Working Paper

Analysis of Sardine Fisheries Management on Lake Kariba, Zimbabwe and Zambia – Structuring a Bayesian Influence Diagram Model

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Foreword

A three-year study on the development of decision support tools for management of large international rivers was conducted by the *Water Resources Project* of the Environment Program at IIASA. The Zambezi river basin in Africa, shared by eight riparian countries, was the main focus of this study. Issues related to the basin addressed by the research study were hydro-biological characteristics, political and socio-economic situation, problems of soil erosion and erosion hazard modeling, and multiobjective optimization of the operating policies for the Zambezi reservoirs.

The present paper describes another natural resource management, namely, sardine fisheries management on the Lake Kariba, one of the biggest man-made lakes and an important source of fish in the region. It combines two elements: analysis of the fisheries management strategy with the application of a Bayesian Influence Diagram, a new tool becoming increasingly popular in the analysis and structuring of various decision problems.

I hope that results of this study will be interesting to a wide range of experts dealing with problems of fisheries management, decision analysis and decision making, and those developing decision support tools.

Professor B.R. Döös
Leader
Environment Program

Abstract

One of the main issues in the fisheries management of Lake Kariba is the question of how much the total effort of sardine fisheries can be increased without threatening the renewal of the stock and the economical profitability of the fisheries. This problem is subjected to uncertain natural processes and diverse and insufficient information available. A bayesian influence diagram model was developed to analyze the decision problem. The Bayesian approach offers means for fusioning probabilistic information from different sources, and assessing the relative information value of quantities included in the model.

CONTENTS

ANALYSIS OF SARDINE FISHERIES MANAGEMENT ON LAKE KARIBA, ZIMBABWE AND ZAMBIA – STRUCTURING A BAYESIAN INFLUENCE DIAGRAM MODEL

O. Varis and S. Kuikka***

1. Introduction

In fisheries management, both biological and economic mechanisms cause uncertainties in decision making. Also, the quantities affecting management are usually involved, and the information used is complex. Investments made for long periods decrease the possibilities to manage the system in short time intervals. Therefore, fisheries management should be based on strategic, long term decision making even though actual decisions are made once a year.

Lake Kariba is a large man made lake between Zimbabwe and Zambia with a surface area of 5 700 km^2. The lake was completed in 1960 when the dam was closed. Water level management is mainly adapted to hydropower production purposes. Large fluctuations in the water level and wave action have created an erosion zone almost devoid of vegetation (Ramberg et al 1987). The catches of littoral fish species have decreased by 60% since 1965. This change is apparently due to loss of reproduction and feeding areas. At the same time, the pelagic catches of sardine, Limnothrissa miodon, have expanded rapidly (Marshall 1987).

This work reviews the experiences from the application of Bayesian influence diagram models to structuring and analysis of sardine fisheries management in Lake Kariba.

The main objectives of this study were:

(1) To find a feasible model structure in which the most essential quantities affecting decision making and their interdependencies are included.

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(2) To analyze the sensitivity of the total model towards all its probabilistic variables as well as the assumed risk attitude as one factor driving the management.

(3) To test the applicability of the influence diagram approach to fisheries management.

(4) To asses the rationality in the fear of collapse of the stock as a basis for the management of sardine stock.

2. Bayesian Influence Diagrams

The original idea of an influence diagram was to provide a framework for interactive probabilistic modeling with special scope to make problem structuring more accessible to users and closer to the analysis (Owen 1978). The emphasis was on developing an interface in which the notations are easily interpretable graphs, the design and evaluation of which can be done interactively. Shachter (1986) points out the possibilities of diagrams in lowering the gap between analysis and formulation of problems and in making application of analytical methods more accessible and tractable to decision makers.

An influence diagram, in this work used in the same sense as Howard & Matheson (1984), and Shachter (1986), describes the influence of quantities and its attributes to one another. The variables, called nodes, can be either decisions, probabilistic or deterministic quantities, expected values or value lotteries (Figure 1). The nodes are connected with directed arcs. The diagram is directed but no feedback is allowed.

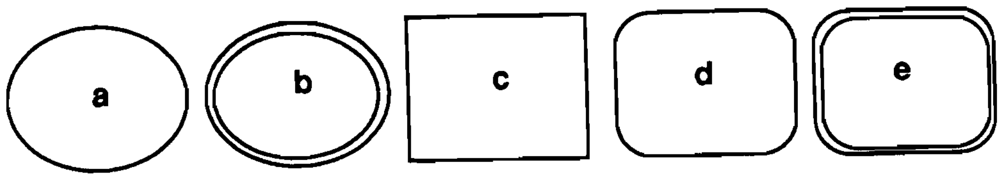

Figure 1. Types of nodes used in influence diagrams by Shachter (1986): (a) probabilistic, (b) deterministic, (c) decision, (d) value lottery, and (e) expected value.

In case an arc directs to a decision node, it means that the value of the predecessor must be known before a decision can be made. In all other cases, an arc stands for a conditional dependency between the two variables.

A number of properties must be assigned to the nodes: the outcomes, and depending on the variable types, arithmetic functions, IF-THEN-ELSE rules or probability distributions. The probabilistic and deterministic nodes can be evaluated or reduced one by one using the Bayes' rule. This facilitates the local evaluation of models. For details, see, for example, Shachter (1986).

3. Sardine Fisheries

Sardine was introduced to Lake Kariba from Lake Tanganyika in 1967–68. It has been extremely successful, and since its introduction the species spread rapidly throughout the lake. First experimental fishing began in 1970 and commercial fisheries in 1971 (Marshall *et al.* 1982). Present sardine catches contribute to more than 90% of the total catch in Lake Kariba.

3.1. Total efforts, catches and catch per unit of effort

Total effort (total number of fishing nights during one year) has increased steadily since 1979 being thirty times higher in 1985 than in 1977 (Figure 2). Recent relative growth has been slower than at the end of the 70's. The fisheries of Zambia are unregulated, but on the Zimbabwean side of the lake fishing is regulated by a licencing system. This system was initiated in 1979–80 to prevent an uncontrolled increase of fishing effort (Bourdillion *et al.* 1985).

Total catches (amount in tons during one year) have increased rapidly since 1974, and reached a level of 24 000 tons in 1985 (Figure 2). More recent data were not available. The total catch has followed the increase of effort except in 1982, when it dropped. Since then the total catch has increased even faster than the total effort demonstrating that the catch has probably not yet reached the maximal level.

The Catch Per Unit Effort (CPUE, mean catch in one fishing night) values decreased sharply until the beginning of the '80s. This was due to the increase in the total catches which diminished the mean biomass in the lake. The most interesting years are 1980–1985 when CPUE values remained quite stable although total catches continued to grow. This may be because (i) the production of the fish stock increases when the biomass decreases and remains stable and demonstrated by the stable CPUE values; or, (ii) fishermen have improved their fishing techniques or increased their actual effort during the fishing nights to get stable income.

Changes in the productivity of pelagically living sardine may be caused by the fact that if the fish biomass is decreased by fishing mortality, there is more nutrition (zooplankton) for the remaining stock facilitating rapid growth and more effective reproduction.

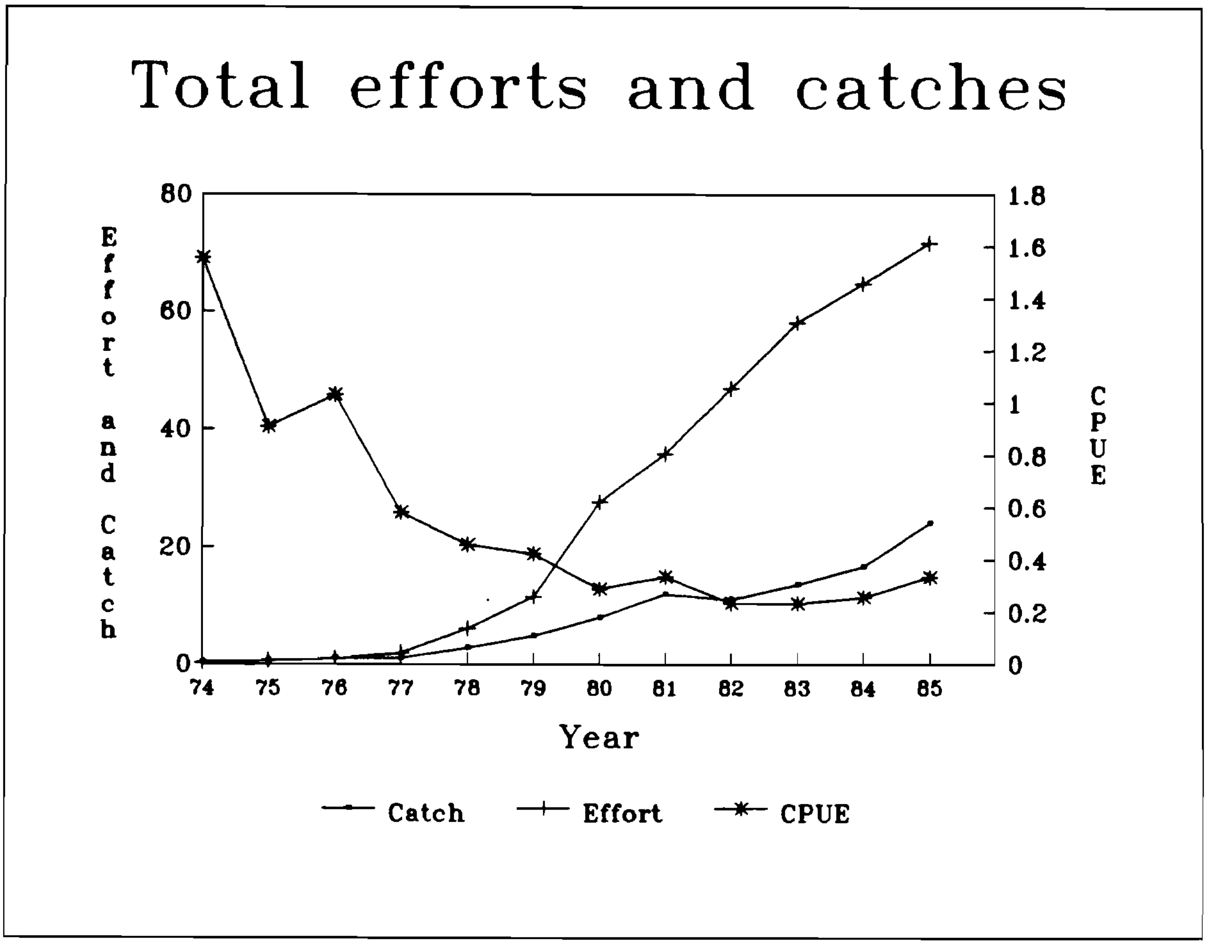

Figure 2. Total effort (1 000 fishing nights), total catch (1 000 tons), and catch per unit of effort (tons/night) in sardine fisheries of Lake Kariba in 1974–85.

The changes in the behavior of fishermen include the development of technology, for example, echo-sounding has become more frequent during the last decade, and increase in the real effort, in particular. Until 1982, the fishermen were paid by the hour, but since then most of them have been receiving a certain percentage of the value of the catch as a salary (Bourdillion *et al.* 1985). It is likely that the fishermen tend to increase their effort during the night to have a salary every night. However, this phenomenon cannot be true under the present conditions, because total effort is reported to be equal to the total number of fishing nights. Therefore, neither of the hypotheses can be proved right or wrong with any reliability. The effect of both hypotheses was tested in the model simulations. To solve the previous problem it would be necessary to collect the effort data so that the real effort (for instance, amount of lifts) can be estimated.

3.2. Water inflows and fish production

Marshall (1982) suggests that the water inflows to Lake Kariba are important factors for fish production. He used CPUE as an index of production, which is somewhat an inexact assumption. In a more recent analysis of CPUE data, Marshall (1987) has showed that there is a negative correlation between the CPUE values and the total catches. In 1981–84 the total catch increased remarkably, even though the total inflow has been very low compared to the previous years (Figure 3). Thus, inflow has probably no clear influence on the production of the fish stock.

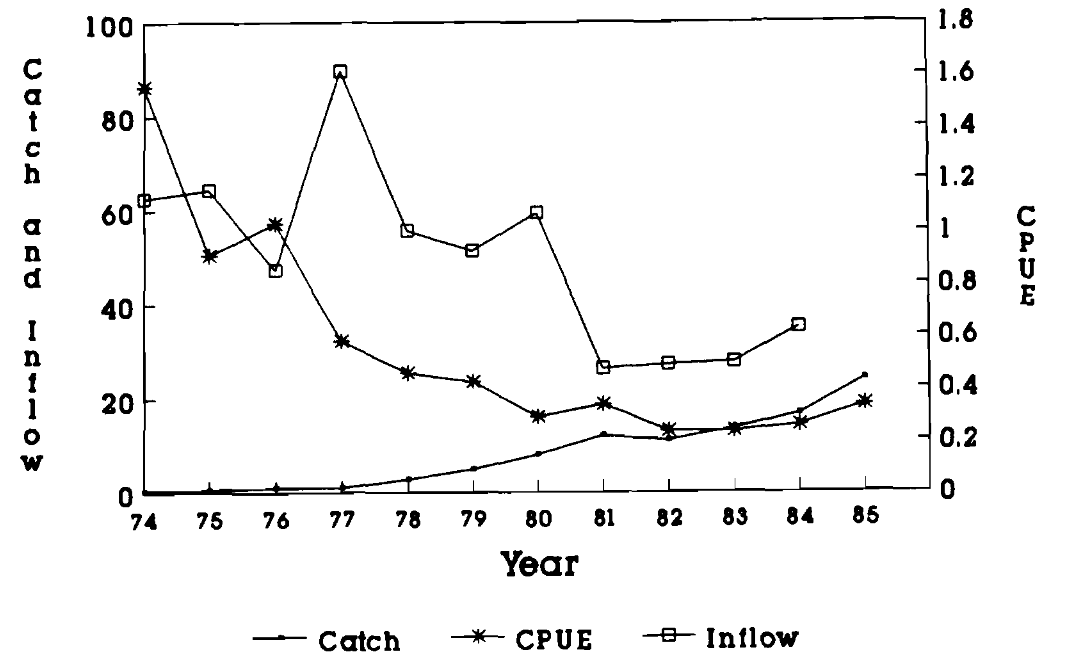

Figure 3. Catch per unit of effort values (Marshall 1987) of sardine fisheries and total inflows (CAPCO 1981) of Lake Kariba.

4. Structuring of the Model

The basic idea behind the structure of the model was to describe such long-term effort decisions, by which the long-term catches of Lake Kariba can be evaluated. This is why the objective function was described by means of the catch, risk of collapse of the stock, and the CPUE values, effort being the only decision variable.

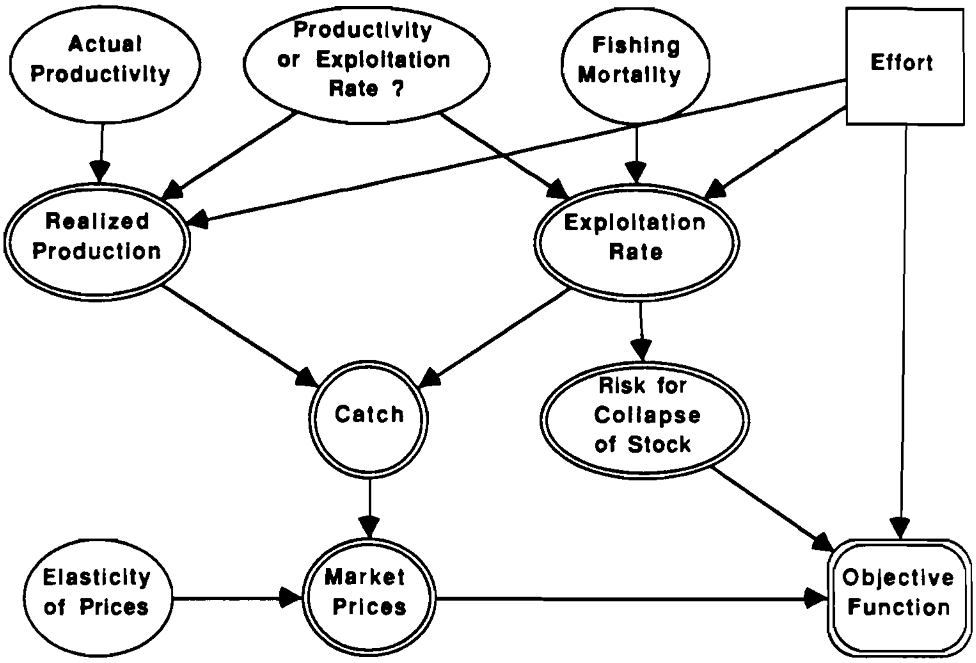

Figure 4. Influence diagram model for the sardine fisheries of Lake Kariba. Also a model without price elasticity was used in the analysis.

The model consists of eleven nodes (Figure 4), with one decision, four probabilistic, four deterministic, and one expected value nodes, described in brief in the following. Essential uncertainties were included in the model as *a priori* distributions. This construction makes it easier to asses the effects of different uncertainties on the overall behavior of the model.

Actual productivity

The distribution for the maximum fish production capacity of Lake Kariba was estimated by the values published (Table 1). The latest available catch (1985) was selected as the minimum value. In addition, one estimate was calculated using the recent yield per hectare values in the Sanyati Basin as an extension to the whole lake. This basin is the most effectively utilized area in Lake Kariba. This assumption is based on the observation that the productivity and density of sardine seem to be similar in all basins (Ramberg *et al.* 1987). The values used and their probabilities were: P(50 kg/ha) = 0.25, P(58 kg/ha) = 0.25, P(65 kg/ha) = 0.25, and P(80 kg/ha) = 0.25. Thus, the distribution was skewed to the left.

Table 1. Sources of information for the distribution of the maximal fish production in Lake Kariba. For more details on the values given by Machena & Fair (1986), see the original paper.

Source	Fish production kg/ha	Total catch
Marshall *et al.* (1982)	62–73	33 000–39 000
Machena & Fair (1986)	27	14 500
Machena & Fair (1986)	38.5	20 600
Machena & Fair (1986)	23	12 300
Machena & Fair (1986)	19	10 200
This report	80	43 000
Maar (1959)	56	30 00

Effort

This is the decision node in the model, decribing the amount of fishing. In this model the relative effort is a decision by which the manager attempts to control the fishing mortality of the stock. On Lake Kariba this is done in practice by allowing or refusing fishing licenses. Values 0.75, 1.0, 1.25, 1.5, 1.75, 2.0 and 2.25 times the reference effort in 1985 were used.

Realized Production

As explained earlier in Section 3.2, the changes in the CPUE values can be explained in two ways: either productivity has increased as a function of total effort, or, the behavior of the fishermen or the fish stock has changed. The impact of these two factors is included in the analysis through the productivity equation that relates production to relative effort f through coefficient a used to describe stability of the CPUE due to increased production and behaviour of the fisherman:

$$P_R = P_A f^a \tag{1}$$

where P_R is realized production ($kgha^{-1}$), P_A is actual production, f is relative effort, and a is the proportional contribution of increased productivity to the observed stability of CPUE with increased total catch. If production is linearly dependent on effort, then $a = 1$, and if effort has no effect on production, then $a = 0$.

Productivity or Exploitation Rate?

This node was included in the model in order to test whether the stability of the CPUE values is due to the increased production of the fish stock or the changed behavior of the fishermen. Outcomes for a and their probabilities were $p(0.5) = 0.2$, $p(0.25) = 0.6$ and $p(0.05) = 0.2$.

Market Prices

The value of the catch was calculated by equation (2).

$$P = [(1+e) - z((re)/q)]r \tag{2}$$

where P is market price, e expresses the elasticity of prices, r is catch, and z and q are scaling factors with respective values 4 and .44. Thus, the decrease in the prices per kg is supposed to be between 20 and 40 per cent when the total catch is doubled.

Elasticity of Prices

The elasticity of market prices was included in the model because the rise in prices of sardine has not been as fast as the inflation (Bourdillon *et al.* 1985). Supposedly this is due to the increased supply of sardine on the market. As a result of the inaccurate data we used, the elasticity as *a priori* distribution, the outcomes and their probabilities $P(e)$ were: $P(0.2) = 0.5$ and $P(0.4) = .5$. Use of these results is explained in the preceding paragraph.

Fishing Mortality

The proportional annual fishing mortality in Lake Kariba was unknown to the analysts. Values 0.6 with probability 0.4, and 0.9 with 0.6, were assumed to account for the uncertainty of the 1985 level of the proportion of the stock caught in one year.

Exploitation Rate

The exploitation rate in the model describes the proportion of production that is exploited by a given effort and prior fishing mortality (equation 3).

$$E = 1 - e^{z} \tag{3}$$

where $z = -\ln(1-d)f^{(1-a)}$, E is exploitation rate and d is fishing mortality (year^{-1}). For the other variables, see equation (1).

Catch

Catch is a deterministic node calculated as a product of exploitation rate and sustainable production. Although this is a simplified assumption, it describes sufficiently well the nature of the utilization process for such short-lived species as the sardine.

Risk for Collapse of Stock

Risk threshold expresses the critical exploitation rate of the stock. The real risk for the collapse of the stock is probably minimal (see Section 7.2), but this fear has been a part of the basis of management strategy during the last few years on the Zimbabwean side of the lake. One of our aims was to try to asses the rationality of this management strategy that supported the inclusion of risk in the model in terms of the sensitivity analysis described below.

Objective Function

The total reward from market prices were maximized, taking into consideration the risk of the collapse of the stock and the reward per unit effort (equation 4).

$$J = \max_{f}\{R(1-e^{-(c+br/f)})\,(1-np)\} \tag{4}$$

where R is the reward from market prices, or directly from the catch in sensitivity analyses below, r is total catch, f is total effort, b and c are scaling constants with values -0.1125 and 2.5, p is the probability level for the risk of the collapse of the stock and n is the assumed influence time of the collapse, see Section 5. The term $e^{-(c+br/f)}$ describes the will of the decision maker to keep the CPUE values above the economically critical level that was assumed to be 0.2 tons per fishing night.

5. Risk Sensitivity Analysis

As a first step in the model analysis, the sensitivity of the model to the risk attitude of managers and to the critical survival rate was explored. This was done separately for models maximizing the market prices, and for those maximizing the catch (Figure 4).

Four risk threshold values for the critical survival rate, of 0.99, 0.96, 0.93 and 0.90 were considered. As the exploitation rate E exceeds or equals these values, a probability p of 0.05 is assigned to the collapse. As total mortality regulates the biomass of the spawning stock, the relationship above describes the essential problem of fisheries management as to how safe low spawning biomass is.

In the analysis of model sensitivity to risk attitude of the decision maker, the aversion range from −100 to 100, the Arrow-Pratt absolute risk aversion (see Pratt 1964) was used.

$$\rho(x) = -\, U''(x)/U'(x) \tag{5}$$

where $\rho(x)$ is the risk aversion as a function of the objective function outcome x and $U(x)$ is its utility. This range was chosen because it corresponds to the distance of one inverse of variance of x from its expected value, which equals to the mean, since normality is assumed. Constant risk aversion with respect to assets was used:

$$\begin{aligned} U(x) &= g + hx && \text{if } \rho = 0 \\ U(x) &= g - h^{(-\rho x)} && \text{if } \rho > 0 \\ U(x) &= g + h^{(-\rho x)} && \text{if } \rho < 0 \end{aligned} \tag{6}$$

where g and h are scaling constants. The difference between the level, which is equivalent to a decision maker with risk attitude ρ, with an option in which the reward equals the expected value of the model, and can be obtained with probability one, can be expressed as:

$$RP(x) = E(x) - CE(x) = 1/2\alpha^2\rho + o(\alpha^2) \tag{7}$$

where E denotes expected value, RP risk premium, CE certainty equivalence, α standard deviation and o terms for smaller order than α^2 (Pratt 1964). As usual, certainty equivalence equals to an amount obtained with certainty, which is indifferent to an uncertain option. In the next section, further sensitivity analyses were carried out assuming that the managers are risk neutral.

The results in Figure 5 show a clear shift in the optimal effort strategy with respect to both the risk attitude and the critical exploitation rate. Proportioned to the variance of the models, the shift in the strategy as a function of risk attitude was very rapid. This holds especially in the case where marketing prices and elasticity involved were omitted, but was also evident with the nominal model. In the former, the model appeared also somewhat unstable around the risk neutral domain. In the risk averse domain, both cases appear conservative; the figures suggest pertaining to the 1985 level if the catch is to be maximized, and a decrease in the effort if the market revenues are to be maximized. Both cases suggest an increase in the effort in the risk prone domain. The risk threshold appeared to become critical earlier to the market valued case, and with the threshold value 0.9, the effort should be cut down, even if risk prone attitude prevails.

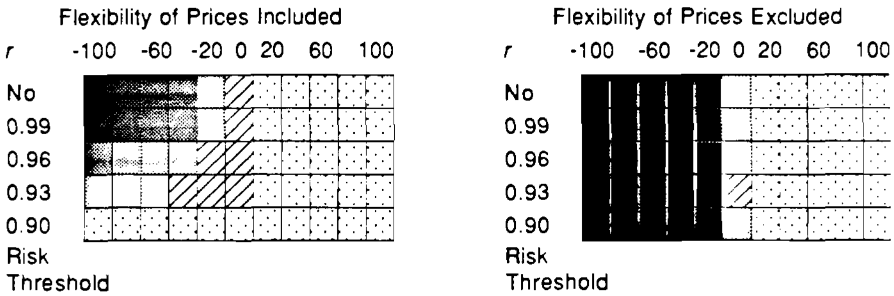

Figure 5. Results of risk sensitivity analyses. For rasters expressing the optimal volume of effort, see Figure 6.

The model with price mechanism seems to be more stable and conservative than the other for it is not as sensitive to risk attitude as the model without price mechanism. As the two models suggest different kinds of strategies for the same risk attitudes, we may assume that a biologically-orientated manager has a different risk attitude than an economic-orientated one.

The results demonstrate that the risk attitude of uncontrolled fisheries of Lake Kariba has been risk prone, especially from the point of view of an economic-oriented management. The price mechanism seems to be some kind of self control mechanism preventing an extreme increase in effort.

The main result of our analysis is, however, that the management strategy (risk attitude) is a more important factor in the decision making than exact biological data. Thus, it may be useless to study the exact state of the resource unless we know what kind of strategy the decision makers want to use, i.e. what his exact aim is.

6. Probabilistic Sensitivity Analyses

Since the present model is not based on sufficient interaction with the fisheries management agencies in Zambia and Zimbabwe, actually emphasis must be laid – despite the structuring of the problem – also on the study of the relative importance of each model variable to the total performance of the model. This was done applying probabilistic sensitivity analysis to each probabilistic node of the model.

The model with price elasticity as *a priori* distribution seemed to be very stable. All the suggested values for the effort were either .75 or 1. The price mechanism seems to add conservatism to the model.

Also the model without price mechanism was quite insensitive to *a priori* information (Figure 6). The effort suggested by the model does not change remarkably when the values of *a priori* distributions are varied. The most critical point in our analysis seems to be the question whether or not the stability of CPUE values is due to the changes in productivity or in the behavior of fishermen.

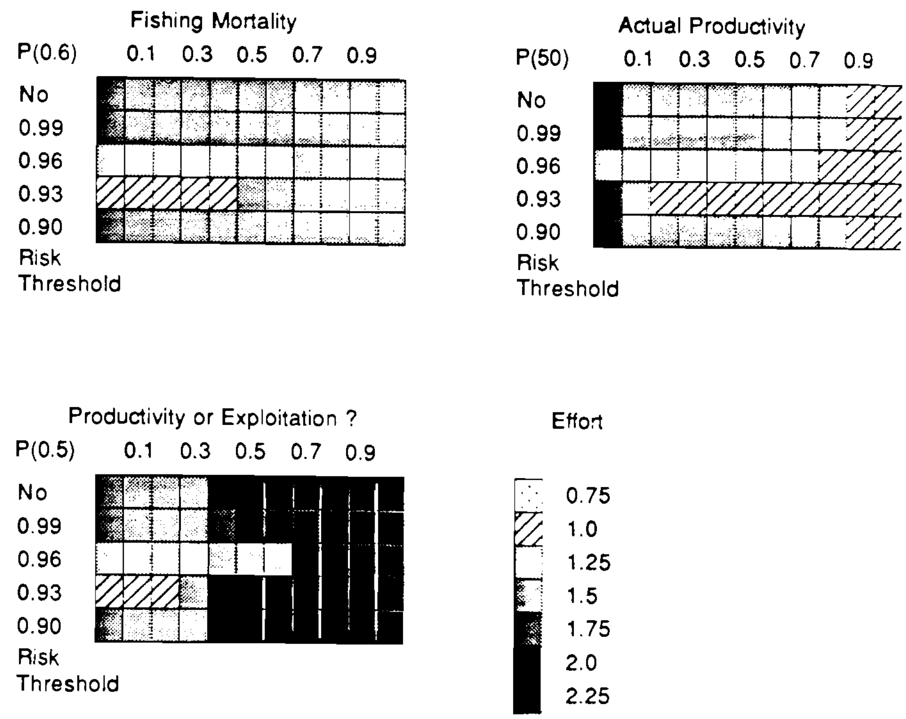

Figure 6. Results of probabilistic sensitivity analyses. Optimal volumes of effort with varying probabilities for prior distributions and different risk thresholds for the collapse of the stock.

According to the formulation of the objective function, the critical exploitation rate of 0.90 seems to be so low that the greater share of the distribution of exploitation rates is over this value. Therefore, the model suggested higher effort values for critical exploitation rates of 0.9 than for the exploitation rate of .93. This could be avoided by reformulating the objective function; however for an exact formulation of the objective function the real aims of the decision makers should be known.

Also, a brief assesment of the value of the information was done for the four *a priori* distributions. The value of the information of real productivity was only two per cent of the total value of the catch, and the value of the other variables was even less. These results show the importance of the management strategy compared to the measured information.

7. Concluding Remarks

7.1. Bayesian influence diagram model in fisheries management

The computerized interactive Bayesian influence diagram model provided a good framework for a systematic handling of the complex fisheries management decision making problem of Lake Kariba. It appeared to be a flexible and time-saving tool in modelling, which can be key factors in practical applications. The notation of the model is illustrative for the decision makers forcing them to analyze the problem systematically. Even if decision makers cannot be involved in the model building process, it is easy for them to add their views about even very complicated relationships to a model that has been constructed by an expert.

Usually in fisheries management the objective function can be expressed in terms of money values which makes it easier to formulate it. The difficult task to combine economic and biological uncertainties is easily solved by the diagram model.

7.2. The Risk of the collapse of the stock as a management problem

Owing to the fishing practice (Bourdillon *et al.*, 1985), it is not possible for one vessel to increase its fishing effort markedly. Therefore, regulating the number of fishing licenses should be a management practice. It should be pointed out that if the stock decreases by so much that recruitment is in danger, then the CPUE values will probably be on such a low level that it is not profitable to fish anymore. This and price elasticity are probably appropriate self-control mechanisms for the fisheries.

Increased fishing on the Zimbabwean side of Lake Kariba is limited due to the fear of over fishing (Kenmuir 1982). This fear is based mainly on the paper by Marshall (1982). However, more recent development of the catches seems to be different to what Marshall expected. Therefore, there is no evidence for the assumption that catches would have reached a maximum level.

Also the analysis of the influence diagram model supported the assumption that there is no reason to use the fear of the collapse of the stock as a basis of management unless the risk for the collapse or the losses are very high (see Figures 5 and 6).

7.3. Possibilities to increase sardine catches on Lake Kariba

It is obvious that sardine is able to use the feeding and reproduction facilities of the lake very effectively; the sardine population increased rapidly after its introduction to the lake (Marshall *et al.* 1982). For the same reason, it is probable that even very small spawning stocks can reproduce large amounts of recruits.

It is believed that the total sardine catch could still be increased (even four times the present yield) by increasing the total effort (Marshall 1984, Magadza 1986). It is possible that there is a negative correlation between the total biomass and the productivity of the fish stock. In 1971, the sardine population declined suddenly, obviously due to overpopulation (Bourdillion *et al.* 1985). This phenomenon supports the previous idea of the negative correlation between the total production and biomass.

If this theory holds true also for Lake Kariba, there is no reason to limit fishing pressure to the present level. The difference between the catches of Lake Tanganyika and Lake Kariba is probably also due to lower growth rates in Lake Kariba (Marshall 1984). As these stocks have the same genetical root, the difference could be due to environmental conditions, most probably due to insufficient amount of food. The increasing fishing pressure should therefore increase the amount of food per individual. This means that an individual can use a higher proportion of the assimilated energy for growth.

The continuity of good catches provides stable environmental conditions. Even if environmental changes do occur, the limitation of the fisheries cannot prevent the collapse of the stock, because sardine is very short-lived. However, it must be taken into consideration that the increasing fishing pressure reduces catches per unit efforts, thus reducing the profitability of the fisheries (see Figure 2). Too low a level would lead either to bankrupt ineffective fishing boats or unnecessary large investments in new and more effective fishing equipments. Recent analysis of catch per unit effort indicates clearly that the profitability of fisheries has decreased (Marshall 1987).

7.4. Proposals for future research

The importance of CPUE values both for the economics of the fisheries and for the biological monitoring of the stock emphasize the meaning of these values in research. Especially, the economically critical level of the CPUE should be known before it is reached, because slowing of the investment rate can be difficult. Also the structure of the costs (running costs/capital costs) should be known if the behavior of the fishing vessels has to be forecasted under changing conditions.

The amount of fish biomass at the time of decision making is the most important information for a fisheries manager. For such short-lived species such as the sardine, this information is, however, not connected clearly to the situation during the following fishing season. Often the decision maker does not know the exact value of the total catch in year $n-1$, because of the delay in information collection. Analysis of CPUE values usually results in more current information than, for example, population analysis, which is based on total catches and efforts, because CPUE values can be collected as a sample for the total catch and effort. Therefore, the use of CPUE values in the fisheries management of Lake Kariba is probably more advisable than the use of virtual population analysis models.

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