A Decade of Namibian Fisheries Science
Payne, A. I. L., Pillar, S. C. and R. J. M. Crawford (Eds). *S. Afr. J. mar. Sci. 23: 205–221*
2001

THE ORANGE ROUGHY FISHERY OF NAMIBIA: LESSONS TO BE LEARNED ABOUT MANAGING A DEVELOPING FISHERY

D. C. BOYER, C. H. KIRCHNER*, M. K. McALLISTER†, A. STABY* and B. I. STAALESEN‡*

Exploration for orange roughy *Hoplostethus atlanticus* in Namibia started in 1994 and within 12 months several aggregations had been discovered, suggesting the existence of a biomass sufficient to support a viable fishery. At that early stage it was realized that few, if any, recognized management procedures existed for newly developing fisheries, especially with the paucity of data such as existed on Namibian orange roughy. The development of the Namibian orange roughy fishery is reviewed to document the management strategies implemented and how the management of the fishery evolved. The first six years of the fishery are described, including the three-year exploration phase, several years of profitable exploitation, and the severe decline in catch rates. Whether the decline is attributable to fishing mortality or to change in the aggregating behaviour of orange roughy, or both, is not clear. Although many aspects of the precautionary approach were followed, a risk analysis applied and a number of innovative management methods implemented (e.g. incentives to promote exploratory fishing, use of Bayesian statistical methods, implementation of a management plan for long-term total allowable catches), the aggregating biomass declined to between 10 and 50% of virgin levels within the six years. The management methods applied are evaluated in the light of the severe decline in catch rate experienced in 1998 and 1999, so that others may learn from the experience.

Key words: assessment, management, Namibia, orange roughy, uncertainty

Some 70% of the world's continental shelf fisheries are classified as fully or overexploited (F.A.O. 1997). In order to meet the ever-increasing demand for fish products, exploratory ventures are searching for unexploited stocks on the continental shelf slopes and beyond (Moore and Mace 1999). When new stocks are discovered, there is inevitably considerable uncertainty about their size or productivity, industry has to decide how much to invest in the fishery, and fishery management authorities are faced with critical decisions on management controls. Commercial catch trends and time-series of research surveys are inevitably lacking and, therefore, the traditional tools for stock assessment are not applicable. All therefore encounter large risks. These risks can be particularly severe for deep-water fish, which tend to be long-lived and hence highly vulnerable to overexploitation, whereas the cost of exploiting stocks at great depth and far from land is often high. Given the current expansion of many fishing fleets into deep- and distant-water fisheries, especially those for Patagonian toothfish *Dissostichus eleginoides*, alfonsino *Beryx splendens* and orange roughy *Hoplostethus atlanticus*, these risks are very real and need addressing.

There are currently few well-established protocols on how to manage a newly developing fishery, apart from some theoretical, untested suggestions (e.g. Smith *et al.* 1992, Clark and Tracey 1994, Clark 1995, Francis and Shotton 1997, Branch 1998, McAllister and Kirkwood 1998, Walters 1998, Miller 1999). One example of an adaptive management proposal for a new fishery that has been put into practice is the ORH1 orange roughy fishery in the Bay of Plenty, New Zealand. The intention for that fishery, which essentially was only discovered in 1994, was to allow catches to increase to 1 000 tons per year over a five-year period in a controlled fishing-down experiment, while the fishery was monitored through surveys and analysis of catch data (Starr *et al*. 1996). Catches were considerably below this target level throughout the period, but surveys still indicated a large reduction in biomass. Recent analysis of the data, however, suggest that the decline was due to a change in distribution of the stock rather than solely attributable to fishing, so an increase in the Total Allowable Catch (*TAC*) in line with the adaptive management programme has been proposed (Anon. 2001).

In any new fishery, managers must decide how to limit entry, and harvesting decision rules and management strategies need to be developed. Decisions on the

* National Marine Information and Research Centre, Ministry of Fisheries and Marine Resources, P.O. Box 912, Swakopmund, Namibia. E-mail: dboyer@mfmr.gov.na
† Renewable Resources Assessment Group, Department of Environmental Science and Technology, Imperial College, Royal School of Mines, Prince Consort Road, London SW7 2BP, UK
‡ Formerly Institute of Marine Research, P.O. Box 1870 Nordnes, N-5817, Bergen, Norway; now Braavallgt. 1c, 5522, Haugesund, Norway

Manuscript received November 2000, accepted August 2001

data to be collected (usually with limited resources) must be made early, and robust stock assessment methods appropriate to data-poor situations need to be applied. Simultaneously, development of the fishery must be encouraged, despite the high costs and the lack of guarantees of long-term, economically viable returns. A formal assessment of the risks of overfishing has been proposed for many types of fisheries, including developing ones (Francis and Shotton 1997), but this has only been applied rarely to management (Bergh and Butterworth 1987, Butterworth and Bergh 1993).

In this paper, the recent development of the Namibian orange roughy fishery is reviewed to document the strategies implemented and how the management of the fishery evolved in tandem with the fishery itself. The first six years of the fishery are described; they include the three-year exploration phase, several years of profitable exploitation, and the subsequent severe decline in catch rates. Many innovative fisheries management tools were applied, including aspects of the precautionary approach. A risk analysis was attempted and Bayesian statistical methods were used to model the resource probabilistically and to incorporate judgements about the potential biases in different indices of abundance. Also, incentives were introduced to promote exploratory fishing, and a long-term management plan was implemented. Despite the implementation of these strategies, the fishery declined sharply within just six years. Finally, some suggestions are given on what went wrong, and why, and how in hindsight different recommendations may have been offered to management.

The paper is structured largely in chronological order. Some notes on the pertinent biological aspects of orange roughy are followed by a description of the deep-water fishery. This is followed by a year-by-year account of the development of the fishery, the data collected, the stock assessment techniques employed and the management decisions implemented. Finally, the most valuable lessons to be learned from the experience with Namibian orange roughy are discussed.

ORANGE ROUGHY

Orange roughy, a trachichthyid fish, has a worldwide distribution (Kotlyar 1996) at depths between 500 and 1 500 m. Major stocks are found off New Zealand and Australia, and smaller ones along the Mid-Atlantic Ridge, off Namibia (Clark *et al.* 2000) and along the Madagascar Ridge in the southern Indian Ocean. The common name is attributable to its body colour and hard skeletal plates that give the head a "rough" appearance. The flesh is soft-boned, firm and white, and it has a subtle taste. It is popular in the USA, where it commands high prices.

The orange roughy fishery in New Zealand started in 1979, and catches peaked in 1989 at 54 000 tons (Robertson 1991, Clark and Tracey 1994). *TAC*s were reduced during the 1990s, reaching <20 000 tons by the end of the decade as some of the main stocks became fully or overexploited, although annual catches were supplemented with short-lived large catches from newly developed fisheries for the species (Clark 2001). The Australian fishery started in 1986, peaked in 1990 with an annual catch of 42 000 tons (Smith 1991), but declined to 5 000 tons by 1995. Until recently the only other fishery of any note, apart from Namibia's, was a small and inconsistent fishery that developed in 1990 in the North Atlantic, yielding peak annual catches of some 4 000 tons (Tracey and Horn 1999). Then, during 1999 and 2000, a largely unregulated fishery developed along the Madagascar Ridge, although its long-term potential is not known.

Orange roughy form dense spawning aggregations during the austral winter, between late June and early August in New Zealand (Clark 1995), Australia (Koslow *et al.* 1994) and Namibia. These aggregations are often associated with bottom features such as pinnacles and canyons, although the fish may form plumes extending up to 200 m above the seabed. The formation of aggregations is well-synchronized and at the same time each year (Clark 1996), although not all individuals spawn annually (Clark and Tracey 1994). The aggregating behaviour persists throughout the year, but at lower densities outside the spawning season. It is assumed that these aggregations are for feeding purposes (Clark and Tracey 1994). A consequence of this seasonal trend in aggregating behaviour is that catch rates are high from June to August, but much lower for the rest of the year (Staby 2000).

Aggregating behaviour makes orange roughy highly susceptible to overfishing, trawl catches of >20 tons within several minutes of bottom contact being common. However, such densities allied to a hard, rough seabed, require fishers to be highly skilled and to have available advanced fish-finding equipment and robust trawl gear. Considerable gear damage and loss of equipment is quite normal.

The longevity of orange roughy is a controversial issue (Tracey and Horn 1999), with some studies concluding that fish may live more than 100 years (Mace *et al.* 1990, Fenton *et al.* 1991, Smith *et al.* 1995) and others claiming that they are much shorter lived (Gauldie 1998; see Francis [1992] for a description of the basic life history characteristics of New Zealand orange roughy). In Namibia it was decided to take the precautionary approach so, for stock assessment

Table I: Number of participants and annual catches in the Namibian orange roughy fishery (inactive licences in parenthesis)

Year	Companies	Vessels	Catch (tons)
1994	1	1	29
1995	1	1	6 743
1996	1	3	11 892
1997	3 (5)	4	15 517
1998	3 (5)	5	11 792
1999	3 (5)	5	2 498

purposes, orange roughy were considered long-lived, with slow growth rates, late maturity and low fecundity (Clark 1995). Therefore, productivity of orange roughy is considered to be low, with long-term yields predicted to be in the order of 1–2% of virgin biomass, and the biomass at maximum sustainable yield B_{MSY} at about 30% of the pristine biomass (Francis *et al.* 1993). A study in 1999 on age and growth of Namibian orange roughy revealed that age at first maturity was attained earlier off Namibia than off Australasia (23 cf. 29 years), that growth was faster, natural mortality higher (0.055 cf. 0.045 year^{-1}) and that productivity was therefore greater. These parameters were used in the assessment of Namibian orange roughy from 2000 onwards. Orange roughy swimbladders are filled with oil and wax, so their target strength, although uncertain, is probably around -50 dB. Fish are therefore difficult to find and assess acoustically (Elliott and Kloser 1993, Clark 1996, Boyer and Hampton 2001a). The well-developed aggregating behaviour often results in catch-per-unit-effort (*cpue*) indices from commercial vessels being biased (Clark 1996, Kirchner and McAllister in press). Similarly, surveys are liable to suffer from high levels of variance. Owing to its low fecundity, fishing-down experiments to determine growth and productivity carry a high risk (Clark and Tracey 1994).

DEVELOPMENT OF THE NAMIBIAN DEEP-WATER FISHERY

Some targeted and incidental fishing on orange roughy had taken place earlier, but 1994 is generally considered the start of the Namibian fishery. A summary of the number of vessels active in the fishery and their annual catches is given in Table I.

In 1994 a single experimental licence was granted to one fishing company to explore the Namibian EEZ in depths exceeding 700 m for monkfish *Lophius* spp., deep-water catfish *Lepidion capensis*, warty dory *Allocyttus verrucosus*, spiky dory *Neocyttus rhomboidalis*, alfonsino *Beryx splendens*, jewel squid *Histioteuthis* spp., and trachichthyids *Hoplostethus* spp.

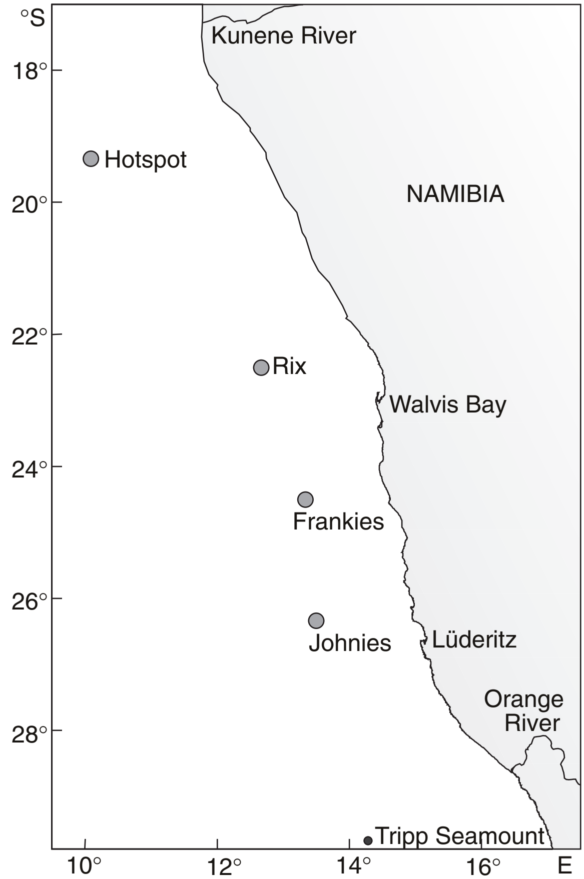

Fig. 1: Map of the northern Benguela, depicting the four Quota Management Areas and the location of the Tripp Seamount, another area where orange roughy have been found

The licensee purchased fishing records of some companies and nations (notably the former Eastern Bloc states) for the period prior to Namibian Independence to determine where orange roughy had been caught. In addition, the licensee conducted a side-scan sonar survey in 1994 to search for suitable habitat, and hence possible areas of orange roughy distribution. In June 1994, exploration started along the southern Namibian shelf break, especially around the Tripp Seamount (29°40´S, 14°17´E; Fig. 1), in a search for suitable topography. Despite several fishing trips each lasting about three weeks, few orange roughy or other

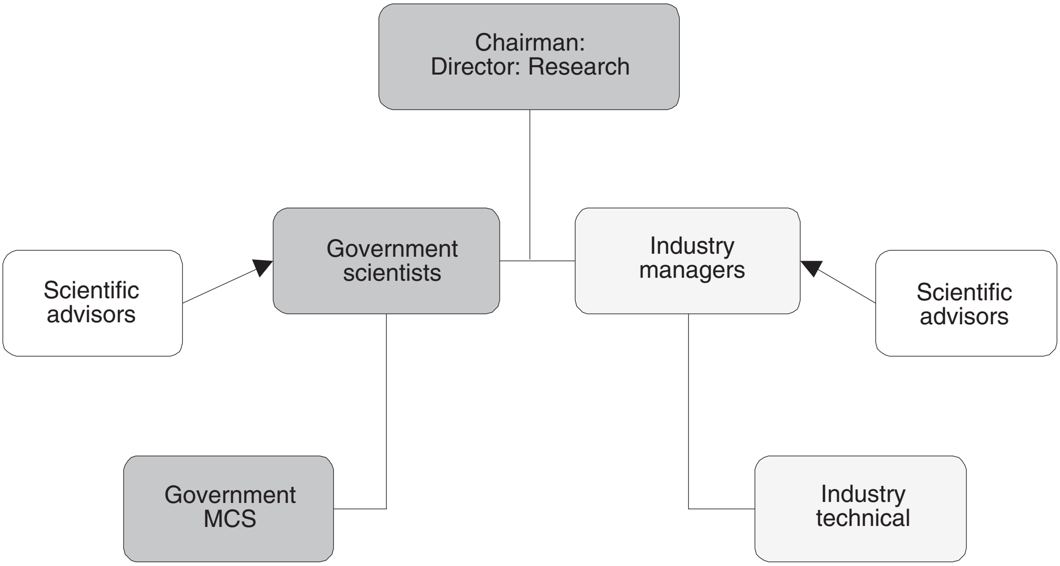

Fig. 2: Structure of the Deep Water Fisheries Working Group, with Government personnel highlighted in grey

fish of commercial value were found.

The area explored was extended northwards and the first orange roughy aggregation was discovered in January 1995, at the aptly named Hotspot (19°20´S, 10°05´E; Fig. 1). During April 1995, a second ground, Rix (22°30´S, 12°40´E), was found, although catches were small and the ground was only determined to be of commercial value early in 1996. Johnies (26°20´S, 13°30´E) was found soon after Rix, and Frankies (24°30´S, 13°20´E) was the final ground to be discovered, early in 1996.

Three of the four grounds are on the shelf break off central Namibia and are separated by about 200 km (Fig. 1). The fourth ground, Hotspot, is off northern Namibia on the southern edge of the Walvis Ridge. The biological characteristics of orange roughy on the central grounds are similar, but those on Hotspot are generally larger and have greater age- and length-at-maturity characteristics (Lesch 2000). Frankies is the only ground where there is more than one aggregation.

The exploratory phase (equivalent to Phase I in Miller's [1999] terminology) of the fishery culminated at the end of 1996, with the call for new companies to apply to join the fishery. In early 1997 the fishing year was changed from a calendar year to May–April and an additional four companies were given licences. Three companies were given quotas, allowing them to fish in the established fishing areas (see below); in deference to the exploratory investment, the original licensee was issued 50% of the annual *TAC*, with the remainder shared between the two newcomers. In all, five vessels received licences to fish for deep-water species. The two newer companies were only permitted to conduct exploratory fishing, an option they did not exercise (Table I).

MANAGEMENT OF NAMIBIAN ORANGE ROUGHY

Once orange roughy had been demonstrated to have the potential for a long-term fishery, the next phase (Phase II – Miller 1999) was to initiate active management and research. Recognizing the lack of trained and experienced "deep-water" fisheries biologists and managers in Namibia, and the lack of data, a working group of government fisheries managers and scientists, plus senior managers from each company (initially just the original licensee) was established in 1995 (Fig. 2). This group, termed the Deep Water Fisheries Working Group (DWFWG) was mandated to "*… promote the rational development of the Namibian deep-water fisheries…*", and furthermore to "*… ensure the long-term sustainable utilisation of the stocks exploited through proactive research and co-management strategies*." This mandate was interpreted to include developing an adaptive management strategy, making recommendations on *TAC*s and promoting compliance. From 1999 onwards, the DWFWG and government scientists submitted recommendations on catch limits independently because consensus on stock abundance could not be reached, government scientists opting for the more precautionary (pessimistic) approach (see below).

The DWFWG was required to ensure that the necessary expertise and resources were available to conduct the relevant research through training of local staff and, where necessary, to recruit consultants on short-term contracts, particularly for stock assessment purposes. The Namibian Ministry of Fisheries and Marine Resources allocated two scientists to orange roughy research and contracted scientists from the National Institute of Water and Atmospheric Research in New Zealand to advise and assist. The fishing industry jointly contracted South African stock assessment and acoustic experts to provide competence in these fields, and also brought in their own scientific consultants, mostly with experience in the New Zealand deep-water fishery. To provide basic biological data on orange roughy, fisheries observers were placed on commercial vessels to collect length frequency and, in some cases, maturity data.

Exploration

In order to promote new fisheries within the Namibian EEZ, experimental guidelines were developed, although to date these have only been applied for orange roughy. Companies were encouraged to search for new fish stocks and to develop new fishing techniques, with the following provisions:

- only a single company (and usually only a single vessel) would be licensed for each experimental venture;
- if the venture was successful, the company would be guaranteed a future proportion of the annual *TAC* after the experimental phase;
- catches would be monitored until a trigger level was reached that initiated research activity;
- interim limitations would be imposed on catches, based on a precautionary "guess" of the appropriate level.

This policy guaranteed participants a long-term interest in order to promote the development of the fishery in a rational and sustainable manner. The last two provisions were included because the Ministry does not have the resources to investigate all potential fisheries, so only those that show signs of economic importance can be "researched" actively.

To further encourage exploration for new grounds, and to define the precise extent of existing grounds, vessels were required from March 1996 to expend a proportion of their total annual fishing effort in areas where little effort had previously been directed. Each known ground was subdivided into inner and outer strata, known as quota management areas (QMAs). The inner QMAs represented areas that provided high average annual *cpue*s (>5 tons tow^{-1}) and the outer QMAs were defined as those areas surrounding the inner QMAs where catches >2 tons tow^{-1} had been achieved. On two of the grounds, Frankies and Rix, only 40% of tows per year were permitted in the inner QMA. Because of the rough terrain at Johnies, this proportion was increased to 50%, but at Hotspot, a clearly defined aggregation on a pinnacle, no further exploratory fishing was required.

This system was simplified for the 1998/99 season to a single stratum per QMA, defined by a circle of 30 mile radius around the geographic centre of each aggregation. This allowed for possible movements of fish between years and made the control aspects easier to monitor.

Unlimited fishing was permitted in the areas outside the QMAs, defined as Exploratory Fishing Areas (EFAs), i.e. *TAC*s related only to fish caught within the QMAs. To encourage vessels to search for new aggregations in the EFA, companies were guaranteed 50% of any *TAC* set for an aggregation that they discovered for a period of three years. The definition of "discovery" was complicated, but essentially it required a company to catch 100 tons of orange roughy within an area of 5 miles radius within a period of three months. The company was then granted exclusive rights to that area, but it had to catch another 500 tons in the following three months before it was accepted as an "aggregation" and hence qualified as a new QMA.

Stock assessment

Abundance estimation surveys were conducted annually between 1997 and 2000 using acoustic and swept-area methods, with the assistance of the fishing companies, but coordinated through the DWFWG. The acoustics surveys were conducted on board the R.V. *Dr Fridtjof Nansen* between 1997 and 1999 and on a commercial vessel in 2000, but with commercial vessels identifying targets (Boyer and Hampton 2001a). The swept-area surveys were carried out by the F.V. *Southern Aquarius* during the first three years, and on a smaller fishing vessel, the F.V. *Emanguluko,* in 2000.

Towards the end of the exploratory phase of the fishery, it was decided to base harvesting decisions on stock assessment and population modelling and to

Table II: An example of the bias factors applied to swept-area estimates from commercial data of orange roughy off Namibia (after Brandão 1999)

Bias factor	Minimum	Most likely range	Maximum
Catchability/herding inside aggregations	0.21	0.36–0.72	0.86
Directed fishing inside aggregations	0.45	0.52–0.80	0.90
Increase/decrease in size of aggregations	0.80	0.80–1.20	1.20
Lost catch	1.00	1.03–1.07	1.10
Skipper-estimated catches	1.06	1.06–1.12	1.12
Catchability/herding outside aggregations	0.50	0.58–0.84	0.92
Directed fishing outside aggregations	0.20	0.30–0.70	0.80
Fish outside defined strata	1.05	1.05–1.15	1.15
Erroneous zero catches	1.02	1.04–1.08	1.11

develop an adaptive management strategy based on formal risk analysis (Walters and Hilborn 1976, 1978, Walters 1986).

Two basic approaches to the management of orange roughy were considered at the start of the fishery: to conduct a fishing-down experiment, so determining the productivity of the resource (Hilborn and Sibert 1988, Hilborn and Walters 1992) or, alternatively, to gather sufficient biological information prior to implementation of any fishing-down policy to ensure that any build-up in fishing effort should be gradual (Clark 1995, but see also Richards and Maguire 1998). The DWFWG opted for the former approach because it was argued that, until sufficient fishing pressure was applied to elicit a change in catch rate, determining productivity would be difficult. However, because there was a high degree of uncertainty and inadequacy in the data, an attempt was made to implement a precautionary approach (Richards and Maguire 1998) at a number of stages of the stock assessment. This involved the use of probabilistic modelling to quantify uncertainty in biomass estimates, and attempting to prevent fishing-down towards the B_{MSY} level too rapidly. A long period of fishing-down to B_{MSY} was planned and, in addition, the recommended *TAC* was set well below the level calculated to meet the fishing-down objectives. A further precautionary strategy was to set non-transferable quotas for each QMA.

A fisheries strategy commonly applied is to attempt to manage a stock at its most productive level, providing a sustainable yield. However, for a developing fishery that level is highly uncertain. The optimal catch target reference point $0.5MB_0$ (Gulland 1971, Shepherd 1981) was initially used in New Zealand, where M is the rate of natural mortality and B_0 is the long-term average unfished stock biomass. This did not perform well, and it was replaced by a stock biomass target reference point of $0.5B_0$ (Clark 1995), often assumed to be the approximate stock size for maximum biological yield (Hilborn and Sibert 1988).

However, in the first models of Namibian orange roughy (Branch and Butterworth 1996), maximum sustainable yield (*MSY*) was assumed to be at $0.3B_0$ (from Francis *et al.* 1992), the level applied in the New Zealand and Australian orange roughy fisheries. It was later decided that this was a risky target for a stock that forms dense aggregations and is thereby vulnerable to rapid depletion and overshooting of the level (Clark 1995), so in 1998 it was decided to set an alternative minimum threshold of $0.5B_0$, which would allow a larger buffer in the fishing-down phase.

FIRST STOCK ASSESSMENT (JANUARY 1997)

The first stock assessment of orange roughy was undertaken in January 1997. The only information available was commercial *cpue*. As at that stage no other method of determining abundance was available, density, and hence biomasses, were calculated for each ground through a swept-area analysis of the data by combining all trawls from the commencement of the exploratory fishery to June 1996 (Branch 1996). Areas with high catch rates and fishing intensity were enclosed in polygons (known as Spawning Boxes), and other strata were defined around the Spawning Boxes based on depth limits of 500 and 1 000 m. Biomass estimates using *cpue* data are normally treated as relative indices, because typically they are biased. As many members of the DWFWG were concerned at applying commercial *cpue* to a stock assessment procedure that requires random samples, an attempt was made to estimate these biases using the collective knowledge of the Group. They included biases from directed fishing by commercial fishers and biases associated with the vertical distribution of orange roughy in the water column with respect to the part sampled by the trawl gear (Table II). Bias correction factors (Table II) were then applied to the baseline estimates. This resulted in absolute abundance estimates for each ground, totalling 306 000 tons (*CV* 0.34) for all grounds combined (Branch 1996). This abundance estimate was considered to be the virgin biomass (pre-exploitation biomass or

Table III: Relative biomass estimates from surveys of orange roughy aggregations before corrections for biases were applied (*CV*s in parenthesis)

QMA	Acoustic estimate (tons)				Swept-area estimate (tons)			
	1997	1998	1999	2000	1997	1998	1999	2000
Rix	21 579 (0.15)	7 572 (0.19)	*	*	ANS	ANS	1 006 (0.59)	ANS
Frankies	17 925 (0.25)	4 940 (0.38)	1 782 (0.25)	4 300 (0.30)	30 995 (0.37)	2 400 (0.60)	3 055 (0.35)	ANS
Johnies	34 179 (0.21)	3 570 (0.43)	*	ANS	57 650 (0.27)	6 980 (0.25)	2 137 (0.40)	3 330 (0.34)
All three QMAs	73 683 (0.12)	16 082 (0.17)						

ANS Area not surveyed
* Behaviour of orange roughy did not permit acoustic assessment

B_0) in further analyses until the commercial swept-area methodology was revised for the 2000 assessment (Kirchner and McAllister in press).

The biases were estimated through a negotiation process until consensus was reached between the various participants. There was considerable disagreement about the use of this method, even with the incorporation of ranges to the biases. The latter were described as probability density functions, with the limits of their ranges tending to reflect the limits of the various "feelings", and the "most likely" range being the consensus (Table II). In retrospect, the distributions for some of the bias factors were likely estimated with excessive certainty, resulting in narrow ranges, especially as the application procedures weighted the biases heavily towards the central part of the range, so losing the extremes. However, sensitivity tests of the various ranges proposed showed that, in general, the resulting biomasses differed by a few tens of thousands of tons, and the *CV* by a few percentage points (Branch 1998). Of greater importance, the application of conventional swept-area methodology to commercial catch data was flawed and the resulting biomass estimate was grossly over-inflated (see Table V and Fourth Stock Assessment below).

A management approach of an initial fishing-down phase was proposed, i.e. taking catches in excess of sustainable yields for a few years, followed by a constant reduction in *TAC* until the maximum sustainable yield level was reached and retained. The likely effects of alternative catch levels over a 14-year period on the orange roughy stock levels were modelled by Butterworth and Branch (1996). The analysis used a deterministic version of an age-structured production model (Francis 1992, Francis *et al.* 1995) in which values of the model parameters, such as growth and age at maturity, were based on New Zealand estimates (Doonan 1991). Butterworth and Branch (1996) recommended an initial strategy of setting a *TAC* of 15 000 tons for seven years, declining eventually to 6 000 tons.

McAllister and Kirkwood (1997) repeated this risk assessment using a Bayesian approach that included stochastic recruitment, accounted for uncertainties of natural mortality and assumed a greater uncertainty of the "virgin" biomass estimate. Risks were calculated, also using a constant *TAC* for seven years, then declining linearly to 6 000 tons after 14 years. The results showed that implementing an initial catch quota of 15 000 tons or even 20 000 tons gave a risk of <10% of stock depletion below $0.5B_0$.

Although both methods showed that a *TAC* of 20 000 tons posed low risk, the DWFWG recognized the uncertainties in the assessment, attributable to lack of data, and proposed a more cautious approach, recommending 15 000 tons for the 1997/98 fishing season. A final *TAC* of 12 000 tons was allocated by the Namibian authorities.

SECOND STOCK ASSESSMENT (JANUARY 1998)

The assessment was repeated in January 1998 using commercial catch data from July 1996 to December 1997, yielding an abundance estimate of 224 000 tons (*CV* 0.44; Branch and Roberts 1998). This time period included two spawning seasons that should have inflated the mean *cpue*, but the latter was some 25% lower than the January 1997 estimate. However, industry argued that some fishing effort had been directed at other deep-water species and that it was not possible to differentiate that effort from fishing directed at orange roughy. Despite considerable scepticism from government scientists, the *cpue* estimate was rejected as unreliable because it was considered negatively

Table IV: Median biomass estimates of aggregations from surveys and commercial data corrected for biases to provide absolute biomass estimates (*CV*s in parenthesis)

Survey type	Median biomass estimate (tons)				
	1994/95	1996	1997	1998	1999
Commercial swept area (all grounds)	305 000 (0.36)	178 000 (0.38)	129 000 (0.37)	47 000 (0.38)	*
Acoustic survey (three main grounds only)	–	–	118 185 (0.22)	26 493 (0.25)	*

* Comparable data not available

biased compared to the 1997 estimate. The 1996 B_0 estimate of 306 000 tons was used again for risk assessments.

Two scientific surveys had been conducted in July 1997 using acoustics and swept-area techniques (Huse *et al.* 1997). The results are summarized in Table III, and Table IV shows the total biomass estimates after the data were corrected for biases (Boyer and Hampton 2001a). These biases were estimated through a similar process to the biases used in commercial-catch-based swept-area estimates, although in this instance the survey practitioners estimated the level and range of the biases.

As the 1997 acoustic survey estimate was much lower than the biomass estimated from *cpue* data, risks were also calculated using the acoustic survey value (adjusted for pre-1997 catch removals) as input to the calculation of B_0, especially as these surveys were considered more rigorous than the swept-area surveys. Risks were calculated for a range of fishing-down *TAC*s (10 000–15 000 tons) and B_{MSY} *TAC*s (4 000–6 000 tons). Using the commercial catch rate estimates of B_0, the results showed that the risk of the stock declining below $0.5B_0$ by the end of the time period would be low (0.24), even for the highest catch strategy. However, using the B_0 calculated from acoustic survey data, the risks were substantial (0.98). Additionally, the 14-year catch strategy was changed to 3- and 6-year scenarios because it was realized that such disparate estimates of B_0 made predictions beyond such a time period too speculative. Even when applying the B_0 calculated from the acoustic index, the risks of B_0 falling below 0.5 after 3 and 6 years were 0.12 and 0.53 respectively. This level of risk was considered acceptable, because catch levels could be reduced in subsequent years if the risk level rose as subsequent data were gathered.

Although fishery-independent indices of abundance are generally more reliable than fishery-dependent ones, the acoustic results were not given full weight in the provision of *TAC* advice. Considerable concern had been raised during the 1998 assessment about the reliability of the acoustic estimates, because the acoustic survey had been implemented for the first time and reservations were expressed about the interpretation of the initial survey results. Judgement about reliability was to be assessed after the second acoustic survey had been conducted in 1998.

As a result of the uncertainties in the assessment, the same *TAC* as the previous year, 12 000 tons, was recommended for the 1998/99 fishing season. This figure was ratified by the Namibian Cabinet.

THIRD STOCK ASSESSMENT (JANUARY 1999)

During July 1998, another pair of surveys was conducted (Dalen *et al.* 1998). The results indicated a severe decline in abundance since the previous surveys (Table III).

In the previous assessments, absolute abundance estimates of the total orange roughy stock within the 200 mile EEZ of Namibia were used in modelling alternative future catch strategies and associated risks. However, the second research survey and commercial swept-area estimates all indicated declines beyond that which could be accounted for by fishing. Additionally there were concerns that the estimates of B_0 based on commercial swept-area analysis could have been severely overestimated. Therefore a new approach, treating the data as relative indices, was implemented.

An age-structured model was fitted to the three indices (commercial swept-area, acoustic and research swept-area series) using Bayesian methods (McAllister and Ianelli 1997, McAllister and Kirchner 2001). This was done for all grounds combined and then for each ground separately. The analysis highlighted a conflict in interpretation of the data. If more weight was given to the indices as absolute abundance estimates, the assessment would "flick over" from pessimistic to optimistic (McAllister and Kirchner 2001). Industry used the highly inflated commercial swept-area abundance indices (which were still considered in the assessment) as well as the argument that the environment was negatively impacting catch rates and

Table V: Commercial swept-area estimates of orange roughy biomass for the initial year of fishing for each ground and in combination using the initial methodology applied in 1997 (old) and that revised for the 2000 (new) assessment (after Kirchner and McAllister in press)

QMA	Initial year	Biomass from old swept-area method (tons)	Biomass from new swept-area method (tons)	Ratio of old/new estimates
Hotspot	1994/1995	21 916	22 081	0.99
Rix	1996	19 724	12 339	1.60
Frankies	1996	124 543	21 893	5.67
Johnies	1994/1995	138 476	17 417	7.95
All QMAs		304 659	73 820	4.13

research survey results, in asserting that the stocks were still largely healthy.

The analysis suggested that the depletion ranged from 0.49 to 0.86 for the four QMAs. Although all indices suggested a decline in the quantity of fish available to the fishery on each ground between 1997 and 1998, it was greater than could be explained by catches alone, suggesting that other factors than fishing had caused the fish to become unavailable to the fishery. Owing to the uncertainty in the state of the stock, a two-step approach to the 1998/99 *TAC* was recommended: the catch level of the previous fishing season was reduced to the rather arbitrary level of 9 000 tons, a level that would not have serious consequences to the profitability of the industry, but should have been within safe limits of sustainability. Another 3 000 tons was to be issued if catch rates and survey estimates warranted such action, so bringing the total *TAC* to the same level as the previous year. Although some government scientists felt that, on precautionary grounds, this *TAC* was too high, it went forward in the *TAC* recommendations. Only 2 500 tons of orange roughy were caught during the year, so the extra quota was not released.

An additional recommendation that was proposed and accepted was to close one of the grounds in order to test whether the decline in abundance of orange roughy on the fishing grounds was attributable to some form of disturbance. Frankies, the ground with the highest depletion in catch rates, was closed in April 1999, although no fishing had actually taken place there since the end of 1998.

FOURTH STOCK ASSESSMENT (FEBRUARY 2000)

Further acoustics and swept-area surveys were conducted on the three main QMAs during 1999 (Staalesen *et al*. 1999). While some of the technical details of the surveys changed, the basic survey strategy remained similar to that of the previous surveys (Boyer and Hampton 2001a). The results are presented in Table III. A clear change in the behaviour of orange roughy was noted during this survey. In general the fish were more dispersed, so identification of acoustic marks was uncertain on two of the grounds. An acoustic biomass estimate was only possible on Frankies, the ground closed to fishing for the previous four months. Swept-area estimates were produced for all three grounds. Once again, the results indicated a further decline in the abundance on Johnies, and possibly also at Frankies (Table III).

The assessment of 1999 was updated, but the commercial *cpue* index was changed to a non-stationarity form (Kirchner and McAllister in press). Their analysis demonstrated that the conventional swept-area approach applied in the earlier assessments had defined "sampling" strata or areas, such that clusters of very high catch rates had been extrapolated to large, poorly sampled areas, so giving rise to grossly overestimated biomass. The revised procedure no longer assumed that orange roughy aggregations were stationary from year to year, but now, for each year, redefined "sampling" strata on the basis of relative catch rates of adjacent commercial tows. Thus, high catch rates were averaged only for those regions in which similar values were found; such catch rates were no longer extrapolated to large, poorly sampled areas. The revised commercial swept-area method gave an estimate of unexploited biomass of about 74 000 tons compared to the 1997 estimate of about 305 000 tons (Table V).

Again, the assessment indicated that the large decline in the various indices seemed not to be accounted for by fishing mortality alone, perhaps reflecting some other processes, such as the effect of fishing on school stability or some form of aperiodic aggregating behaviour (Brandão and Butterworth 2000). A further alternative tested was that of mass emigration of fish from the fishing grounds, such as could be expected from large-scale habitat alteration. As an example, note was taken of the rapid decline in availability of orange roughy in the Challenger Plateau fishery in New Zealand in the early 1990s and more recently in the Chatham Rise stock (Annala and Sullivan 1996). These possible causes of an apparent change in abundance were statistically evaluated by McAllister and Kirchner (in press). They suggested that the catch removal hypothesis had a low level of probability (i.e. credibility) on Frankies, Johnies and Hotspot, but still had a high level of probability on Rix (McAllister and Kirchner 2001). This was because the declines in the indices on the first three grounds were the steepest and most difficult to account for by catch removal only. The two hypotheses of a temporary change in availability of orange roughy yielded moderate levels of probability on Rix, Hotspot and Frankies, but very low levels on Johnnies. The mass emigration hypothesis had considerably higher level of probability than the others on Hotspot and Johnies, but still moderate on Rix and Frankies. This was the only hypothesis to retain credibility on all four grounds after data analysis.

During the assessment, the results on alternative hypotheses for orange roughy behaviour were acknowledged to be based on a new methodology that needed further testing and peer-review. Owing to the newness of the methodology, the results were difficult to interpret, especially when compared across fishing grounds. As the results were based on relatively few data points and several uncertain technical inputs, and the likelihood of different hypotheses being true on the various grounds seemed counter-intuitive, the results were considered to be too preliminary to be used to support management decisions. McAllister and Kirchner (2001, in press) give a detailed discussion of the development of this new methodology.

In the face of the various conflicting evidence presented, government scientists maintained a precautionary approach in their provision of *TAC* advice. A lower *TAC* was recommended on the basis that low stock sizes were still probable given the data and given that the most parsimonious hypothesis, catch removal, could not yet be ruled out. This proposal was considered fitting for a long-lived species such as orange roughy, for which a reduction in catches now would not result in any loss in long-term yield. This hypothesis indicated that the QMAs were all below the $0.5B_0$ level and that catches needed to be reduced to 1 200 tons to halt the decreasing trend. That figure was recommended as a *TAC* for 2000/2001, with the option to increase it should the commercial catch rates or survey indices improve substantially. The authorities followed these recommendations, granting an initial *TAC* of 1 200 tons. However, following some pressure from industry after they made a few good catches, it was subsequently increased by 540 tons, despite neither mean catch rates nor survey results providing clear evidence of an improvement in the state of the stock.

State of the stock in the year 2000

Acoustic surveys of Frankies and Rix and a swept-area survey of Johnies were conducted in July 2000 (Boyer *et al.* 2001). The estimates indicated little change in the general status of the stock, and commercial catch rates confirmed this interpretation.

The development of the orange roughy fishery had, by mid 2000, reached the end of its third phase (Miller 1999). Biological research had been conducted such that there was some idea, albeit rather uncertain, of long-term productivity. A defined management strategy had been set up, and the necessary monitoring and control systems had been established.

DISCUSSION

This paper has documented some of the important stages and processes in the development of the orange roughy fishery in Namibia. A key issue raised at the outset was how to manage a new fishery. The development of deep-water fisheries is littered with tales of rapid development, spectacular early catches, followed by even more rapid and spectacular collapses (Miller 1999, and see Moore 1999 for a review).

The Namibian authorities went to great lengths to guard against such a sequence of events in their orange roughy fishery. Assessment and management created a paradoxical situation whereby state-of-the-art assessment and modelling yielded high quality advice, yet the fishery virtually collapsed within a very short time. There was close cooperation with industry at all stages. A number of strategies for dealing with uncertainty were incorporated into the stock assessment, including a Bayesian approach and management process, and attempts were made to apply the precautionary approach (F.A.O. 1995). In addition, adaptive management was applied through institutional learning. As a result there should be some lessons to be learned from the assessment and management of orange roughy in Namibia. Some aspects provide good examples of how a new developing fishery should be managed; others are clearly illustrative of procedures to be avoided. In particular, one of the main reasons why the management of orange roughy failed to prevent stock collapse was underestimation of some of the uncertainties, particularly those reliant on basic understanding of the biology and behaviour of orange roughy (Ludwig *et al.* 1993).

Francis and Shotton (1997) provide an elegant classification of uncertainty in the assessment and management of fish stocks. These categories are used here to illustrate the Namibian attempts at managing its orange roughy resource and in particular some of the major types of uncertainty that detracted from its success.

Process uncertainty

Process uncertainty accounts for the natural variability in biological processes, and particularly those that control stock productivity. Orange roughy inhabit deep water where environmental conditions are assumed to be relatively constant. Measurements of oxygen, salinity and temperature during four annual research surveys indicate that, at least at the accuracy of measurement, there was little variability. Likewise, commercial vessels report catching orange roughy within a temperature band of 3°C suggesting that, even if there is some variability, the fish try to minimize this by seeking a constant environment. Therefore it is intuitive to expect the biological processes that control the productivity of this stock to have a low degree of stochasticity.

One of the hypotheses tested to account for the large decline in orange roughy biomass on the spawning grounds was that spawning periodicity was either very long or highly variable (McAllister and Kirchner 2001). On purely biological grounds this seems unlikely, but it cannot be disproved. Although little was known about the degree of variability of the key biological processes determining the productivity of orange roughy off Namibia, it seems unlikely that this would have accounted for the observed decline in abundance.

Observation uncertainty

Observation uncertainty refers primarily to the ability to collect data on the fishery, stock abundance and biological parameters with reasonable precision and accuracy. Namibia is recognized as having a high degree of control over commercial catches: all orange roughy vessels carry two fisheries observers and all landings are made at a single harbour under the control of fisheries inspectors (Oelofsen 1999, Boyer and Hampton 2001b). Therefore, there was little observation uncertainty in monitoring catches of orange roughy.

The geographic position of orange roughy aggregations, far from any national borders, and the fact that Namibia has a strong monitoring, control and surveillance policy, which not only does not tolerate transgressors, but also has the means to apprehend them. Therefore, illegal and hence unrecorded, catches are not suspected to have been a factor.

As little was known about orange roughy at the beginning of the fishery, much research was directed at the resource. Shipboard and port sampling were initiated to monitor changes in population structure, both between grounds and over time within grounds, as well as to track reproductive development. These activities were conducted with the full support of the industry, and generally with their active participation. While there was doubtless some uncertainty in this monitoring process, especially early on, it seems unlikely that this could have accounted for any large errors in the assessment of the stock.

In order to determine the abundance of orange roughy, two types of surveys were conducted in 1997 and have been repeated each year since. As there are many uncertainties in the estimates, it was decided in 1998 that they should be used only to monitor trends rather than absolute abundance. Additionally, the errors of acoustic estimates have been modelled in an attempt to assess the probability distribution of the estimates (Boyer and Hampton 2001a), so accounting for the most important uncertainties.

However, virtually all research on Namibian orange roughy has been directed at the aggregating component of the stock, through either commercial sampling or surveys. Little is known about the fish outside the aggregations, and the lack of knowledge of this component of the stock may have had severe consequences for the ability to assess abundance accurately. This is discussed in more detail below.

Model uncertainty

This form of uncertainty deals primarily with deciding on the best method of representing the stock dynamics of the species in question (McAllister and Kirchner [2001] refer to this as "structural uncertainty"). The conceptual model of the Namibian orange roughy population and community dynamics contained a number of critical assumptions, not least of which concerned stock structure. Initially the stock was considered to be a single unit, but by 1997 it was assumed that each QMA was, for both stock dynamics and management purposes, entirely separate, this being the most precautionary approach. In addition, it was assumed that a constant proportion of the stock migrated annually to the QMAs to spawn. This proportion was unknown, but it was implicitly assumed that most of the stock spawned each year. From these assumptions, it followed that any decline in the stock would be attributable to fishing mortality rather than to changes in behaviour of the stock or stochasticity in the natural behaviour patterns.

Between 1997 and 1999, the swept-area abundance estimates based on commercial data declined between

2- and 8-fold on the various grounds, and the research-based swept-area estimates by 10–55 times. Similarly, the acoustics estimates dropped by an order of magnitude. Four hypotheses were proposed and tested to account for these declines: first, that it was due to the direct impact of fishing; second, that the aggregating behaviour of orange roughy was being disrupted by fishing activities; third, that there was some previously unrecorded stochasticity or periodicity in the spawning frequency of Namibian orange roughy; finally, that there had been a mass emigration or mortality. Modelling suggested, on the basis of the goodness of fit to the data for models based on these hypotheses, that the catch removal hypothesis remained plausible only on Rix. The mass emigration hypothesis remained plausible on all four fishing grounds, and the hypotheses invoking behavioural changes had low credibility on Johnnies and Hotspot but remained credible on the other two grounds. Biologists argued, on the basis of their experience with other fish stocks, that depletion by catch removals was more likely, but they were unable to provide empirical data to support their case. No consensus has yet been reached on whether these hypotheses are biologically feasible.

During the initial stages of the fishery, many biological parameters on Namibian orange roughy were unknown, creating uncertainty in estimating the productivity of the resource. These parameters were for the first two years of assessment assumed to be the same as for New Zealand orange roughy. While this may be intuitively sensible, it did create an additional source of uncertainty. Sensitivity analysis involving testing a range of plausible values showed which were the most critical parameters, e.g. age at maturity, growth and natural mortality. Considerable effort was then expended to determine these parameters using Namibian data, which were used from 2000 onwards. Indeed, the use of a fishing-down strategy to determine optimal fishing levels, rather than taking the less-aggressive approach of studying the biology and productivity, as recommended by Clark (1995), though seemingly safe at the time, can now be seen to have been a high-risk strategy.

In the Bayesian assessment, priors were included for key parameters such as natural mortality, to account formally for the uncertainty of such parameters in the stock assessment process (McAllister and Kirchner 2001, in press). Also, a Beverton-Holt stock-recruitment relationship was assumed, and recruitment was also allowed to assume some variability, using the same values as in New Zealand.

Another type of model uncertainty was introduced in the initial estimates of abundance using commercial *cpue* data as a proxy for swept-area data. It was assumed that the area of an aggregation was fixed, so mean catch rates were raised by the same area each year to calculate abundance. Kirchner and McAllister (in press) analysed the spatial distribution of the aggregations and concluded that the area was, in fact, not constant, so assuming stationarity greatly inflated the abundance estimates.

In addition, an assumption made during the initial phases of this fishery was that *cpue* tracked abundance, despite strong indications from Clark (1996) that this may not be so for orange roughy. Indeed, some initial indications of declining catch rates in 1996 were discarded as artefacts and the decline was only accepted and incorporated in the stock assessment in 1998. Indeed, the *cpue* data, especially when used in a swept-area type model, were repeatedly used by industry as evidence for the robustness of the stock. As noted above, this type of analysis should have been used with considerably more circumspection for an aggregating species such as orange roughy, especially with the lack of knowledge of the species' aggregating dynamics.

Surveys of orange roughy were conducted using swept-area and acoustic techniques. Once two surveys had been conducted and a time-series existed, these were used as relative indices, recognizing the uncertainty in the estimates attributable to various biases (Boyer and Hampton 2001a). However, a major uncertainty that is still not resolved is whether the surveys, by targeting spawning aggregations, were surveying a constant portion of the total stock each year, or whether this was variable. This again relates to the lack of understanding of the behaviour of orange roughy, and particularly of the aggregations.

It is concluded that the uncertainties introduced through the use of inappropriate model structure or assumptions contributed significantly to an overall failure to predict the decline in orange roughy abundance off Namibia, this form of uncertainty being driven by a lack of knowledge of the biological processes.

Estimation uncertainty

Estimation uncertainty is a secondary type of uncertainty derived from some or all of the above three types.

It was recognized from the early days of the fishery that any attempt to estimate optimal catch levels would be fraught with uncertainty, a natural consequence of any new fishery where information is lacking. To compensate for the lack of data, extensive use was made of sophisticated models. Priors on more than 3–5 key biological and catch parameters and several annual process error terms were introduced through Bayesian statistics, allowing for uncertainty to be incorporated in a rigorous and structured way into the assessment models (McAllister and Kirchner 2001).

Hence, the stock assessment (and risk analysis) was based on best guesses by the available "experts" and elaborate analyses of the limited data available to provide indications of biases and uncertainty in stock biomass estimates. However, some argued that high levels of analysis did not compensate for the limitations of the data being used (as suggested by Ulltang 1996, Rose 1997, Schnute and Richards 2001). Similarly, the priors for catchability were constructed through discussion and agreement by consensus. While this had the advantage of combining accumulated knowledge and experience of many people, it often lacked objectiveness. In hindsight, some of the uncertainties may have been underestimated, possibly by a large amount, especially those that affect the estimation of abundance.

Another unforeseen consequence of achieving consensus was a narrowing of uncertainty. It is suggested that, while this process of constructing priors has its merits, input should be permitted without pressure. Further, all inputs should be used, in other words, there should not be any attempt to reach consensus. Similarly, opposing views (and trends) should not be averaged, because doing so reduces very real uncertainty.

During the initial assessments, the biomass at *MSY* was treated as a target reference point. However, recent literature suggests that this should be a limit reference point (Mace and Gabriel 1999, Serchuck *et al.* 1999). In addition, New Zealand assessments suggested that B_{MSY} for orange roughy was around 0.3 of the virgin stock level (Francis *et al*. 1992) and is derived from a target rate of fishing mortality where catches change with stock fluctuations and are hence maximized. This method requires good estimation of stock size and productivity. However, owing to the uncertainties in this estimate, the more conservative (precautionary) approach of Clark (1995) was followed, i.e. assuming B_{MSY} to be closer to $0.5B_0$, a level derived from a constant catch strategy and hence the more conservative of the two methods. That this level is "precautionary" is highlighted by the fact that the stated management aim in Australia is to rebuild orange roughy stocks to $0.3B_0$ by 2004 (Bax 2000).

It is currently not possible to state whether the estimates of virgin biomass, B_{MSY} and productivity were erroneous or whether there were changes in the behaviour of orange roughy, making the component of the stock assessed in, for instance, 1997 different from that assessed in subsequent years. Certainly the original estimates of abundance using commercial catch data were positively biased, but detailed reanalysis of the early surveys, when the biomass appeared to be high, indicate that the original survey estimates were essentially valid and that the perceived large decline in abundance of fish in the QMAs is real.

Once again it has to be concluded that the major uncertainty in estimating biomasses and productivity emanated from the underlying conceptual model that was assumed for orange roughy, rather than stochasticity in the biological processes or observation uncertainty.

Implementation uncertainty

Implementation uncertainty refers to the extent to which management policies and recommendations were implemented. The recommendations made by the Deep Water Fisheries Working Group originally, and later by government scientists, were generally implemented by the authorities with a high degree of faithfulness. In 1997, the authorities were more cautious than the DWFWG. Therefore, this form of uncertainty does not seem to have played a major role.

However, there is definitely room for several improvements to the form of management advice. Assessments tended to present results in the form of a mean and a range of probability (90% probability intervals in earlier assessments, but usually 95% in the later ones). In reality, recipients of such information tended to become fixated on the point value (the mean) and to ignore the range. As point estimates are meaningless when *CV*s are large, e.g. >0.3, it may have been more constructive to give ranges only, perhaps using a fairly wide probability interval of, for example, 80%. Additionally, the outputs of some procedures had such wide probability intervals that the results were uninformative and hence of little use for management. Finally, without concrete evidence to validate, or at least support these results, managers (and often scientists too) failed to trust the outputs.

A set of fishing conditions was applied to promote exploratory fishing. However, these were too complicated to monitor and enforce efficiently. As a result, industry tended to "explore" when catch rates on aggregations were low, i.e. out of the spawning period, when the chances of finding new aggregations or defining the limits of known aggregations were reduced. Incentives to encourage exploration were developed in conjunction with industry, but the costs were deemed to outweigh the potential benefits, so exploration was limited. If the proportion of exploratory fishing trawls had been calculated over shorter time periods, e.g. per month or per trip rather than per year, then this strategy may have yielded greater benefits, although it would have been more costly to industry.

Some management protocols were applied, especially in respect of exploratory fishing, but no procedures were developed for setting harvesting levels on the known grounds. This forced annual debate on the state of the stocks and harvesting levels, an extremely costly and time-consuming exercise for all involved.

Notwithstanding the above, it seems reasonable in general to conclude that implementation of scientific recommendations and management procedures had little impact on the subsequent decline in catches. Indeed, *TAC* levels were set even lower than those recommended and so may have extended the life of the fishery. Vessel participation in the fishery was strictly limited to a maximum of five, compared to, for example, the Australian orange roughy fishery in which, in 1999, there were 34 vessels still fishing for orange roughy, down from a maximum of 67 in 1990 (Bax 2000).

Institutional uncertainty

Institutional uncertainty is a serious concern in Africa where political, and hence policy, instability is common. Namibia has had a strong, stable government for the past decade. The government formulated clear policy towards the utilization of marine resources and, despite some pressure from the fishing industry, largely abided by it. Owing to the importance of fishing to the Namibian economy, most efforts to protect resources and to increase the long-term output of fisheries gained widespread political, social and economic support. The official policy towards the development of new fishery resources remained unchanged, but some adaptive institutional learning naturally occurred as the orange roughy fishery developed. The establishment of a working group consisting of government managers and scientists and senior industry representatives also reinforced the stability in the assessment and management of the resource.

One restriction in this developing country of Namibia was the lack of local scientific competence. This was solved by contracting international expertise and, because such expertise was temporary, a progressive training programme was implemented such that by 2000 most of the survey and assessment work was conducted locally.

CONCLUSIONS

The Namibian orange roughy fishery developed and declined in just six years. The establishment of the fishery was planned and controlled in a rational manner. During the initial "discovery" phase, catches were monitored. A research programme was launched to determine and monitor the state of the stocks, while management routines were being established. Monitoring and control was implemented during the second phase, and strategies to promote further exploration and the collection of pertinent data were also introduced. The third phase saw consolidation of all these activities such that by 2000 much of the research, management and control of the fishery were routine. The scientifically based recommendations were followed with a large degree of faithfulness, and the fishery was, in general, well controlled. Despite this, catches declined unexpectedly fast and, within a couple of years, all stocks were estimated to have been depressed below B_{MSY}.

Elaborate attempts were made in the assessments to estimate the abundance of the stocks and to quantify the risks associated with various harvesting levels. One of the greatest difficulties for the assessment was to formulate precautionary advice on *TAC*s in the face of conflicting interpretations of available data and assessment results, and their implications for resource status. The spawning behaviour of orange roughy was, and still remains, poorly understood, and the dynamics of aggregation formation and dispersion are similarly unknown. Therefore, alternative assumptions covering a wide range of biological possibilities were used in the formulation of the qualitative conceptual models of stock dynamics and behaviour, so making interpretation of results difficult.

Biomass was overestimated in the first stock assessment owing to the use of a conventional swept-area estimate of abundance from data on commercial catch rate. The initial survey results, although considerably less than the commercial swept-area estimates, also indicated that the harvesting rates achieved in the early years of the fishery would lead to a gradual fishing-down of the stock towards B_{MSY}. Subsequent catch and survey data indicated a dramatic decline in abundance of all stocks, apparently at rates greater than could be accounted for by fishing. Whether this was attributable to overestimating abundance during the early surveys, in which case overfishing could have caused the decline, or to a change in fish behaviour during the spawning period when the stocks were surveyed, remains unknown.

Management usually aims to balance the biological risk of overfishing with the economic loss of underfishing, including taking account of future discounting. However, with a long-lived fish such as orange roughy there is little loss of yield through underfishing. In retrospect, the precautionary approach should have been more rigorously applied, and the limited expansion in effort allowed between 1997 and 1998 should have been avoided until at least two years of research survey data had been obtained, to improve the assessment of abundance. Further time would also have allowed more information on the biology of Namibian orange roughy, in particular on spawning and aggregation dynamics, to be gathered.

The development and decline of the Namibian orange roughy fishery should serve as a warning to other newly discovered fisheries. Even for those with excellent management and fisheries control, full cooperation of industry and high levels of research and population assessment, catch levels need to be severely limited until sufficient understanding of behaviour and stock dynamics allows stock-specific reference points, such as B_{MSY}, to be determined with confidence. Only then should a fishery become a fully operational commercial activity managed to attain optimal sustainable harvesting rates.

ACKNOWLEDGEMENTS

We acknowledge the considerable assistance from the members of the Deep Water Fishery Working Group for their unending support and input during the development of the Namibian orange roughy fishery, and as a result for providing many of the innovative ideas outlined in this paper. The library staff at the National Marine Information and Research Centre, in particular Ms N. Coetzee, are specially thanked for their willingness and dedication in providing the many references used in this paper, as is Mr T. A. Branch, currently at the University of Washington, USA, for his constructive comments on a draft version of the manuscript. Dr M. R. Clark (National Institute of Water and Atmospheric Research, New Zealand) and an anonymous reviewer made a number of constructive comments that helped considerably in producing an open and honest account of the development of the Namibian orange roughy fishery. The Ministry of Fisheries and Marine Resources is thanked for the financial support they provided to MKM.

LITERATURE CITED

ANNALA, J. H. and K. J. SULLIVAN 1996 — Report from the Fishery Assessment Plenary, April–May 1996: stock assessments and yield estimates. Unpublished report, NIWA, Wellington, New Zealand: 207 pp.

ANON. 2001 — ORH 1 Adaptive management programme proposal – 2001. Report to the Ministry of Fisheries Deepwater Working Group **01/20**: 32 pp. (mimeo).

BAX, N. J. (Comp.) 2000 — Stock assessment report 2000: orange roughy (*Hoplostethus atlanticus*). Unpublished report, CSIRO Division of Marine Research, Hobart: 81 pp. (mimeo).

BERGH, M. O. and D. S. BUTTERWORTH 1987 — Towards rational harvesting of the South African anchovy considering survey imprecision and recruitment variability. In *The Benguela and Comparable Ecosystems*. Payne, A. I. L., Guland, J. A. and K. H. Brink (Eds). *S. Afr. J. mar. Sci.* **5**: 937–951.

BOYER, D. and I. HAMPTON 2001a — Development of acoustic techniques for assessment of orange roughy *Hoplostethus atlanticus* biomass off Namibia, and of methods for correcting for bias. In *A Decade of Namibian Fisheries Science*. Payne, A. I. L., Pillar, S. C. and R. J. M. Crawford (Eds). *S. Afr. J. mar. Sci.* **23**: 223–240.

BOYER, D. C. and I. HAMPTON 2001b — An overview of the living marine resources of Namibia. In *A Decade of Namibian Fisheries Science*. Payne, A. I. L., Pillar, S. C. and R. J. M. Crawford (Eds). *S. Afr. J. mar. Sci.* **23**: 5–35.

BOYER, D. C., STABY, A., LESCH, H. and I. HAMPTON 2001 — Orange roughy survey – 16 to 28 July 2000. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia: 52 pp. + 11 Appendices. (mimeo).

BRANCH, T. A. 1996 — Baseline biomass estimates for orange roughy off Namibia, using swept-area technique. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia **DWFWG/WkShop/Jan97**: 13 pp. (mimeo).

BRANCH, T. A. 1998 — Assessment and adaptive management of orange roughy off southern Africa. M.Sc. thesis, University of Cape Town: 204 pp.

BRANCH, T. A. and D. S. BUTTERWORTH 1996 — Accounting for the influence of bias on baseline estimates of orange roughy off Namibia. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia **DWFWG/WkShop/Jan97**: 24 pp. (mimeo).

BRANCH, T. A. and R. D. ROBERTS 1998 — Swept-area estimates for Namibian orange roughy. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia **DWFWG/WkShop/Jan98/6**: 11 pp. (mimeo).

BRANDÃO, A. 1999 — Annual swept-area estimates for Namibian orange roughy off Namibia. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia. **DWFWG/WkShop/Jan99/19**: 29 pp. (mimeo).

BRANDÃO, A. and D. S. BUTTERWORTH 2000 — Are acoustic survey biomass estimates for orange roughy aggregations compatible with catch-induced depletion alone? Unpublished report, Ministry of Fisheries and Marine Resources, Namibia: **DWFWG/WkShop/Jan2000/11**: 13 pp. (mimeo).

BUTTERWORTH, D. S. and M. O. BERGH 1993 — The development of a management procedure for the South African anchovy resource. In *Risk Evaluation and Biological Reference Points for Fisheries Management.* Smith, S. J., Hunt, J. J. and D. Rivard (Eds). *Can. Spec. Publ. Fish. aquat. Sci.* **120**: 83–99.

BUTTERWORTH, D. S. and T. A. BRANCH 1996 — The likely effect of alternative future catch levels on the stock of orange roughy off Namibia. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia **DWFWG/Wkshop/Jan97**: 16 pp. (mimeo).

CLARK, M. R. 1995 — Experience with management of orange roughy (*Hoplostethus atlanticus*) in New Zealand waters, and the effects of commercial fishing on stocks over the period 1980–1993. In *Deep-water Fisheries of the North Atlantic Oceanic Slope.* Hopper, A. G. (Ed.). Dordrecht, The Netherlands; Kluwer Academic: 251–266.

CLARK, M. R. 1996 — Biomass estimation of orange roughy: a summary and evaluation of techniques for measuring stock size of a deep-water fish species in New Zealand. *J. Fish Biol.* **49**(Suppl. A): 114–131.

CLARK, M. R. 2001 — Are deepwater fisheries sustainable? The example of orange roughy (*Hoplostethus atlanticus*) in New Zealand. *Fish. Res.* **51**: 123–135.

CLARK, M. R., ANDERSON, O. F., FRANCIS, R. I. C. C. and

D. M. TRACEY 2000 — The effects of commercial exploitation on orange roughy (*Hoplostethus atlanticus*) from the continental slope of the Chatham Rise, New Zealand, from 1979 to 1997. *Fish. Res.* **45**: 217–238.
CLARK, M. R. and D. M. TRACEY 1994 — Changes in a population of orange roughy, *Hoplostethus atlanticus*, with commercial exploitation on the Challenger Plateau, New Zealand. *Fishery Bull., Wash.* **92**: 236–253.
DALEN, J., BOYER, D., STAALESEN, B., STABY, A. KIRCHNER, C., CLARK, M., HAMPTON, I., KVINGE, B. and J. JOHANNSON 1998 — Orange roughy survey, 1 July–25 July 1998, Cruise report No. 4/98, NORAD-FAO/UNDP PROJECT GLO 92/013. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia: 92 pp. + 32 Appendices (mimeo).
DOONAN, I. J. 1991 — Orange roughy fishery assessment, CPUE analysis – linear regressions, NE Chatham Rise 1991. *N.Z. Fisheries Assessment Research Document* **91/9:** 48 pp. (mimeo).
ELLIOTT, N. G. and R. J. KLOSER 1993 — Use of acoustics to assess a small aggregation of orange roughy, *Hoplostethus atlanticus* (Collett) off the eastern coast of Tasmania. *Aust. J. mar. Freshwat. Res.* **44**: 473–482.
F.A.O. 1995 — *Code of Conduct for Responsible Fisheries*. Rome; F.A.O.: 41 pp.
F.A.O. 1997 — Review of the state of the world fishery resources: marine fisheries. *F.A.O. Fish. Circ*. **920**: 173 pp.
FENTON, G. E., SHORT, S. A. and D. A. RITZ 1991 — Age determination of orange roughy, *Hoplostethus atlanticus* (Pisces: Trachichthyidae), using ^{210}Pb:^{226}Ra disequilibria. *Mar. Biol.* **109**: 197–202.
FRANCIS, R. I. C. C. 1992 — Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Can. J. Fish. aquat. Sci*. **49**: 922–930.
FRANCIS, R. I. C. C., CLARK, M. R., COBURN, R. P., FIELD, K. D. and P. J. GRIMES 1995 — Assessment of the ORH 3B orange roughy fishery for the 1994–1995 fishing year. *N.Z. Fisheries Assessment Research Document* **95/4**: 43 pp. (mimeo).
FRANCIS, R. I. C. C., ROBERTSON, D. A., CLARK, M. R. and R. P. COBURN 1992 — Assessment of the ORH 3B orange roughy fishery for the 1992/93 fishing year. *N.Z. Fisheries Assessment Research Document* **92/4**: 45 pp. (mimeo).
FRANCIS, R. I. C. C., ROBERTSON, D. A., CLARK, M. R., DOONAN, I. J., COBURN, R. P. and J. R. ZELDIS 1993 — Assessment of the ORH 3B orange roughy fishery for the 1993/1994 fishing year. *N.Z. Fisheries Assessment Research Document* **93/7**: 43 pp. (mimeo).
FRANCIS, R. I. C. C. and R. SHOTTON 1997 — "Risk" in fisheries management: a review. *Can. J. Fish. aquat. Sci.* **54**: 1699–1715.
GAULDIE, R. W. (Ed.) 1998 — *The Second Fish Age Workshop*. Lower Hutt, New Zealand; IGNS: 42 pp.
GULLAND, J. A. 1971 — Science and fishery management. *J. Cons. int. Explor. Mer* **33***:* 471–477.
HILBORN, R. and J. SIBERT 1988 — Adaptive management of developing fisheries. *Mar. Policy* **12**: 112–121.
HILBORN, R. and C. J. WALTERS 1992 — *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty*. New York: Chapman & Hall: 570 pp.
HUSE, I., DAHL, M., ØVREDAL, J. T., BOYER, D., STAALESEN, B., STABY, A. FOSSEN, I., CLARK, M. and R. KLOSER 1997 — Orange roughy survey, 15 July – 1 August July 1997, Cruise report 4/97, NORAD-FAO/UNDP PROJECT GLO 92/013. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia: 61 pp. + 12 Appendices (mimeo).
KIRCHNER, C. H. and M. McALLISTER (in press) — A new improved method to compute swept area estimates of biomass from commercial catch rate data: application to Namibian orange roughy (*Hoplostethus atlanticus*). *Fish. Res.*
KOSLOW, J. A., BULMAN, C. M. and J. M. LYLE 1994 — The mid-slope demersal fish community off southeastern Australia. *Deep-Sea Res.* **41A**: 113–141.
KOTLYAR, A. N. 1996 — *Beryciform Fishes of the World Ocean*. Moscow; VNIRO Publishing: 367 pp.
LESCH, C. 2000 — A comparison of the meristic and morphometric characteristics of three commercially fished orange roughy, *Hoplostethus atlanticus* aggregations in the Namibian exclusive economic zone. M. Appl. Sci. thesis, Australian Maritime College: 34 pp.
LUDWIG, D., HILBORN, R. and C. J. WALTERS 1993 — Uncertainty, resource exploitation, and conservation: lessons from history. *Science* **260**: 17–36.
MACE, P. M., FENAUGHTY, J. M., COBURN, R. P., and I. J. DOONAN 1990 — Growth and productivity of orange roughy (*Hoplostethus atlanticus*) on the north Chatham Rise. *N.Z. Jl mar. Freshwat. Res*. **24**: 105–119.
MACE, P. M. and W. L. GABRIEL 1999 — Evolution, scope and current applications of the precautionary approach in fisheries. In *Proceedings of the 5th MILEFS, 1999. NOAA tech. Memo.* **MILEFS-F/SPO-40**: 64–73.
McALLISTER, M. K. and J. N. IANELLI 1997 — Bayesian stock assessment using catch-age data and the sampling/importance resampling algorithm. *Can. J. Fish. aquat. Sci.* **54**: 284–300.
McALLISTER, M. K. and C. H. KIRCHNER 2001 — Development of Bayesian stock assessment methods for Namibian orange roughy *Hoplostethus atlanticus*. In *A Decade of Namibian Fisheries Science*. Payne, A. I. L., Pillar, S. C. and R. J. M. Crawford (Eds). *S. Afr. J. mar. Sci*. **23**: 241–264.
McALLISTER, M. K. and C. H. KIRCHNER (in press) — Accounting for structural uncertainty to facilitate precautionary fishery management: illustration with Namibian orange roughy. In *Targets, Thresholds, and the Burden of Proof in Fisheries Management*. Mangel, M. (Ed.). *Bull. mar. Sci.*
McALLISTER, M. K. and G. P. KIRKWOOD 1997 — Bayesian risk assessment of alternative catch quota policies for orange roughy in Namibia: some preliminary results. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia **DWFWG/WkShop/ Feb97**: 11 pp. (mimeo).
McALLISTER, M. K. and G. P. KIRKWOOD 1998 — Using Bayesian decision analysis to help achieve a precautionary approach for managing developing fisheries. *Can. J. Fish. aquat. Sci*. **55**: 2642–2661.
MILLER, R. J. 1999 — Courage and the management of developing fisheries. *Can. J. Fish. aquat. Sci.* **56**: 897–905.
MOORE, J. A. 1999 — Deep-sea finfish fisheries: lessons from history. *Fisheries* **24**(7): 16–21.
MOORE, J. A. and P. M. MACE 1999 — Challenges and prospects for deep-sea finfish fisheries. *Fisheries* **24**(7): 22–23.
OELOFSEN, B. W. 1999 — Fisheries management: the Namibian approach. *ICES J. mar. Sci.* **56**: 999–1004.
RICHARDS, L. J. and J-J. MAGUIRE 1998 — Recent international agreements and the precautionary approach: new directions for fisheries management science. *Can. J. Fish. aquat. Sci.* **55**: 1545–1552.
ROBERTSON, D. A. 1991 — The New Zealand orange roughy fishery: an overview. In *Australian and New Zealand Southern Trawl Fisheries Conference. Issues and Opportunities*. Williams, M., Smith, P. and K. Abel (Eds). *Aust. Bur. Rural Resour.* **10**: 38–48.

ROSE, G. A. 1997 — The trouble with fisheries science! *Revs Fish Biol. Fish*. **7**: 365–370.

SCHNUTE, J. T. and L. J. RICHARDS 2001 — Use and abuse of fishery models. *Can. J. Fish. aquat. Sci.* **58**: 10–17.

SERCHUK, F. M., RIVARD, D., CASEY, J. and R. K. MAYO 1999 — A conceptual framework for the implementation of the precautionary approach to fisheries management within the Northwest Atlantic Fisheries Organization (NAFO). In *Proceedings of the 5th MILEFS NSAW, 1999. NOAA tech. Memo*. **MILEFS-F/SPO-40**: 103–119.

SHEPHERD, J. G. 1981 — Cautious management of marine resources. *Math. Biosci.* **55**: 179–187.

SMITH, A. F. M. 1991 — Bayesian computational methods. *Phil. Trans. R. Soc. Lond., Ser. A* **337**: 369–386.

SMITH, D. C., FENTON, G. E., ROBERTSON, S. G. and S. A. SHORT 1995 — Age determination and growth of orange roughy (*Hoplostethus atlanticus*): a comparison of annulus counts with radiometric ageing. *Can. J. Fish. aquat. Sci.* **52**: 391–401.

SMITH, S. J., KRUSE, G., EGGERS, D. M., MARASCO, R. J., PAUTZKE, C. and T. J. QUINN (Eds) 1992 — Risk evaluation and biological reference points for fisheries management: a review. In *Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations*. Kruse, G., Eggers, D. M., Marasco, R. J., Pautzke, C. and T. J. Quinn (Eds). University of Alaska, Fairbanks, and Alaska Sea Grant College Program Report **93-02**: 339–353.

STAALESEN, B., BOYER, D., STABY, A. KAINGE, P., GAMATHAM, J., SHIMHANDA, M., WELLS, S., BARANGE, M., HAMPTON, I., REES, A., OLSEN, M., MØRK, T. and T. JOHANNSON 1999 — Orange roughy survey, 6 – 29 July 1999, Cruise report 5/99, NORAD-FAO/UNDP PROJECT GLO 92/013. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia: 72 pp. + 12 Appendices (mimeo).

STABY, A. 2000 — Update of the orange roughy fishery. Unpublished report, Ministry of Fisheries and Marine Resources, Namibia **DWFWG/WkShop/2000/4**: 12 pp. (mimeo).

STARR, P., CLARK, M. and C. FRANCIS 1996 — ORH1 – Blueprint for controlled development of an orange roughy fishery? *Seafood N.Z.*: 29–31.

TRACEY, D. M. and P. L. HORN 1999 — Background and review of ageing orange roughy (*Hoplostethus atlanticus*, Trachichthyidae) from New Zealand and elsewhere. *N.Z. Jl mar. Freshwat. Res*. **33**: 67–86.

ULLTANG, Ø, 1996 — Stock assessment and biological knowledge: can prediction uncertainty be reduced? *ICES J. mar. Sci.* **53**: 659–675.

WALTERS, C. J. 1986 — *Adaptive Management of Renewable Resources*. New York: Macmillan: 384 pp.

WALTERS, C. J. 1998 — Evaluation of quota management policies for developing fisheries. *Can. J. Fish. aquat. Sci.* **55**: 2691–2705.

WALTERS, C. J. and R. HILBORN 1976 — Adaptive control of fishing systems. *J. Fish. Res. Bd Can.* **33**: 145–159.

WALTERS, C. J. and R. HILBORN 1978 — Ecological optimization and adaptive management. *A. Rev. Ecol. Syst.* **9**: 157–188.