. Final Research Report for Ministry of Fisheries Research Project MOF2002/03L Objective 3.

Breen, P.A.; Kim, S.W. (submitted). An integrated Bayesian evaluation of Hooker's sea lion bycatch limits. Wakefield Symposium Series, Alaska Sea Grant.

Butterworth, D.S.; Punt, A.E. (1999). Experiences in the evaluation and implementation of management procedures. *ICES Journal of Marine Science 56:* 985 – 998.

Childerhouse, S; Dickie, G.; Hessel, G. (2004). Ageing live New Zealand sea lions (*Phocarctos hookeri*) using the first post-canine tooth. *Wildlife Research 31:* 177-181.

Dickie, G. (1999). Population dynamics of New Zealand fur seals (*Arctocephalus forsteri*) and New Zealand sea lions (*Phocarctos hookeri*). MSc Thesis, University of Otago, Dunedin, New Zealand.

Gales, N.J.; Fletcher, D.J. (1996). Abundance, distribution and status of the New Zealand sea lion *Phocarctos hookeri*. New Zealand Department of Conservation, PO Box 10-420, Wellington, New Zealand.

Gibbs, N.J.; Duignan, P.J.; Gareth, W.J. (2002). Autopsy of pinnipeds incidentally caught in commercial fisheries, 2001/2001. Final Report 11-11-2002 to the Department of Conservation. Institute of Veterinary, Animal and Biomedical Sciences, Massey University, Palmerston North, New Zealand.

Gibbs, N.J.; Duignan, P.J.; Gareth, W.J. (2003). Autopsy of pinnipeds incidentally caught in fishing operations 1997/98, 1999/2000, and 2000/01. Unpublished report to the Department of Conservation, PO Box 10-420, Wellington, New Zealand.

Wade, P. (1998). Calculating limits to the allowable human caused mortality of cetaceans and pinnipeds. *Marine Mammal Science 14*: 1-37.