Thesis for the Degree of Master of Fisheries Science

# A Comparative Analysis of Surplus Production and Analytical Models for Assessing Kapenta (*Limnothrissa miodon*) Stock in Lake Kariba

by

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KOICA-PKNU International Graduate Program of Fisheries Science

The Graduate School

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Kariba 호에 서식하는 Kapenta 자원량 평가를 위한 잉여생산모델과 분석적 모델의 비교분석연구


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by

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A dissertation

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## Abstract

Surplus production (SP) models, a Maximum Entropy model (ME) and an Analytical Model are analyzed for fishery stock assessment for Kapenta (*Limnothrissa miodon*) in Lake Kariba. Five traditional surplus production models; Schaefer, Schnute, Walters and Hilborn, Fox and Clarke, Yoshimoto and Pooley (CYP) models are tested for effort and catch data of Kapenta which

occupies about 80% of fish landings in Lake Kariba. The CYP model is the only model that has a high goodness of fit and is statistically significant but the model showed a lower Mean Square Error than the Walters and Hilborn model. The ME model was a better estimate of catch than the Walters and Hilborn Model and estimated annual biomass for the fishery. The Analytical Model showed a more conservative Allowable Biological Catch (ABC) than the ME model and the estimated fishing mortality (F) for 2009 to be lower than that of 1982 as well as the fishing mortality at ABC suggesting that there is a small room to increase fishing intensity. Both the Analytical Model and the ME model estimated comparable estimates for 1982 stock biomass.

# Introduction

The clupeid *Limnothrissa miodon* (Boulenger, 1906), commonly known as Kapenta, was introduced into Lake Kariba in the 1967/8 (Mandima, 1999) from Lake Tanganyika to occupy the newly formed and vacant pelagic niche which none of the indigenous Zambezi riverine fish fauna showed potential to occupy, after the damming of the Zambezi River. It is a silvery planktivorous sardine (Marshall, 1991) which established commercially viable stocks within the first 5 years of its introduction and by 1974 commercial exploitation had started (Mandima, 1999).

Lake Kariba is a shared water body between Zimbabwe and Zambia and the two countries have attempted to manage fishing capacity in the lake through input controls (issuance of fishing permits) and technical controls (such as establishing fishing grounds, size of fish and enforcing minimum mesh sizes). In both countries fisheries management was (and still is) designed to ensure biological sustainability through the use of conventional biological scientific models and assumptions (Nyikahadzoi et al., 2010). However, it has been observed that Kapenta catches have steadily declined since the early 1990's giving rise to questions of whether the fishery has reached overexploitation levels. There has been growing interest in determining the optimal level of harvest.

The major goal for natural resource managers is to attain sustainable utilization in order to ensure perpetuity of resources. Furthermore, the general purpose in managing fisheries is ensuring resource exploitation in an optimal fashion (Pyo, 2006). Resource managers for Lake Kariba aim at increasing production in the fisheries sector in order to strengthen the rural economy, create employment and enhance household food security. It is therefore crucial that there be a measure of sustainability in the fisheries sector in order to achieve this target.

Maximum sustainable yield (MSY) is the best known proxy for sustainability and is defined as the greatest level of catch that can be achieved whilst maintaining resource sustainability. MSY and maximum economic yield

(MEY) represent the main reference points for fisheries sustainability and benchmarks for fisheries management (Pyo, 2006).

In the absence of specific information on age and growth of a fishery, the most commonly applied alternatives to fisheries stock assessment techniques are commonly referred to as Surplus Production Models (SP models) (e.g. Schaefer, 1954; Schnute, 1977; Walters and Hilborn, 1976, Fox, 1970, Clarke, Yoshimoto and Pooley, 1992, Pella and Tomlinson, 1969). One advantage of surplus production bioeconomic models is the use of limited information to provide guidance (Clarke et al, 1992). These models assume that the catch in a particular year is a linear function of effort (Pyo, 2006). These SP models can be represented by the equilibrium state where the level of catch is equal to the level of surplus growth. However, with this assumption, the models cannot estimate biomass annually. The key role of fisheries bioeconomic analysis is to provide managers with an indication of the potential benefits that can accrue from a fishery or analyze the effects of different fisheries management policies (Pascoe, 1998).

The maximum entropy (ME) model developed by Golan et al. (1996a, 1996b) can be used to overcome several limits on the SP model. These can be applied to estimate yearly fisheries stock, MSY, and the maximum sustainable biomass using non-linear programming (Pyo, 2006).

The Acceptable Biological Catch (ABC) is another measure that can be estimated and used as a reference point for fisheries managers. Using analytical models such as the Zhang and Megrey (2010), ABC can be estimated using a series of steps involving growth parameters of the fish species. Estimates from such models are deemed more accurate than others that do not base their estimates on growth parameters.

The objective of this study is to evaluate and compare an Analytical Model, a Surplus Production Model and a Maximum Entropy Model (ME), using time series data for catch and effort of Kapenta from Lake Kariba as well as growth parameters for the Analytical Model. Kapenta is a major species occupying almost 80% of the total fisheries landings in Lake Kariba and plays a major food security role in the Zimbabwe's economy. It is also crucial to know the appropriate biological model to use for bioeconomic purposes of the Kapenta fishery. Ultimately, the study seeks to come out with the most accurate biological reference points that aid in decision making towards the sustainability of the fishery.

## Background

Lake Kariba (277 km long; 5,364 km$^2$; 160 km$^3$; 29 m mean depth and 120m max. depth, 40km at its widest point) is located on the Zambezi River between latitudes 16E28'to 18E04'S and longitudes 26E42'to 29E03'E. It was the largest man-made reservoir in the world at the time of construction. It is now the second largest reservoir in Africa by volume (181km$^3$). The catchment area covers 663,817 km$^2$ extending over parts of Angola, Zambia, Namibia, Botswana and Zimbabwe. The dam wall (128 x 580 m) was completed in 1960 and the filling phase lasted from December 1958 to September 1963 when the water reached the mean operation level at 485m above mean sea level. About

45% of the water surface lies on the Zambian side and the rest lies on the Zimbabwean side of the lake. The impact of the artisanal inshore fishery on the two sides of the lake can be considered not to affect each other because of the deep channel in between the two shores along most of the lake (http://www.fao.org/docrep/006/y5056e/y5056e0i.htm).

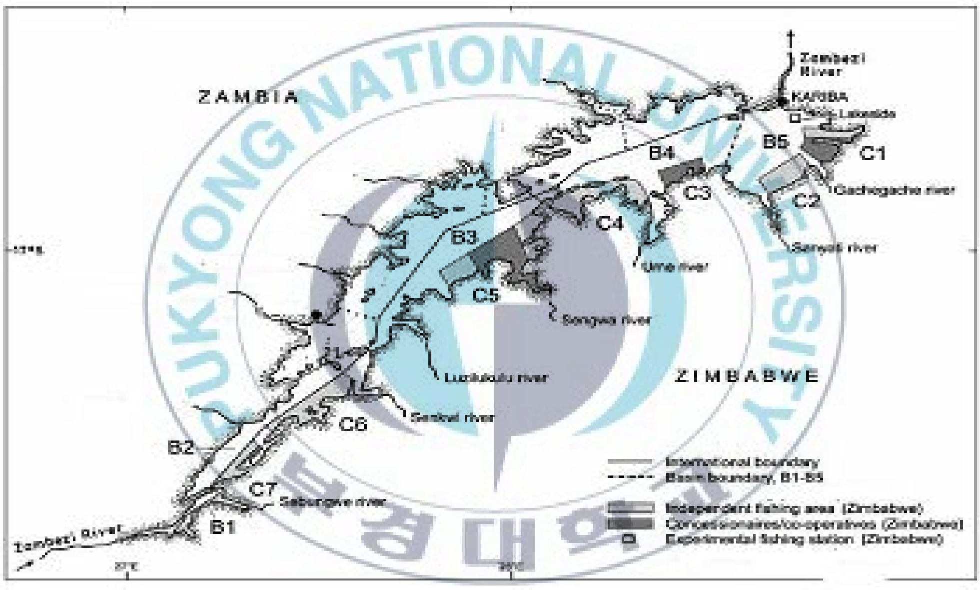


**Figure 1:** Map of Lake Kariba showing fishing zones on the Zimbabwean and Zambian waters (Source: ttp://www.fao.org/docrep/006/y5056e/y5056e0i.htm)

## Fisheries of Lake Kariba

There are two main fisheries in Lake Kariba, the commercial Kapenta fishery and the artisanal (inshore fishery) which have been fairly well studied and have abundant information. The aquaculture sector has not yet fully established as only one major company operates in the lake.

## Artisanal (Inshore) Fishery

The main species exploited within the inshore fishery are some cichlids (*Oreochromis niloticus, Sargochromis codringtonii, and Tilapia rendalli*), a cyprinid (*Labeo altivelis*), a characid (*Hydrocynus vitattus*), two mormyrids (*Mormyrus longirostris, Mormrops anguilloides*) and a clarid (*Clarias gariepinus*). Nile tilapia (*Oreochromis niloticus*), an exotic species has become the dominant species in most water bodies and now dominates fish landings. Artisanal inshore gillnetting began in 1962 on the Zimbabwean side of the lake and catches rose to a peak of about 2,500tonnes in 1964. From then catches have declined almost linearly to around 1,000tonnes in 1970 (Karenge and Kolding, 1995). The estimated annual catch in the inshore fishery in 2001 was 3,400 tonnes. The inshore fishery contributed approximately 26% of the total catch from Lake Kariba (http://www.fao.org/fi/oldsite/FCP/en/ZWE/body.htm).

The most recent survey of the inshore fishery on the Zimbabwean side of the lake, found 1,272 fishers operating with 3,198 nets and 596 boats. There are approximately 40 fishing villages along the lake shore, and the number of fishing villages fluctuates slightly from year to year.

**Commercial Kapenta Fishery**

Kapenta fishing began in 1974 and since then effort grew rapidly. The number of rigs (fishing units) has increased since the inception of the fishery from 5 units in 1976 to about 605 in 2009. The mechanism of fishing involves the use of lift nets from pontoons at night with light attraction and fishing is carried out throughout the year. The fishery is capital intensive and occurs year-round. The management of the fishery is primarily through enforcement of regulations. Entry into the fishery is limited through licensing in order to control fishing effort. The acceptable minimum mesh size is 8 mm (diamond mesh) in order to reduce the likelihood of recruitment and growth overfishing. Fishing is limited to areas more than 20 m deep in order to protect the Kapenta juveniles (pre-recruits). Fishing is also prohibited within a 2-km radius of all river mouths to protect species on spawning runs up the river (http://www.fao.org/fi/oldsite/FCP/en/ZWE/body.htm)

The craft design and size are generally uniform throughout the lake on both countries with all operators using the same net mesh size of 8mm. The fishery has developed into a multi-million dollar industry with landings vastly outstripping the inshore fishery. Unlike the inshore fishery where stocks are separate for both Zimbabwe and Zambia, Kapenta stocks are shared between the two countries and the fishing grounds are shared in the pelagic zones of the lake. This implies that any changes in terms of fishing practice by one nation will affect the other equally.

The Kapenta fishery is a very important source of protein for Zimbabweans. It is also exported to neighbouring countries thus providing an important source of foreign currency. The importance of Kapenta as a cheap source of protein has become particularly critical in recent years due to the economic crisis in the country (Nyikahadzoi, 2010).

# Materials and Methods

## Production function estimation of SP models

Options for developing complex bioeconomic models are relatively limited with limited data thus one approach requiring minimal data is using surplus production models requiring only a time series of catch and effort data (Chae and Pascoe, 2005).

Two main types of surplus production models exist; those based on the logistic growth function and those based on the exponential growth function. Five models with distinctly different biological relationships are assessed for their applicability to the Kapenta fishery: the Schaefer (1957) model, the Fox (1970) model, the Schnute (1977) model which is a modification of the Schaefer model, the Walters and Hilborn (1976) model and a modification of the Fox model, the Clarke, Yoshimoto and Pooley (1992) model.

The models consist of two distinctly different production (i.e. yield and effort) relationships: The Schaefer, Schnute and the Walters and Hilborn models have a parabolic or logistic relationship and the Fox and CY&P models follow a Gompertz curve (Richards, 1959). Both are composed of the intrinsic growth rate of stock (r), biomass (X) and the environmental carrying capacity (K), which is the maximum stock level or virgin biomass as follows:

For logistic growth models: $$\mathbf{G = rX\left(1 - \frac{X}{K}\right);}$$

For exponential growth models $$\mathbf{G = rX\ln\left(\frac{K}{X}\right)}$$

From the basic catch and effort data, CPUE or its approximation and the associated level of effort are then computed. Two models of Schaefer and Fox use the finite difference approximation (Pyo, 2006, Clarke et al., 1992)

$$\mathbf{dU/dt} \approx \frac{\bar{U}_{t+1} - \bar{U}_{t-1}}{2},$$

where $\bar{U}_t$ is the average CPUE for the given year:

Schaefer:

$$\frac{\bar{U}_{t+1} - \bar{U}_{t-1}}{2\bar{U}_t} = \mathbf{r\text{-}}(\frac{r}{qK})\ \mathbf{(\bar{U}_t)\text{-}\ q(\bar{E}_t),}$$

Fox:

$$\frac{\bar{U}_{t+1} - \bar{U}_{t-1}}{2\bar{U}_t} = \mathbf{r\text{-}ln(qK)\text{-}\ rln(\bar{U}_t)\ \text{-}\ q(\bar{E}_t),}$$

where $\bar{E}_t$ is the total effort expended in year t. The parameters r, q and K are estimated by Pearson or ordinary Least Squares (OLS) regression analysis with a time series of catch and effort data (Pyo, 2006).

Schnute (1977) argues that the Fox and Schaefer models predict next year's CPUE without specifying next year's anticipated effort which contradicts most theories of fisheries biology. Furthermore, it has a problem of involving finite difference approximation which assumes that CPUE is linear over the course of the year (Clarke et al., 1992).

Schnute developed a modified version of the Schaefer model using an integration procedure:

Schnute:

$$\ln\left(\frac{\bar{U}_{t+1}}{\bar{U}_t}\right) = r - \left(\frac{r}{qK}\right)\left(\frac{\bar{U}_t + \bar{U}_{t+1}}{2}\right) - q\left(\frac{\bar{E}t + \bar{E}t+1}{2}\right)$$

CYP (1992) developed a model which follows Schnute's lead and applies a similar approach to the Fox model, using a Taylor approximation:

CY&P:

$$\ln(\bar{U}_{t+1}) = \left(\frac{2r}{2+r}\right)\ln(qK)) + \left(\frac{2-r}{2+r}\right)\ln(\bar{U}_t) - \left(\frac{q}{2+r}\right)(\bar{E}_t + \bar{E}_{t+1}).$$

Walters and Hilborn (1976) developed the difference equation method which is relatively simpler than the Schnute model:

Walters and Hilborn:

$$\left(\frac{\bar{U}_{t+1}}{\bar{U}_t}\right) - 1 = r - \left(\frac{r}{qK}\right)(\bar{U}_t) - q\,\bar{E}_t.$$

The above are only estimates therefore regression analysis also tells us how close or far they are to the actual figures. Different models were tested so as to come up with the “best” estimates for more accurate management decisions to be made.

## Maximum Entropy Model

### Formulation of the ME model

Difficult dynamic problems are faced under the conventional estimation rules which are that; an ill-posed problem that the number of parameters to be estimated exceeds the number of observations and an underdetermined or under-identified problem which cannot be alleviated by obtaining more data.

Given probabilities $pi$ such that $\Sigma pi$ for random variables, $x_i$ Shannon (1948) defined the entropy as a measure of uncertainty in the probability that maximizes

$$\mathbf{H(p)} = \sum p_i \ln p_i = -p \ln p \quad \mathbf{(1)}$$

Subject to data consistency (available evidence points) in the form of J moment conditions

$$\sum p_i x_{ij} = a_{ij}, j = 1,2,\ldots..,J \quad \mathbf{(2)}$$

And normalization-additivity (adding up) constraint

$$\sum p_i = 1, \quad \mathbf{(3)}$$

Where J<N. The ME model seeks to make the best predictions possible from the limited data information that is available, transforming the empirical moments into the probability distribution representing our state of knowledge (Golan et al., 1996b).

**ME model for stock assessment of Kapenta**

For a ME model of fish stock assessment, fisheries production function can be formularized using a Cobb-Douglas production and logistic growth function as follows:

$$C_t = A E_t^{\alpha} X_t^{\beta} \exp(\varepsilon_t) \qquad (4)$$

$$X_{t+1} = [X_t + rX_t(1 - \frac{X_t}{K}) - C_t]\exp(\mu_t) \qquad (5)$$

Where $\alpha$ and $\beta$ are parameters representing the effort and stock elasticity respectively, and $\varepsilon_t$ and $\mu_t$ are error terms for C and X at time t, respectively. The above functions can be converted to log form as follows:

$$\ln C_t = \ln A + \alpha \ln E + \beta \ln Xt + \varepsilon_t \qquad (4')$$

$$\ln X_{t+1} = \ln X_t + \ln S_t + \mu_t \qquad (5')$$

where $$S_t = 1 + r(1 - \frac{X_t}{K}) - \frac{C_t}{Xt}$$

In this formulation the observable variables are $C_t$ and E and the parameters to be internally derived from the formulation are the probability distributions of A, $\alpha$, $\beta$, r, $X_t$, K, $\varepsilon_t$ and $\mu_t$. Therefore the formulations are involved in an ill-posed problem as they have much more parameters estimated than observed variables. Furthermore, there is a method to impose prior restrictions on the parameter estimates by spanning the possible parameter range for each parameter. For example, if A, $\alpha$ and $\beta$ are believed that they range between 0 and 1, they will be specified by a tri-uniform distribution such as [0, 0.5, 1].

$$\mathbf{A} = p_1^A \times 0 + p_2^A \times 0.5 + p_3^A \times 1 \quad \textbf{(6)}$$

$$\alpha = p_1^\alpha \times 0 + p_2^\alpha \times 0.5 + p_3^\alpha \times 1 \quad \textbf{(7)}$$

$$\beta = p_1^\beta \times 0 + p_2^\beta \times 0.5 + p_3^\beta \times 1 \quad \textbf{(8)}$$

In such context, limited prior information for r and K can be imposed by using the estimates from SP model as follows:

$$r = p_1^r \text{ x } 0 + p_2^r \text{ x } \frac{m}{2} + p_3^r \text{ x } m \tag{9}$$

$$K = p_1^K \text{ x } 0 + p_2^K \text{ x } \frac{n}{2} + p_3^K \text{ x } n \tag{10}$$

$$X_t = p_{t1}^X \text{ x } 0 + p_{t2}^X \text{ x } h/2 + p_{t3}^X \text{ x } h \tag{11}$$

$$\varepsilon_t = p_{t1}^{\varepsilon} \text{ x } (-e) + p_{t2}^{\varepsilon} \text{ x } 0 + p_{t3}^{\varepsilon} \text{ x } (+e) \tag{12}$$

$$\mu_t = p_{t1}^{\mu} \text{ x } (-e) + p_{t2}^{\mu} \text{ x } 0 + p_{t3}^{\mu} \text{ x } (+e) \tag{13}$$

where m, n and h stand for upper bounds of r, K and $X_t$ respectively, and e is specified to be symmetric around zero for $\varepsilon_t$ and $\mu_t$.

In conclusion, the generalized stochastic non-linear ME for stock assessment of Kapenta in Lake Kariba can be structured in scalar-summation notation, using a criterion with non-negative probability factors, as

$$\text{Max}[-\sum_g \sum_j p_j^g \ln p_j^g - \sum_l \sum_t \sum_j p_{tj}^l \ln p_{tj}^l] \tag{14}$$

Subject to the data consistency with (4'), (5'), (6), (7), (8), (9), (10), (11), (12), (13) in which m, n, h and e are replaced by 2, 185000[1] and 92500 [1]and 0.3, respectively, and the adding up constraints:

$$\sum_j^3 p_j^g = 1, \sum_j^3 p_{tj}^X = 1, \sum_j^3 p_{tj}^{\varepsilon} = 1, \sum_j^3 p_{tj}^{\mu} = 1 \qquad \textbf{(15)}$$

where

g = A, $\alpha$, $\beta$, r, K and l = X, ε and μ, and t = 1, 2, 3 ….n-1.

This formulation is a general non-linear inversion procedure for recovering both time variant parameters. These estimates may also be used for defining measures of uncertainty and precision for fish stock assessment (Golan et al., 1996a).

[1] The values were obtained by selecting the value of K and $\frac{K}{2}$ that provided the least Mean square error value between observed and estimated catch in simulations in the ME model. These values would then be used as the reserve input in the model

## Analytical Model

### Biological Parameters

#### *Length weight parameters*

Parameters for length and weight were obtained from Fishbase together with data for 1982 length-weight frequencies. This data enabled the conversion of length to weight data using the equation: $W = \alpha L^{\beta}$. The parameters $\alpha$ and $\beta$ for *Limnothrissa miodon* were found to be 0.01 and 2.86 respectively. The value of $\beta$ showed that the species has an isometric growth according to Tresierra and Culquichicón (1993).

### Growth Parameters

Several studies on the growth of *Limnothrissa miodon* were carried out during the 1982-1992 period by Cochrane (1984), Marshall (1987) and Chifamba (1992). Cochrane's (1984) von Bertalanffy growth parameters were selected and used in the analysis as they fitted well with length-frequency data for the 1982 analysis. The parameters referred to are: the asymptotic length ($L_\infty$) = 8.1cm, the estimated growth coefficient (K) = 1.74 and $t_0$ = -0.13. $L_\infty$ is the asymptotic length; $K$ is the growth coefficient and $t_0$ age of fish when the size is zero. The parameters are substituted into the von Bertalanffy equation, which is expressed as follows:

$$L_t = L_\infty\left(1 - e^{-k(t-t_0)}\right)$$

**Mortality**

***Natural Mortality***

Natural mortality was calculated using the equation by Zhang and Megrey (2006) which is expressed as a function of the growth coefficient ($K$), the power parameter of the weight and length relationship ($\beta$), the age of fish when the size is zero ($t_0$), and the critical age ($t_{mb}$).

$$\boldsymbol{M} = \frac{\beta K}{e^{K(t_{mb}-t_0)} - 1}$$

Where $t_{mb} = C_i \cdot t_{max}$. Here $t_{max}$ is the maximum age observed in the population (Beverton and Holt, 1959; Zhang and Megrey, 2006), and $C_i$ is the constant for specific ecological groups, demersal species (0.440), pelagic species (0.302) and overall mean (0.393). The species under investigation is a pelagic species therefore the value of 0.302 was considered in estimating natural mortality.

***Fishing Mortality***

The method used to calculate fishing mortality was through the equation proposed by Zhang and Megrey (2010). This method is expressed as a function of the biomass by length ($B_{l_i}$) to biomass ($B_{l_{i+\Delta t}}$), the natural mortality ($M$), the time needed to grow from length-class $l_i$ to length class $l_{i+\Delta t}$ , and weight by length ($G_{l_i}$):

$$F_{l_i} = \frac{log_e\left(\frac{B_{l_i}}{B_{l_{i+\Delta t}}}\right) - M \times \Delta t_{l_i} + G_{l_i}}{\Delta t_{l_i}}$$

and the weighted fishing morality was estimated using the equation;

$$Weighted\ F_{l_i} = \frac{\sum B_{l_i} F_{l_i}}{\sum B_{l_i}}$$

***Total Mortality***

The total mortality (Z) was estimated by calculating the sum of natural mortality ($M$) and fishing mortality ($F$).

$$Z = M + F$$

**Biomass**

The total catch for 1982 of 12,586 tonnes was used in the estimation of the total biomass for the species. A biomass based length cohort analysis model by Zhang and Megrey (2010) was used in the estimation of biomass in this analysis. Five essential pieces of information were required, to carry out this task, which were as follows:

- One year of length composition data for the catch;
- Weight of catch for each length-class ($l_i$);
- Estimate of Natural mortality ($M$)
- von Bertalanffy Growth parameters ($K$, $t_0$, and $L_\infty$);
- Allometric parameters relating length to weight ($\alpha$ and $\beta$)

Five steps were followed according to the Zhang and Megrey (2010) method to achieve the desired result:

Step 1: Calculation of weight from length for each length-class ($l_i$) using the allometric weight equation.

$$W_{l_i} = \alpha \times {l_i}^{\beta}$$

Step 2: Calculation of $G_{l_i}$ to convert length to weight to calculate $G$ per length class using the follow equation.

$$G_{l_i} = log_e\left(\frac{W_{l_i+\Delta l}}{W_{l_i}}\right)$$

Where, $l_i$ is length-class, $l_i + \Delta l_i$ represent the time needed to grow from length class $l_i$ to length class $l_i + \Delta l_i$.

Step 3: $\Delta t$ - the time needed to grow from length class $l_i$ to length class $l_i + \Delta l_i$, calculated for each length-class ($l_i$):

$$\Delta t_{l_i} = \frac{1}{K} log_e\left(\frac{L_\infty - l_i}{L_\infty - l_{i+\Delta l}}\right)$$

Step 4: Population biomass in the longest length-class ($l_i$) is estimated based on the biomass-based catch equation and the estimate of $F_T$.

$$B_{l_i} = C_{l_i} \times \frac{(M + F_T) \times \Delta t_{l_i} - G_{l_i}}{F_T \times \Delta t_{l_i}}$$

Where, $F_T$ is assumed to be equal to 0.5M for a lightly exploited stock, M for a moderately exploited stock, or 2M for a heavily exploited stock. *Limnothrissa miodon* is considered a heavily exploited stock. $C_{l_i}$ denotes the total catch by weight by length-class ($l_i$). In this study, total catch in 1982 was 12,586 tonnes.

Step 5: Involves the progression from the longest length-class to the smallest length-class ($l_i$) to calculate $B_{l_i}$ using the follow equation:

$$B_{l_i} = B_{l_i+\Delta l}\, exp\left[\frac{M}{K} log_e\left(\frac{L_\infty - l_i}{L_\infty - l_{i+\Delta l}}\right) - G_{l_i}\right] + C_{l_i}\, exp\left[\frac{M}{2K} log_e\left(\frac{L_\infty - l_i}{L_\infty - l_{i+\Delta l}}\right) - \frac{G_{l_i}}{2}\right]$$

**Acceptable Biological Catch (ABC)**

Due to lack of specific reference points to ensure that a fish species is not exploited to unsustainable levels many fisheries around the world are in danger of collapse. Concerted efforts have been made by resource managers to set these biological reference points (BRP's) using available information on the fishery. The BPRs are usually fishing mortalities (F) or abundance levels (thresholds).

One of major limitations of BRPs based on yield per recruit such as $F_{max}$ is that the effects on the spawning population are essentially ignored. As a worst case scenario, suppose that infinite fishing pressure were applied at critical age *t* but that fish matured at ages older than *t*. The maximum yield per recruit would be taken, but at the expense of rendering the population extinct. The class of BRPs coming out of this approach is denoted $F_{x\%}$, where it is generally in the range of 20%-40%. Reference fishing mortality ($F_{x\%}$) result in a spawning stock biomass or egg production per recruit that is x% of that with no fishing (Quinn and Deriso, 1999).

Quinn and Szarzi (1993), cited by Quinn and Deriso (1999) suggested that fishing mortalities between $F_{30\%}$ and $F_{45\%}$ in terms of spawning abundance instead of spawning biomass would result in sustainable harvests. The information used to estimate the $F_{x\%}$ was: length class, weight at length relationship, maturity rate, selectivity at length and mortality at length (Zhang and Megrey, 2010).

$$F_{x\%} = \frac{\sum_{i=i}^{i_\lambda} B_i' \cdot m_i \cdot e^{G_i - (M + F_{40\%} \cdot S_i)\left(\frac{1}{K} ln\left(\frac{(L_\infty - l_i)}{(L_\infty - l_{i+1})}\right)\right)}}{\sum_{i=i}^{i_\lambda} B_i \cdot m_i \cdot e^{G_i - M\left(\frac{1}{K} ln\left(\frac{(L_\infty - l_i)}{(L_\infty - l_{i+1})}\right)\right)}}$$

Where, $m_i$ is the maturity rate by length $i$, $M$ is natural mortality, $S_i$ is selectivity at length $i$, $B_i^{'}$ number of population at length $i$, $K$ is growth coefficient of von Bertalanffy parameter, $L_\infty$ is asymptotic length, $G_i$ is growth coefficient by weight at length $i$ and $l_i$ length class.

If F=0, $B_i = B_{i-1} \cdot e^{G_{i-1} - M \cdot \Delta_{i-1}} = B_{i-1} \cdot e^{G_{i-1} - M\left(\frac{1}{K} ln\left(\frac{(L_\infty - l_i)}{(L_\infty - l_{i+1})}\right)\right)}$

If F =x%, $B_i^{'} = B_{i-1}^{'} \cdot e^{G_i - (M + F_{40\%} \cdot S_{i-1})\left(\frac{1}{K} ln\left(\frac{(L_\infty - l_i)}{(L_\infty - l_{i+1})}\right)\right)}$

In this study to estimate ABC, x% stands for 40%

$$G_i = ln\left(\frac{W_{i+1}}{W_i}\right)$$

$F_{40\%}$ of the level of biomass ($B_{40\%}$) was estimated by the equation:

$$B_{40\%} = B_c \times \frac{\frac{SB}{R}|_{F_{40\%}}}{\frac{SB}{R}|_{F_c}}$$

Where, $B_c$ is the current biomass, $\frac{SB}{R}|_{F_{40\%}}$ is the spawning biomass per recruit with $F_{40\%}$, and $\frac{SB}{R}|_{F_c}$ is the spawning biomass per recruit with current $F$.

Subsequently this information was analyzed with Acceptable Biological Catch (ABC), which provides an acceptable level of capture of a species or species group.

**Table 1: Methods used to determine ABC (MOMAF, 2000)**

| |
|---|
| **Tier 1** Information available: Reliable estimates of annual B and F, $B_{MSY}$, $F_{MSY}$, $F_{X\%}$, M and environmental factor. |
| 1a) Stock status: $B/B_{MSY} > 1$<br>$F_{ABC} = F_{MSY}$<br>1b) Stock status: $\alpha < B/B_{MSY} \leq 1$<br>$F_{ABC} = F_{MSY} \text{ x } (B/B_{MSY} - \alpha)/(1-\alpha)$<br>1c) Stock status: $B/B_{MSY} \leq \alpha$: $F_{ABC}=0$ |
| **Tier 2** Information available: Reliable estimates B, $B_{X\%}$ and $F_{X\%}$.<br>2a) Stock status: $B/B_{40\%} > 1$<br>$F_{ABC} = F_{40\%}$<br>2b) Stock status: $\alpha < B/B_{40\%} \leq 1$<br>$F_{ABC} = F_{40\%} \text{ x } (B/B_{40\%} - \alpha)/(1-\alpha)$<br>2c) Stock status: $B/B_{40\%} \leq \alpha$: $F_{ABC}=0$ |
| **Tier 3** Information available: Reliable estimates B and $F_{0.1}$<br>$F_{ABC} = F_{0.1}$ |
| **Tier 4** Information available: Time-series catch and effort data.<br>4a) Stock status: $CPUE/CPUE_{MSY} > 1$<br>ABC=MSY<br>4b) Stock status: $\alpha < CPUE/CPUE_{MSY} \leq 1$<br>$ABC = MSY \text{ x } (CPUE/CPUE_{MSY} - \alpha)/(1 - \alpha)$<br>4c) Stock status: $CPUE/CPUE_{MSY} \leq \alpha$: ABC =0 |
| **Tier 5** Information available: Reliable catch history.<br>$ABC = M \text{ x } Y_{AM}$ (arithmetic mean catch over an appropriate time period), $0.5 \leq P \leq 1.0$ |
| i) Equation used to determine ABC in tiers 1-3:<br>$ABC = \frac{BF_{ABC}}{M+F_{ABC}}\left(1 - e^{-(M+F_{ABC})}\right)$<br>Where $B_i$: *Biomass at age i M: instantaneous coefficient of actual mortality,* $F_{ABC}$: *instantaneous coefficient of fishing mortality for ABC determined by the data available and the stock status, r: recruit age,* $t_L$: *maximum fishing age.*<br><br>ii) For tiers 1, 2 and 4, α is set at a default value of 0.05. |

Basing on the information available, Tier 2b) was used in the analysis.

Spawning stock biomass-per-recruit(SBPR) analysis was conducted. Reference points of F and SBPR for a percentage of maximum spawning potential are calculated. When F= 0, the spawning biomass per recruit (SB/R) is,

$$\frac{\mathrm{SB}}{\mathrm{R}} = \sum_{t=t_r}^{t_\lambda} m_t \cdot e^{-M(t_c - t_r)} \cdot e^{-(M+F)(t-t_c)} \cdot W_\infty\left(1 - e^{-K(t-t_0)}\right)$$

Where $m_t$ is the maturity rate by time, $K$ is growth coefficient, $t_0$ is the age of fish when the size is zero, $t_c$ is age of first capture, $t_r$ is the recruitment age, $W_\infty$ is the asymptotic weight, $F$ is the fishing mortality, $M$ is the natural mortality.

**Catch and effort data**

Data for catch and effort from the inception of the fishery in 1974 to 2009 were acquired from both Zimbabwe and Zambia from Lake Kariba Fisheries Research Institute and the Ministry of Fisheries respectively. FAO data from FishStatJ was used to corroborate the data from both countries and in most cases they were tallying.

The mechanism of fishing in the industry is the same for both countries in both craft and fishing gear (type and mesh size) therefore no standardization of effort was carried out.

The time series for catch and CPUE shows a pattern where initially, catch rates were high and effort levels were low. Catch however falls as effort levels rise and the stock is depleted. Pascoe (1998) states that effort and CPUE are highly correlated. The figure below shows the CPUE and effort trends in the fishery.

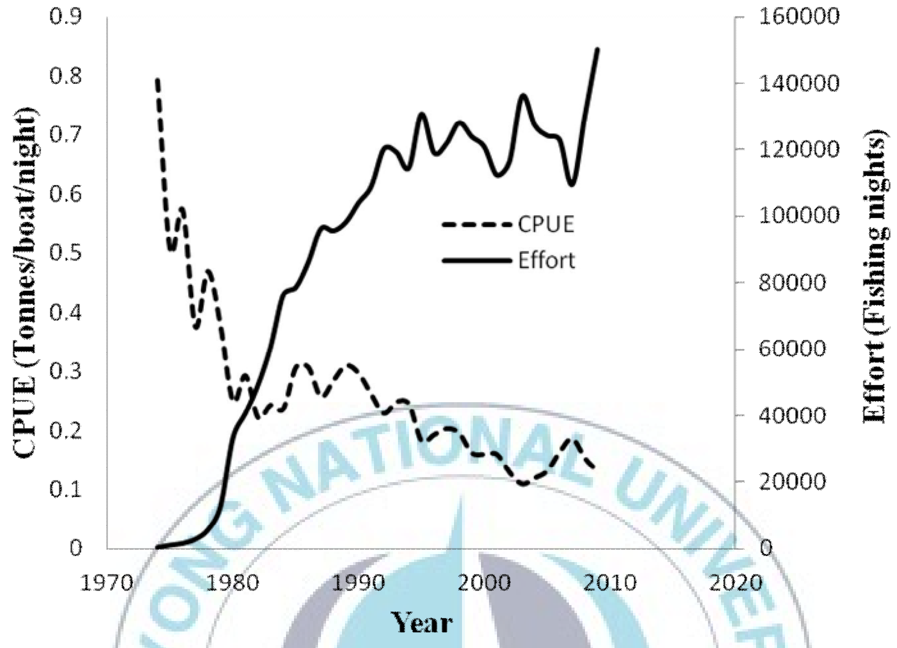


**Figure 2: Kapenta CPUE and Effort trends in Lake Kariba**

The table below shows the Kapenta statistics from the inception of the fishery in 1974 to the most recently available data.

**Table 2: Lake Kariba Kapenta statistics 1974-2009**

| | Zimbabwe | | Zambia | | Combined | | |
|---|---|---|---|---|---|---|---|
| | Catch (tonnes) | Effort (nights fished) | Catch (tonnes) | Effort (nights fished) | Catch (tonnes) | Effort (nights fished) | CPUE |
| 1974 | 487 | 615 | | | 487 | 615 | 0.79 |
| 1975 | 654 | 1,294 | | | 654 | 1,294 | 0.51 |
| 1976 | 1,050 | 1,833 | | | 1,050 | 1,833 | 0.57 |
| 1977 | 1,171 | 3,111 | | | 1,171 | 3,111 | 0.38 |
| 1978 | 2,772 | 5,903 | | | 2,772 | 5,903 | 0.47 |
| 1979 | 4,874 | 12,847 | | | 4,874 | 12,847 | 0.38 |
| 1980 | 8,395 | 33,516 | | | 8,395 | 33,516 | 0.25 |
| 1981 | 12,006 | 40,935 | | | 12,006 | 40,935 | 0.29 |
| 1982 | 8,450 | 37,776 | 2,601 | 11,686 | 10,989 | 49,462 | 0.22 |
| 1983 | 8,548 | 38,865 | 6,227 | 22,083 | 14,830 | 60,948 | 0.24 |
| 1984 | 10,394 | 41,234 | 7,702 | 35,236 | 18,106 | 76,470 | 0.24 |
| 1985 | 14,586 | 41,403 | 9,360 | 37,378 | 24,179 | 78,781 | 0.31 |
| 1986 | 15,747 | 45,790 | 10,449 | 40,520 | 26,543 | 86,310 | 0.31 |
| 1987 | 15,823 | 52,414 | 8,994 | 43,933 | 24,818 | 96,347 | 0.26 |
| 1988 | 18,366 | 53,403 | 8,907 | 42,296 | 27,272 | 95,699 | 0.28 |
| 1989 | 20,112 | 54,919 | 10,409 | 43,440 | 30,521 | 98,359 | 0.31 |
| 1990 | 21,758 | 59,193 | 9,185 | 44,938 | 30,942 | 104,131 | 0.30 |
| 1991 | 19,306 | 62,208 | 9,258 | 46,819 | 28,564 | 109,027 | 0.26 |
| 1992 | 18,931 | 71,066 | 8,658 | 49,259 | 27,599 | 120,325 | 0.23 |
| 1993 | 19,957 | 68,155 | 9,722 | 51,231 | 29,680 | 119,386 | 0.25 |
| 1994 | 19,232 | 71,249 | 8,910 | 43,462 | 28,142 | 114,711 | 0.25 |
| 1995 | 15,280 | 75,443 | 8,674 | 55,381 | 23,954 | 130,824 | 0.18 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1996 | 15,423 | 73,524 | 7,593 | 45,693 | 23,016 | 119,217 | 0.19 |
| 1997 | 17,034 | 75,633 | 7,813 | 46,436 | 24,847 | 122,069 | 0.20 |
| 1998 | 15,288 | 74,770 | 9,822 | 53,475 | 25,110 | 128,245 | 0.19 |
| 1999 | 11,208 | 64,091 | 8,955 | 59,960 | 20,163 | 124,051 | 0.16 |
| 2000 | 10,500 | 65,625 | 8,863 | 55,394 | 19,363 | 121,019 | 0.16 |
| 2001 | 9,500 | 59,375 | 8,500 | 53,125 | 18,000 | 112,500 | 0.16 |
| 2002 | 7,150 | 55,000 | 8,000 | 61,538 | 15,150 | 116,538 | 0.13 |
| 2003 | 7,500 | 68,182 | 7,481 | 68,009 | 14,981 | 136,191 | 0.11 |
| 2004 | 8,735 | 72,792 | 6,574 | 54,784 | 15,309 | 127,576 | 0.12 |
| 2005 | 10,158 | 78,138 | 6,251 | 46,256 | 16,409 | 124,394 | 0.13 |
| 2006 | 12,503.04 | 78,144 | 7,659 | 44,926 | 20,162 | 123,070 | 0.16 |
| 2007 | 10,940.16 | 78,144 | 9,476 | 31,421 | 20,416 | 109,565 | 0.19 |
| 2008 | 12,157.2 | 81,048 | 7,860 | 49,258 | 20,017 | 130,306 | 0.15 |
| 2009 | 9,727.974 | 87,384 | 9,993 | 62,948 | 19,721 | 150,332 | 0.13 |

**Determining accuracy of a model**

Forecasts are usually produced for the whole out of sample period, which would then be compared to the actual values, and the difference between them aggregated in some way. The forecast error for observation, *i* is defined as the difference between the actual value for the observation *i* and the forecast made for it.

**Mean Square Error**

Denoting *s* steps ahead forecasts of a variable made at a time *t* as $f_{t.s}$ and the actual value of the variable at time *t* as $y_t$, then the mean square error can be defined as:

$$\textbf{MSE} = \frac{1}{T-(T_1-1)} \sum_{t=T_1}^{T} (y_{t+s} - f_{t.s})^2$$

where $T$ is the total sample size (in sample + out of sample), and $T_1$ is the first out of sample forecast observation. Thus in sample model estimation initially runs from observation 1 to ($T_1$ – 1), and the observations $T_1$ to T are available for the out of sample estimation, i.e. a total holdout sample of T - ($T_1$ – 1).

The MSE value would be compared with those of other models for the same data and forecast period and the model with the lowest value of the error measure would be argued to be most accurate (Brooks, 2002).

**Theil *U*-Statistic**

A popular criterion used is the Theil *U*-statistic (1966) which whose metric is designed as follows:

$$U = \sqrt{\frac{\sum_{t=1}^{n-1}\left(\frac{\hat{y}_{t+1} - y_{t+1}}{y_t}\right)^2}{\sum_{t=1}^{n-1}\left(\frac{y_{t+1} - y_t}{y_t}\right)^2}}$$

Theil's *U* statistic is a measure of the degree to which one time series ($X_i$) differs from another ($Y_i$) (http://www.uvm.edu/giee/AV/Spatial_Modeling_Book/4/node33.html).

A *U*-statistic of one implies that the model under consideration and the benchmark model are equally (in)accurate, while the value of less than one implies that the model is superior to the benchmark and vice versa of $U > 1$ (Brooks, 2002).

# Results

## Surplus Production Models

To calculate MSY for the Kapenta fishery the five SP models were estimated using the ordinary least square (OLS) as shown in the table below. The CYP model was the only model among the five models that fitted the data well as the other models had very low adjusted $R^2$ (goodness of fit). The CYP model accounted for 82.7% of variation dependent variables whilst the other four models were all below 2%.

**Table 3: Estimated parameters and statistic in SP Models**

| Models | Independent variables | Parameters | Adj $R^2$ | t-statistic | D-W statistic[2] | Multicollinearity[3] |
|---|---|---|---|---|---|---|
| **Schaefer** | Constant | -1.36 | 0.052 | -0.906 | 1.296 | Tolerance 0.284 |
| | CPUE | 0.032 | | 0.099 | | VIF |
| | Nights fished (E) | 9.12E-07 | | 1.124 | | 3.517 |
| **Fox** | Constant | -0.107 | 0.053 | -1.378 | 1.292 | Tolerance 0.331 |
| | Ln(U) | 0.018 | | 0.223 | | VIF |
| | Nights fished (E) | 9.82E-07 | | 1.305 | | 3.026 |
| **Schnute** | Constant | 0.092 | 0.017 | 0.583 | 2.488 | Tolerance 0.256 |
| | (U + U1)/2 | -0.486 | | -1.165 | | VIF |
| | (E + E1)/2 | -2.04E-07 | | -0.359 | | 3.9 |
| **Walters and Hilborn** | Constant | 0.343 | 0.174 | 1.989 | 2.138 | Tolerance 0.327 |
| | CPUE | -0.914 | | -2.731 | | VIF |
| | Nights fished (E) | -1.53E-06 | | -1.494 | | 3.056 |
| **CYP** | Constant | -0.347 | 0.827 | -3.342 | 2.153 | Tolerance 0.299 |
| | Ln(U) | 0.688 | | 5.792 | | VIF |
| | E + E1 | -8.40E-07 | | -1.419 | | 3.346 |

[2] **Durbin–Watson statistic** is a test statistic used to detect the presence of autocorrelation. d = 2 indicates no autocorrelation. The value of d always lies between 0 and 4. If the Durbin–Watson statistic is substantially less than 2, there is evidence of positive serial correlation. As a rough rule of thumb, if Durbin–Watson is less than 1.0, there may be cause for alarm (http://en.wikipedia.org/wiki/Durbin-Watson_statistic)

The table below shows the complete estimates of all five models derived from the regression analysis:

**Table 4:** Parameter estimates of assessed SP models.

| | Schaefer | Schnute | W&H | Fox | CYP |
|---|---|---|---|---|---|
| r | -1.36 | 0.092 | 0.343 | 0.018 | 0.36995 |
| q | 9.12E-07 | 2.04E-07 | 1.53E-06 | 9.82E-07 | 1.99E-06 |
| K | 41224772 | 927691.7 | 245116.9 | 2544.157 | 165287.6 |

From the results above it is evident that the Schaefer model does not fit the fishery well since some parameters have negative signs. It will therefore be omitted from further analysis.

In the table above, Schnute shows a very low r value whilst the Walters and Hilborn and CYP model have a higher and relatively similar values of r. Furthermore, the estimated q is similar in the two models. Schnute estimates a relatively high carrying capacity, K, followed by the Walters and Hilborn

[3] **Multicollinearity** is a statistical phenomenon in which two or more predictor variables in a multiple regression model are highly correlated. A tolerance of less than 0.20 or 0.10 and/or VIF of 5 or 10 and above indicates a multicollinearity problem (http://en.wikipedia.org/wiki/Multicollinearity)

model. The exponential models estimate lower carrying capacities than the logistic models.

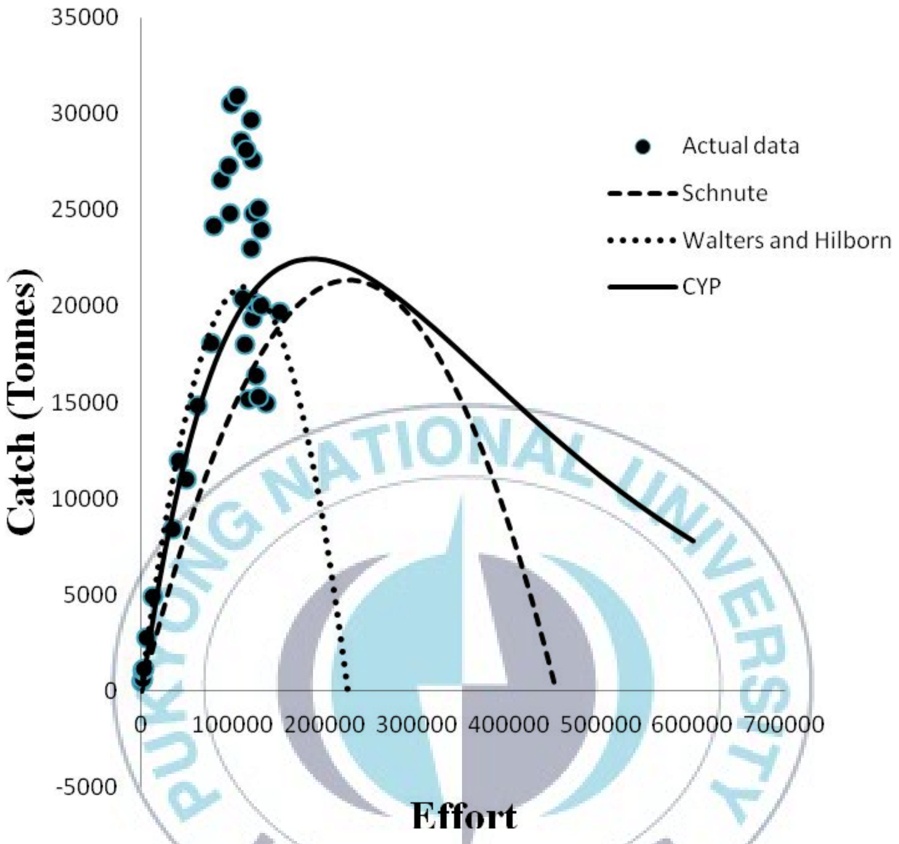


**Figure 3: Yield-effort relationships for the Schnute, Walters and Hilborn and CYP models**

The figure above shows the yield effort relationship for 3 models except the Schaefer model whose ranges were too large, and the Fox model whose ranges were too small, to enable comparison thus were omitted. The actual catch data shows a closer relationship to the Walters and Hilborn model than it does to the CYP model.

A further test of the models was undertaken by comparing the estimated catch given the levels of observed effort and the actual catches. Catch estimates were calculated using the equations: $C = qkE(1 - q\frac{E}{r})$ for logistic models and $C = qkE\exp(-(\frac{q}{r})E$ for exponential models (Pascoe, 1998). Actual effort data was substituted into both equations to come up with the estimated catch.

The two figures below show the actual and estimated catches for both logistic and exponential models respectively.

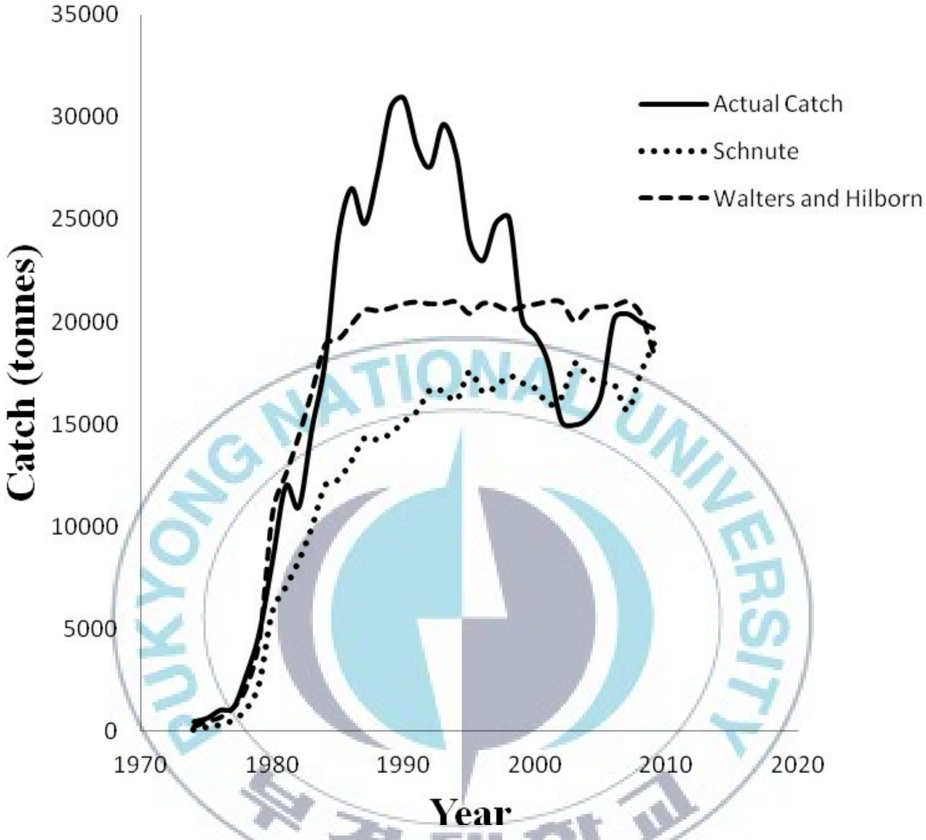


**Figure 4: Actual and estimated catch of Kapenta 1974-2009 (Logistic models)**

Catch estimated using the Walters and Hilborn model was generally closer to the actual catches in both the early years and the later years compared to the Schnute model estimates. In the figure below CYP was closer to the actual catches than the Fox model which was very different from the actual catches.

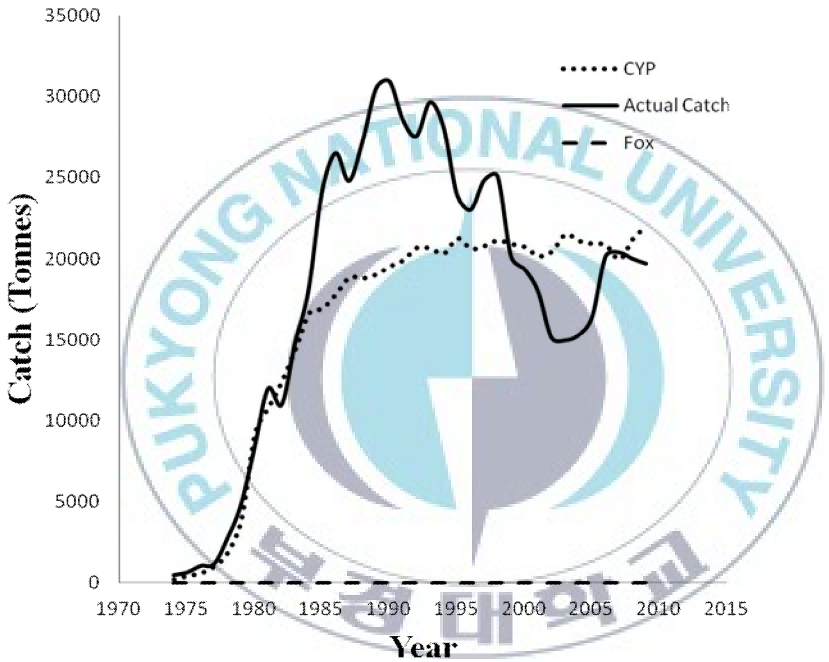


**Figure 5: Actual and estimated catch of Kapenta 1974-2009 (Exponential models)**

A measure of the ability of the models to estimate catch is the mean square error (MSE)(Pascoe, 1998). This is estimated as the average of the squared difference between the observed and estimated values (Gujarati, 1995). The model with the lowest value of the error measure would be argued to be the most accurate. MSE were estimated for each model for the observed and estimated catch.

The figure below shows the MSE values of the lowest 3 models (the Schaefer and Fox models were omitted because their values were too large thus would affect the scale).

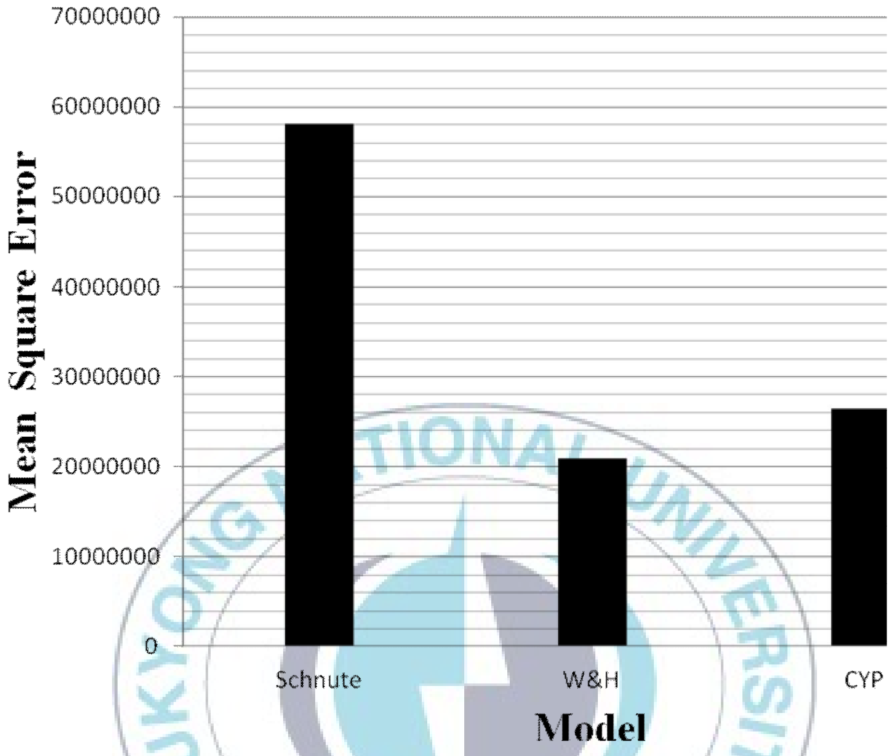


**Figure 6: Mean Square Error of traditional SP models**

On the basis of the MSE criterion, the Walters and Hilborn model could be considered to be the best of the alternative models examined despite having a lower goodness of fit than the CYP model. However, both models will be used as comparisons to other models in the study.

MSY was estimated for the CYP and Walters and Hilborn models and are shown in the table below:

**Table 5: MSY estimates by the CYP and Walters and Hilborn models**

| Model | E(msy) | C(msy) | B(msy) |
|---|---|---|---|
| **Walters and Hilborn** | 112,091.5 | 21,018.77 | 122,558.4 |
| **CYP** | 185,833.9 | 22,495.17 | 60,805.9 |

From the results above the CYP estimates a higher effort at MSY (Emsy) of which this level has not been surpassed since the inception of the fishery. It therefore suggests that the effort can still be increased.

The Walters and Hilborn model estimates an Emsy lower than that of the CYP and catch trends show that when the fishery surpassed the levels estimated by the Walters and Hilborn model catches began declining. The MSY of 21,018.77 tonnes estimated by the Walters and Hilborn model suggests that from 1985-1988 the fishery was overexploited. Furthermore, the estimated effort at MSY, Emsy, suggests that the fishery was over capacitated from 1992-2006 and from 2008-2009.

**Maximum Entropy Model**

The GAMS (General Algebraic Modeling System) Program was used to solve the numerical optimization problems using non-linear programming.

The table below shows the parameters that were estimated by the model for use in the analysis.

**Table 6: Estimated parameters in ME Model**

| A | $\alpha$ | $\beta$ | r | K |
|---|---|---|---|---|
| 0.165 | 0.636 | 0.39 | 0.422 | 240,500 |

The Intrinsic rate of growth (r) for the ME model is higher than that estimated by the Walters and Hilborn model. The carrying capacity estimated by the ME model is lower than that estimated by the Walters and Hilborn model.

Integrating the estimated parameters in the table above into estimated equations comes up with the following:

$$C_t = 0.165E_t^{0.636}X_t^{0.39} \tag{16}$$

$$X_{t+1} - X_t = 0.422(1 - \frac{Xt}{240,500}) - C_t \tag{17}$$

From the results of equation (16) the Kapenta fishery demonstrates increasing returns to effort and stock since the sum of the exponents, $\alpha$ and $\beta$, is 1.026. The effort elasticity of catch, $\alpha$, suggests that a 10 percent increase in effort will increase the Kapenta catch by 6.4 percent. The stock elasticity, $\beta$, is estimated to be 0.39 implying that doubling the stock size would result in a 39% increase in catch (holding all others constant). The technical efficiency (defined as the improvement of fishing gear to improve fishing yields (Sun, 1999)) is low with a value of 0.165. This means less effort could be employed to realize the same level of catch using more efficient (technical) methods.

**Table 7: Estimated annual stock of Kapenta in Lake Kariba by ME model**

| Year | Estimated Probabilities | | | Estimated stock |
|---|---|---|---|---|
| | $X_t = 0$ | $X_t = 92{,}500$ | $X_t = 185{,}000$ | |
| 1974 | 0.836 | 0.164 | 0 | 15,170 |
| 1975 | 0.805 | 0.195 | 0 | 18,037.5 |
| 1976 | 0.769 | 0.231 | 0 | 21,367.5 |
| 1977 | 0.73 | 0.27 | 0 | 24,975 |
| 1978 | 0.629 | 0.33 | 0.041 | 38,110 |
| 1979 | 0.534 | 0.33 | 0.136 | 55,685 |
| 1980 | 0.513 | 0.33 | 0.157 | 59,570 |
| 1981 | 0.523 | 0.33 | 0.147 | 57,720 |
| 1982 | 0.527 | 0.33 | 0.143 | 56,980 |
| 1983 | 0.447 | 0.33 | 0.223 | 71,780 |
| 1984 | 0.311 | 0.33 | 0.359 | 96,940 |
| 1985 | 0.186 | 0.33 | 0.484 | 120,065 |
| 1986 | 0.072 | 0.33 | 0.598 | 141,155 |
| 1987 | 0.164 | 0.33 | 0.506 | 124,135 |
| 1988 | 0 | 0.313 | 0.687 | 156,047.5 |
| 1989 | 0 | 0.33 | 0.67 | 154,475 |
| 1990 | 0 | 0.33 | 0.67 | 154,475 |
| 1991 | 0.13 | 0.33 | 0.54 | 130,425 |
| 1992 | 0.225 | 0.33 | 0.445 | 112,850 |
| 1993 | 0.099 | 0.33 | 0.571 | 136,160 |
| 1994 | 0.208 | 0.33 | 0.462 | 115,995 |
| 1995 | 0.292 | 0.33 | 0.378 | 100,455 |
| 1996 | 0.347 | 0.33 | 0.323 | 90,280 |

| | | | | |
|---|---|---|---|---|
| 1997 | 0.367 | 0.33 | 0.303 | 86,580 |
| 1998 | 0.424 | 0.33 | 0.246 | 76,035 |
| 1999 | 0.481 | 0.33 | 0.189 | 65,490 |
| 2000 | 0.536 | 0.33 | 0.134 | 55,315 |
| 2001 | 0.58 | 0.33 | 0.09 | 47,175 |
| 2002 | 0.622 | 0.33 | 0.048 | 39,405 |
| 2003 | 0.663 | 0.33 | 0.007 | 31,820 |
| 2004 | 0.651 | 0.33 | 0.019 | 34,040 |
| 2005 | 0.625 | 0.33 | 0.045 | 38,850 |
| 2006 | 0.597 | 0.33 | 0.073 | 44,030 |
| 2007 | 0.566 | 0.33 | 0.104 | 49,765 |
| 2008 | 0.603 | 0.33 | 0.067 | 42,920 |
| 2009 | 0.575 | 0.33 | 0.095 | 48,100 |

The logistic growth function, estimated using ME model was used to estimate MSY of 25,372.75 tonnes. The value is higher than that estimated for the Walters and Hilborn model of 21,018.77 tonnes. Conversely, the biomass at MSY (Bmsy) estimated by the ME model of 120,250 tonnes was lower than that estimated by the Walters and Hilborn model of 122,558.4 tonnes. The ME model estimates an effort at MSY to be 109,731 fishing nights. It is observed that the estimates of the ME model are closer to those of the Walters and Hilborn model estimates than they are to those estimated by the CYP model.

Table 7 above shows the annual estimated biomass by the ME model. It estimates that there is a steady decline in stock from 1988 when the stock was estimated to be at its maximum.

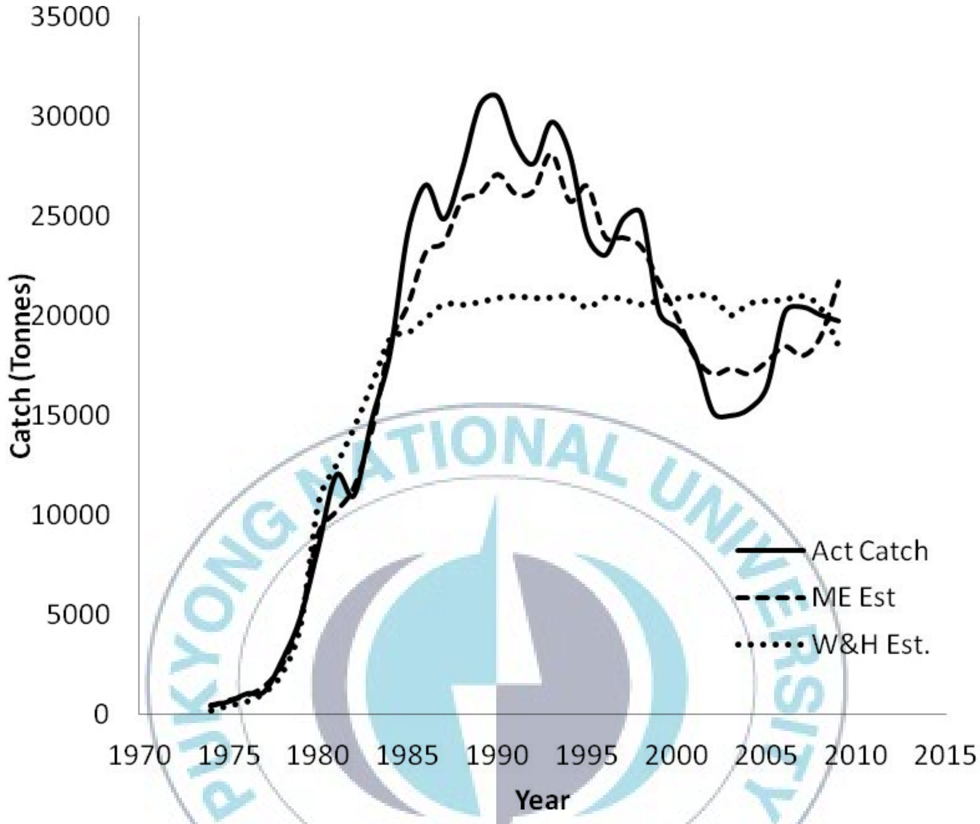


**Figure 7: Estimated catch by Walters and Hilborn and ME models**

The estimated catch of the ME model was calculated using equation (16). Both Walters and Hilborn and ME models seem to have an estimated catch that is close to the actual catch in the early years of the fishery. The estimates of the Walters and Hilborn model are further from the actual catches in the later years compared to the ME model.

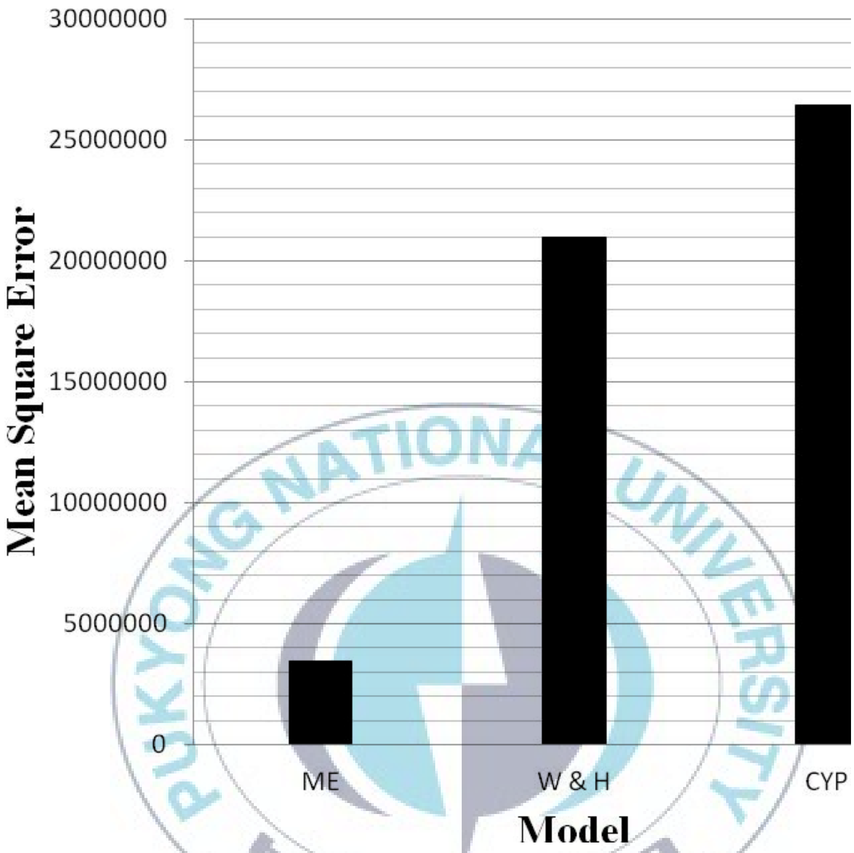


**Figure 8: Mean square error of models**

In comparison, the mean square error method shows that the ME model has a lower value than the other two models hence closer estimated catch values to the actual catch values. Furthermore, the Theil $U$ statistic calculated for all three models (0.00087, 0.0022 and 0.0027 respectively) shows that the ME model is more accurate than the other two models.

## Analytical Model

### Mortality

The estimates of mortality were calculated using three different methods which are represented in the table below:

**Table 8: Fishing mortality parameters for *Limnothrissa miodon* in Lake Kariba in 1982**

| Model/parameters | M (/year) | F (/year) | Z (/year) |
|---|---|---|---|
| Zhang & Megrey (2006) | 1.924 | - | - |
| Zhang & Megrey (2010) | - | 0.320 | - |
| Total mortality (Z = F +M) | - | - | 2.244 |

The fishing mortality was calculated to be 0.927/year for 2009, which is the most recently available data for catch in Lake Kariba.

**Biomass**

The von Bertalanffy parameters from Cochrane (1984) were used in the estimation of biomass for the 1982 stock (using parameters: K = 1.74/year. $L_\infty$ = 8.1cm and $t_o$ = -0.13) using the Zhang and Megrey (2010) model. A biomass of 54,272 tonnes was estimated for 1982. The ME model estimated a biomass of 56,980 tonnes is comparable to this figure. The most abundant size class is 4.75cm estimated to be 8,852 tonnes. The distribution of biomass by length class is shown in the figure below:

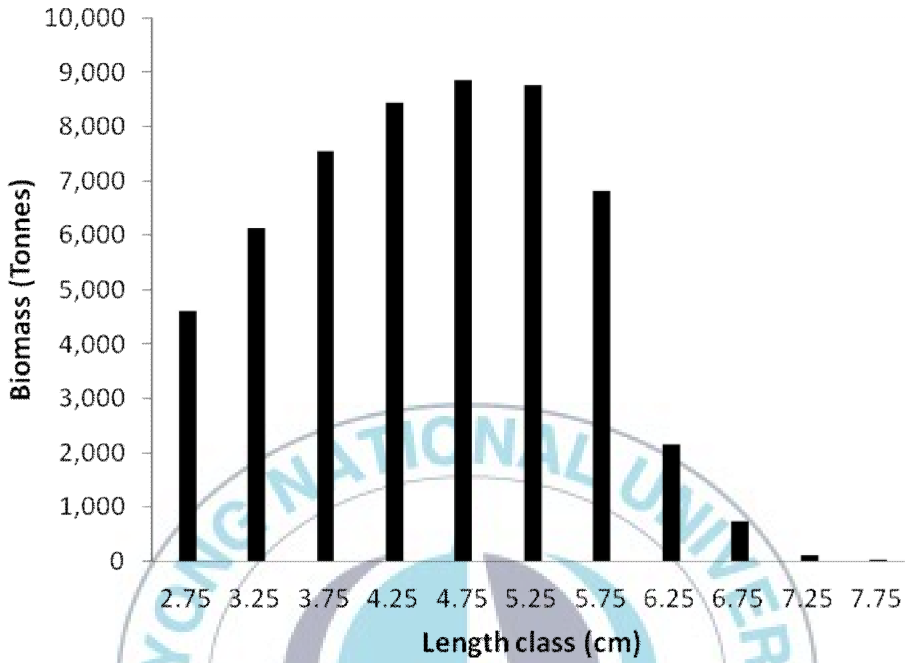


**Figure 9: Biomass by class of *Limnothrissa miodon* in Lake Kariba 1982**

### Acceptable Biological Catch (ABC)

The Acceptable Biological Catch for 1982 was estimated to be 21,744 tonnes with a $F_{abc}$ of 1.210/year. Using the fishing mortality ($F_c$) for 1982, the spawning biomass per recruit (SPBR) was estimated to be 3.424cm and the SBPR for $F_{35\%}$ was estimated to be 3.966cm. Furthermore, the estimated biomass at $F_{35\%}$ ($B_{35\%}$) was 62,509 tonnes which is 115% the biomass at the estimated at $F_c$ (fishing mortality in 1982).

### Estimating current level of ABC using hybrid formulation

An attempt was made to estimate the exploitation status of the 2007-2009 period of the fishery by incorporating results from the ME model into the biological assessment method. Biomass estimates from the ME model (Table 7) were used together with catch data for the 2007-2009 period. The following formula was applied:

$$\mathbf{ABC_{2007\text{-}2009}} = \frac{F_{ABC}\ x\ B^{-}{}_{2007-2009}}{M+F_{ABC}}\ \mathbf{x\ (1\text{-}}e^{-(M+F_{ABC})}\mathbf{)}$$

Where: $B^{-}{}_{2007-2009}$ is the average biomass for 2007-2009 (from ME model) and $ABC_{2007\text{-}2009}$ is the estimated ABC for the period 2007-2009. The value was estimated to be 17,329.53 tonnes. This value was then compared to the average catch, of 20,051.44 tonnes, for the period 2007-2009 derived from the actual catch data. Using this comparison, $ABC_{2007\text{-}2009}$ is less than the calculated average catch for 2007-2009 suggesting that the fishery was overexploited during this period.

## Discussion

Three different types of models (Analytical, SP and ME models) were tested in this analysis and compared in order to come up with parameters that can aid in the management of the Kapenta fishery in Lake Kariba.

Five surplus production models were initially tested on the catch and effort data of the Kapenta fishery. Of the five models tested, the CYP model was the only among the models that showed a high goodness of fit. However, the Walters and Hilborn model produced better estimates of catch as shown by the MSE and Theil *U* statistic being lower than CYP. The Walters and Hilborn model estimated a low intrinsic growth rate for the Kapenta fishery. The MSY of 21,018.77 tonnes estimated by the model suggests that from 1985-1998 the fishery was overexploited during this period. Furthermore, the estimated effort at MSY, Emsy, suggests that the fishery was over capacitated from 1992-2006 and from 2008-2009.

The ME model can also be used to estimate parameters such as MSY and the maximum sustainable biomass of the fishery. Furthermore, it can be applied to estimate the yearly fish stock, which cannot be done by the surplus production model. The model takes account of the full range of uncertainties into non-linear programming. Catch and effort are the observed variables in the model whilst the unknown parameters are probability distribution of constant, environmental carrying capacity (K), biomass and two parameters, $\alpha$ and $\beta$, which represent elasticity of effort and biomass respectively. The ME formulation seeks a solution that maximizes the distribution of probabilities reflecting our uncertainty about parameters subject to data consistency and normalization additivity requirements. This approach offers a method of recovering the desired parameters of stock assessment with a minimal amount of prior information when the state system is nonlinear and the state observation is noisy (Pyo, 2006).

The ME model and Walters and Hilborn model both estimated low intrinsic growth rates (r) of 0.422 and 0.343 respectively. The ME model estimated a lower environmental carrying capacity (K) to that of the Walters and Hilborn model. The value of Cmsy (yield/catch at MSY) for the ME model of 25,372 tonnes is higher than that of the Walters and Hilborn model which estimated Cmsy to be 21,018 tonnes. The estimated biomass at MSY, Bmsy, for the ME model of 120,250 tonnes was also lower than Walters and Hilborn estimate of 122,558.4 tonnes. The ME model estimates that the annual biomass of the Kapenta fishery is on a decline which could suggest that the fishery is overexploited.

The Analytical model is generally deemed a more reliable model since it incorporates growth and produces population abundance and thus more accurate than those not incorporating growth parameters (Zhang and Megrey 2010). The ABC estimated for 1982 of 21,744 tonnes using the analytical method is more conservative than MSY estimated by the ME model (25,373 tonnes).

An attempt was made to create a hybrid between the ME model and the analytical (biological) model. From this analysis, the estimated ABC for 2007-2009 was lower than the average catch for the same period. This could suggest that the fishery is overexploited. However, more recent data is required for length frequency analysis to be able to come up with more reliable estimates.

The F level estimated for 2009 is lower than $F_{ABC}$ and also catch in 2009 was lower than ABC for 1982 therefore, basing on this information, there is a small room for an increase in fishing intensity. However, there is no information on current biomass. There are therefore uncertainties in the catch statistics and bid parameters which are based on 1982 data.

In conclusion, considering issues mentioned above, a conservative management action should be taken which maintains the current level of fishing regime which it is safer for the total allowable catch to be the current level.

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# References


Beverton, R.J.H. and S.J. Holt. 1957. *On the dynamics of Exploited Fish Populations*. Chapman & Hall fish and Fisheries Series. Vancouver, Canada. 533 pp.

Brooks, C., 2002. *Introductory Econometrics for Finance*. Cambridge.

Chae, Dong-Ryul and S. Pascoe, 2005. Use of simple bioeconomic models to estimate optimal effort levels in the Korean coastal flounder fisheries. *Aquat. Living Resour*. 18, 93-101.

Chifamba, P. C., 1992. Daily Rings on otholiths as a method for ageing the sardine *Limnothrissa miodon* in Lake Kariba. *Trans. Zimbabwe Sci. Ass*. 66.

Clarke, R. P., S. S. Yoshimoto and S. G. Pooley, 1992. A bioeconomic analysis of the North- western Hawaiian Islands lobster fishery. *Marine Resource Economics*, 7(3), 115-140.

Cochrane, K. L., 1984. The influence of food availability, breeding seasons and growth on commercial catches of *Limnothrissa miodon* (Boulenger) in Lake Kariba. *J.Fish Biol.*, 24, 623-635.

Fox, W. J. Jr., 1970. An exponential surplus yield model for optimizing exploited fish populations. *Transactions of the American Fisheries Society*, 99(1), 80-88.

Golan, A., G. Judge, L. Karp. 1996a. A Maximum Entropy Approach to Estimation and Inference in Dynamic models or Counting Fish in the Sea using Maximum Entropy. *Journal of Economic Dynamics and Control*, 20, 559-582.

Golan, A., G. Judge, D. Miller. 1996b. *A maximum entropy Econometrics*. John Wiley and Sons.

Gujarati, D. N., 1995. *Basic Econometrics* (3rd International Edition). USA: McGraw-Hill.

Hilborn, R. and C.J. Walters, 1992. *Quantitative Fish Stock Assessment: Choice, Dynamics and Uncertainty*. New York: Chapman and Hall.

http://en.wikipedia.org/wiki/Durbin-Watson_statistic

http://en.wikipedia.org/wiki/Multicollinearity

http://www.fao.org/fi/oldsite/FCP/en/ZWE/body.htm

http://www.fao.org/docrep/006/y5056e/y5056e0i.htm

http://www.uvm.edu/giee/AV/Spatial_Modeling_Book/4/node33.html

Karenge, L.P. & Kolding, J. 1995, *Inshore fish population changes in Lake Kariba, Zimbabwe*. pp. 245-275 In T.J. Pitcher & P.J.B. Hart (eds.) *Impact of species changes in African lakes*, Chapman & Hall, London

Mandima, J. J., 1999. The food and feeding behavior of *Limnothrissa miodon* (Boulenger, 1906) in Lake Kariba, Zimbabwe. *Hydrobiologia* 407, 175-182.

Marshall, B.E., 1991. The Impact of the introduced sardine *Limnothrissa miodon* on the ecology of Lake Kariba. *Biological Conservation*, 55(2), 151-165.

Marshall, B. E., 1987. Growth and mortality of the Introduced Lake Tanganyika clupeid, *Limnothrissa miodon*, in Lake Kariba. *J. Fish Biol.*, 31,603-615.

MOMAF. 2000. Studies on the TAC- based Fisheries Management System and Quota Allocations for Jointly Exploited Fisheries Resources under EES Regime. Ministry of Land, Transport and Maritime affairs. Korea. 542 pp.

Nyikahadzoi, K., Hara, M., Raakjaer, J., 2010. Transforming ownership and governance – Lessons from capital intensive pelagic fisheries in South Africa and Zimbabwe. *International Journal of the Commons*, 4(2).

Pascoe, S. 1998. *A Bioeconomic Analysis of the UK Fisheries of the English Channel*. PhD Thesis, University of Portsmouth, UK.

Pella, J.J., P.K. Thomlinson. 1969. A Generalized Stock Production Model. *Bulletin of the Inter- American Tropical Tuna Commission*, 13, 419-496.

Pyo, Hee-Dong. 2006, A Comparative Analysis of Surplus Production Models and a Maximum Entropy Model for Estimating the Anchovy Stock in Korea. *Jour. Fish. Mar. Sci. Edu.*, 18(1), 19-30.

Quinn, T.D. and R.B. Deriso. 1999. *Quantitative Fish Dynamics. Oxford University Press*. New York. 542 pp

Richards, F. J. 1959. A flexible growth function for empirical use. *Journal of Experimental Biology*, 10, 290-300.

Schaefer, M. B., 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Bulletin of the Inter-American Tropical Tuna Commission*, 1(2), 26-56.

Schnute, J., 1977. Improved estimates from the Schaefer production model: theoretical considerations. *Journal of the Fisheries Research Board of Canada*, 34(5), 583-603.

Shannon, C.E. 1948. A Mathematical Theory of Communication. *Bell System Technical Journal* 27, 379-423.

Sun, Chin-Hwa. 1999. Optimal Number of Fishing Vessels for Taiwan's Offshore Fisheries: A Comparison of Different Fleet Size Reduction Policies. Marine Resource Economics, 13, 275-288

Theil, H. 1966. *Applied Economic Forecasting*. North-Holland. Amsterdam.

Tresierra, A. and Z. Culquichicón. 1993. Fisheries Biology. Trujillo. Perú. 432pp.

Zhang, C. I. and B.A. Megrey. 2006. A revised Alverson and Carney Model for estimating the instantaneous rate of natural mortality. *Transactions of the American Fisheries Society,* 135, 620- 633.

Zhang, C.I. and B.A. Megrey. 2010. A Simple Biomass-Based Length-Cohort Analysis for Estimating Biomass and Fishing Mortality. *Transactions of the American Fisheries Society*, 139, 911- 924.