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The application of a phosphorus mass balance model for estimating the carrying capacity of Lake Kariba

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Abstract: The aim of this study was to use an empirical mass balance equation to estimate the carrying capacity of Lake Kariba, where cage culture for Nile tilapia *Oreochromis niloticus* has been practiced since 1996. The carrying capacity for the lake was estimated at 33.2 × 103 t per year using the Dillon–Rigler phosphorus budget model.

Key words: Cage aquaculture, carrying capacity, Lake Kariba, phosphorus load, *Oreochromis niloticus*, Zambezi River

1. Introduction

Water quality deterioration due to excessive nutrient loading is an environmental concern in intensive recirculating fish aquaculture systems (1). Excess phosphorus loading emanating from the fish feed can alter the trophic status of a lake, resulting in eutrophication. Although total P load from aquaculture depends on fish feed P content and the digestibility of the feed used, it has been estimated that for every ton of cage tilapia production, 23–29 kg of total P is added to the environment (2). Thus, intensive aquaculture operations, if not properly monitored, can result in excessive phosphorus loading, which can negatively impact the water body. Quantitative estimations of nutrients in relation to ecosystem changes are therefore essential to ensure that environmental conditions and fisheries remain sustainable in lakes (3).

Phosphorus is the basic restrictive element in lakes that can be measured to test a lake's trophic status and make assumptions as to its productivity, from which equations can then be used to determine carrying capacity. In aquaculture, carrying capacity is defined as the standing stock of a particular species at which production is maximized without negatively affecting growth rates (1). Carrying capacity is very useful for making environmentally related decisions. It is, however, very difficult to measure carrying capacity accurately due to the innumerable variables that affect population sustainability in the environment (4).

Modeling of the aquatic ecosystem response to P loadings from cage culture is important in Lake Kariba, a man-made lake that was constructed for the generation of hydroelectric power but is now a multipurpose reservoir that supports several economic activities that include tourism and harvesting fish from the wild. Fish farming has also become important in the last decade, and its importance is likely to increase. As such, there is a need to have estimates for the lake's carrying capacity for aquaculture development. The estimate of aquaculture carrying capacity is also useful as it aids in preproject environmental impact assessment. The Zimbabwean Environmental Management Act (5) stipulates that an environmental impact assessment has to be conducted prior to any development in order to mitigate the potential negative impacts.

Dynamic models (6) or statistical models (2) can be used to model the response of the aquatic ecosystem to increases in P loading. The choice of the model should depend on what it is to be used for and the quality of available data (7), but it should generally be useable without need for expensive and time-consuming data collection by highly trained technicians (2). Simple predictive models are as accurate as the complex data intensive models because each additional parameter results in the introduction of a further source of error (8). Many statistical models that predict the P concentration in lakes use mass balance equations and relate these to trophic states that have been developed (9–12). The Dillon–Rigler model (10) is

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considered to have the best predictive abilities. It has been found to perform best in shallow lakes, deep lakes, and reservoirs in both temperate and tropical regions (13).

This paper provides an estimate of Lake Kariba's aquaculture carrying capacity based on the Dillon–Rigler (10) phosphorus budget, which was applied in a series of steps.

2. Materials and methods

Lake Kariba is a tropical man-made lake that was created in 1958 by damming the middle section of the Zambezi River at the Kariba gorge and is shared between Zambia and Zimbabwe (Figure). Geographically, the lake is located between 16°28′S and 18°6′S and between 26°40′E and 29°3′E. It is 485 m above sea level (14). The lake has a catchment area of 1.19 × 106 km^2, which extends over Angola, Zambia, Namibia, Botswana, and Zimbabwe. Stretching for 276 km, it has an average width of 19 km while the maximum depth is 120 m (mean depth: 29.2 m), with a surface area of 5.5 × 103 km^2.

The only aquaculture farm on the Zimbabwean side of Lake Kariba is based in the Sanyati Basin (Figure), where *Oreochromis niloticus* has been farmed by Lake Harvest (Pvt.) Limited since 1996. In 1998, annual production was 54 t, and by 2000 annual production had increased to 1968 t. Production continued to increase such that by 2002, it had reached 2333 t per year and it peaked at 3000 t per year in 2004. From 2004 to 2010, annual production fluctuated within the range of 2000 to 3000 t. Fish are reared in floating cages in the lake and are fed a commercial pelleted diet. According to the farm records of Lake Harvest Private Limited (15), the nitrogen and phosphorus content in the feed is 4.8% and 0.98%, respectively. Estimated annual rates of nitrogen and phosphorus discharges into the lake from the operations are 321.2 t and 53.6 t, respectively. The food conversion ratio (FCR) is 1.7 (15). The characteristics of Lake Kariba and the *Oreochromis niloticus* cage culture farm that were used in the calculations are shown in the Table.

3. Results

The results of estimation of carrying capacity using the Dillon–Rigler (10) phosphorus budget model are presented below. The carrying capacity assessment was based on the whole lake area and volume as recommended by Beveridge (16).

Step 1:

Steady state total P concentration in the water body to be farmed was used. In tropical lakes and reservoirs, [P] should be taken as the annual mean total P concentration of surface waters and should be based on a number of samples taken during the year. We used data from literature collected by Lake Harvest Private Limited (15), based on limnological surveys undertaken in 2010. Therefore, surface water [P] was at 0 m depth = 10 µg L^{-1}.

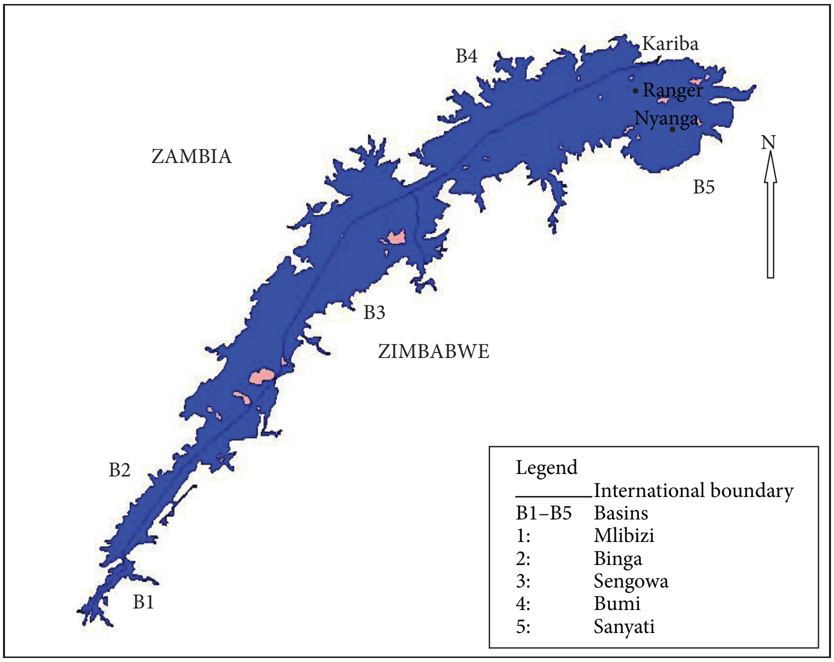

Figure. Map showing location of the aquaculture farm at sites marked as Ranger and Nyanga in the Sanyati Basin (B5) of Lake Kariba.

Step 2:

The capacity of the water body for intensive cage fish culture is the difference [ΔP] between [P] prior to exploitation $[P]_i$ and the final desired/acceptable [P] once fish culture is established, $[P]_f$.

Determine [ΔP]:

$[\Delta P] = [P]_f - [P]_i$.

[ΔP] is related to P loadings from the fish cages (L_{fish}), the surface area of the lake (A), its flushing rate (ρ), and the ability of the water body to handle the loadings (i.e. the fraction of L_{fish} retained by the sediments R_{fish}).

$[\Delta P] = L_{fish}\,(1 - R_{fish})\,ź$

ź can be calculated from hydrographic data either from the literature or survey work (2), where ź = V/A, and V = volume of the water body (m^3) and A = surface area (m^2). The ź symbol was used from the literature (14).

Therefore, $L_{fish} = [\Delta P]ź\rho/(1 - R_{fish})$.

ρ is the flushing rate ($year^{-1}$) and is equal to ρ = Q/V. Q is the average total water volume out-flowing each year. Q can be calculated by the direct measurement of outflows, or in some circumstances can be determined from published data on total long-term average flows from catchment area surface runoff (Ad.r), precipitation (Pr), and evaporation (Ev), such that:

Q = Ad.r + A (Pr – Ev) (2,16).

In this study, the Q used was from the Zambezi River Authority's (17) actual flow data.

R_{fish} was calculated using an x value of 0.9 based on the study by Kunz et al. (18), which concluded that approximately 90% of total incoming P in Lake Kariba was eliminated from the water column by sedimentation. R_{fish} is the most difficult parameter to estimate (19). It is estimated that at least 45%–55% of the total P wastes from cage rainbow trout are likely to be permanently lost to sediments as a result of solids deposition (19). For Lake Kariba we adapted a value of 0.9 (18) since there are no data yet from tilapia cages. This is the most likely approximation, although the estimation is based on incoming total P from land discharges.

$R_{fish} = x + [(1 - x) R]$,

where x is the net deposition of total P lost permanently to the sediments as a result of solids deposition. For Kariba, Kunz et al. (18) gave x as 0.9.

R: Phosphorus retention coefficient is calculated from the equation below (10), where ρ = flushing rate ($year^{-1}$):

$R = 1/1 + 0.75\rho^{0.507}$.

Acceptable total P loading (L_a) is estimated by multiplying L_{fish} and lake surface area. Lake surface area (A) is 5.5 × 103 km^2 according to Balon and Coche (14). Lake mean depth (ź) is 10 m. We used the Sanyati Basin mean depth from Balon and Coche (14) for our study. Total outflow Q (10^6 m^3) was calculated from a mean flow of 1.7 × 103 m^3 s^{-1}.

Table. Morphometric, hydrologic, and phosphorus budget parameters of Lake Kariba and characteristics of the aquaculture farm.

	Symbol	Values
Drainage area (km^2)	A_d	1.19 × 106
Surface area (km^2)	A_o	5.5 × 103
Mean depth (m)	Ź	29.2
Total outflow (m^3 $year^{-1}$)	Q	53.6 × 109
Flushing rate ($year^{-1}$)	ρ = Q/V	0.34
Phosphorus retention coefficient	R	0.69
Phosphorus content (%)		0.98
Food conversion ratio (FCR)		1.7

Q (10^6 m^3) 53.6 × 109 m^3 $year^{-1}$,

ź = V/A,

where V is volume in m^3 and A is surface area in m^2.

ρ = Q/V.

V = km^3 from Balon and Coche (14).

V = 1.57E + 11 m^3.

A = 5.5 × 103 km^2 from Balon and Coche (14).

Therefore, ρ = 0.34, using x = 0.9.

Intensive cage fish production (t $year^{-1}$) can be estimated by dividing L_a by the average total-P waste per ton of fish production.

P content of tilapia fish feed being used is 0.98% (15). For 1 t of fish weight, 1.7 t of food is used, which contains 16.66 kg P. The P content of tilapia = 0.75% wet weight of fish = 7.5 kg/t of fish from the Tilapia Aquaculture Dialogue (20).

Therefore, P losses to the environment = 9.16 (the difference between kg P per ton of feed and P content of Tilapia), meaning that 9.16 kg/t of fish is produced.

Carrying capacity calculation:

1. Average P from literature values: 10 µg L^{-1}, 10 mg m^{-3}.
2. According to Beveridge (2), maximum acceptable P concentration can be 250 mg m^{-3}. In this analysis, we used a P level of 0.5 mg L^{-1} based on the recommendation by the Zimbabwe Environmental Management Act (5) as a standard for total P in effluent discharged into water bodies.

3. Determine Δ[P]:

$[\Delta P] = L_{fish}\,(1 - R_{fish})\,ź\rho$,

where $L_{fish} = [\Delta P]ź\rho/(1 - R_{fish})$.

Using x = 0.9 from Kunz et al. (18) and calculating R from $R = 1/1 + 0.75\rho^{0.507}$,

where ρ = flushing rate ($year^{-1}$),

R = 0.69,

$R_{fish} = x + [(1 - x) R]$,

$R_{fish} = 0.96$,

ź = 10,

ρ = 0.34,

$L_{fish} = [\Delta P]ź\rho/(1 - R_{fish})$ (note that ΔP is 490),

L_{fish} = 55,386.05 mg m^{-2} $year^{-1}$,
55.39 g m^{-2} $year^{-1}$.
$L_a = L_{fish}$ × surface area of lake,
L_a is acceptable total-P loading,
304,623.26.
Carrying capacity = L_a/P losses,
33.2 × 103 t/year (whole lake).

From the above calculations, the estimated carrying capacity is 33.2 × 103 t per year.

4. Discussion

The current aquaculture production in Lake Kariba is 7 × 103 t per year. The estimated carrying capacity based on the Dillon–Rigler (10) phosphorus budget model is 33.2 × 103 t per year. This result is over 4.5 times higher than the present fish production level. This calculated value can be taken as a baseline that can be used as an indicator of a possible ecologically sustainable aquaculture production level for Lake Kariba. With the existing proposal to increase production to 25 × 103 t per year, according to the results of this study, this may be still within the acceptable ecological limits. However, since the challenge in Lake Kariba is to ensure that the lake does not become hypereutrophic, such increases should be done in a step-wise manner accompanied with rigorous monitoring of nutrient loading. Such a precautionary approach will ensure that the system does not instantly tip over from oligotrophy to hypertrophy. As the carrying capacity is increased in this inland water body, actual observed data on the environmental effects and changes in the fish farm should be collected and fed into the model in order to increase reliability and ultimately to develop an appropriate specific on-farm model that takes into account the specific conditions in Lake Kariba as well as the external factors at all the cage culture farms on Lake Kariba, including the Zambian side.

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