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Phosphorus-based Carrying Capacity of Aquaculture Sites in Lake Victoria, Kenya

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Abstract

Cage fish aquaculture is increasing rapidly in the African Great Lakes and reservoirs. In Lake Victoria, there is increasing number of cage fish farmers in the shallow bays of the lake. However, despite the proliferation of cages in the lake, there has been little regulation of cage aquaculture of the Nile tilapia (*Oreochromis niloticus*) in Lake Victoria leading to socio-economic conflicts and water quality concerns. In this study, we determined total phosphorous (TP) levels and derived water balance parameters, which were then used to compute TP assimilation capacity and fish production potentials for five sites within Kadimu Bay, one of the bays with active cage fish farming in Winam Gulf of Lake Victoria, Kenya. A mass-balance model was used to estimate the TP and fish carrying capacities of the fish cage sites in the bay. The model application is described in details in order to allow for replication in other African lakes and reservoirs, and in order to provide a framework for managing cage aquaculture and water quality. For all the sites, the TP assimilation capacity was exceeded by the TP released by the fish cages. Additionally, the maximum estimated fish production capacities were much less than the current fish production levels for all the sites. It is recommended that policies governing aquaculture production in the lake be reviewed based on these scientific findings and that the mass-balance model has potential applications for managing cage aquaculture in African lakes and reservoirs for sustainable fish production and water quality control.

Keywords: Mass-balance model, eutrophication, sustainability, *Orechromis nilotic*

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Introduction

Population growth and increase in per capita fish consumption demands water resources to be more efficient in terms of fish production on a global scale (Halwarth et al., 2007). The rising food demand is putting more pressure on wild fisheries resources (Worm et al., 2009) and cage fish farming is one of the alternatives increasingly being used to enhance fish production particularly in the tropics (FAO, 2010). Cage fish farming uses ecosystem services for the breakdown of organic matter, recycling of nutrients and supply of oxygen (Beveridge, 2004). However, a certain level of fish biomass may exceed the system capacity to function normally leading to a breakdown in ecosystem function through negative feedbacks such as eutrophication (Beveridge, 2004; Pillay, 2008; David et al., 2015), a process through which excess nutrients load especially phosphates and nitrates leads to increased algal production causing changes in ecosystem function and structure (Volleinweider, 1998). Cage aquaculture often results into water quality changes and pollution through unconsumed, undigested and metabolic wastes from fish cages. Consequently, appropriate cage densities and fish production levels are required in order to provide optimum production without jeopardizing water quality and ecosystem function. The concept of ecological carrying capacity (Dillon and Rigler, 1975; Ross et al., 2013; David et al., 2015) that sets maximum limit for aquaculture production is a potential policy and management tool for sustainable cage aquaculture and resilience of fresh water ecosystems to perturbations.

Aquaculture is increasing rapidly in African inland aquatic ecosystems (Njiru et al., 2004; Rothuis, 2014). In Lake Victoria for example, it is estimated that there are in excess of 4,000 cages on the Kenyan side of the lake (Njiru et al., 2018; Orina et al., 2018). Despite the popularity of the system, there have not been scientific studies to estimate the production carrying capacity of the lake as well as the ecological carrying capacity of cage sites for optimum aquaculture production. Such production should not jeopardize the ecological functions of the lake and should allow for sustainability and resilience of the ecosystem to perturbations. Sustainable cage culture production should focus on estimating the quantity of production that can be sustained by the environment without dramatic change in ecological processes, ecosystem services, species population and community structure (Beveridge, 2004; David et al., 2015). Mass-balanced models are commonly being used to determine the optimum feeding regimes in cage aquaculture (Dillon and Rigler, 1975; Beveridge, 2004) and hence the carrying capacity of water bodies (Pulatsu, 2003; Ross et al., 2013; David et al., 2015). Phosphorus is a major limiting factor that control phytoplankton productivity especially in fresh water ecosystems (Vollenweider, 1998; Pillay, 2008) and therefore limits food chain productivity and often leads to eutrophication of aquatic systems when in excess. In this study, we used a mass-balanced model to estimate the total phosphorous and fish production carrying capacity of five cage sites for Nile tilapia (*Oreochromis niloticus*) production in Kadimu Bay, one of the five active aquaculture sites in Lake Victoria, Kenya. The applied methodology and results should provide a pioneering benchmark for managing aquaculture production in African lakes and reservoirs.

Materials and Methods

Study area

The study was conducted within Kadimu Bay (Figure 1), one of the five main bays of Lake Victoria, Kenya. The bay is situated between latitude 0° 5′ 10′′ S and longitude 34° 6′4′′E and lies within the tropical monsoon climate (Kottek, 2006). The depth range of the bay is between 3 to 16 m, about 947 km^2 in area and spans a distance of about 4.3 km (Calamari et al., 1995). Its shallow and sheltered nature makes it suitable for cage fish farming. The larger Winam Gulf that forms the Kenyan side of Lake Victoria lies on latitude 0° 14′24′′S and longitude 34° 34′ 48′′E (Geheb, 1977). The annual average precipitation over the lake is about 1 300 mm with average annual temperature of about 22.9°C (Masongo et al., 2005). Most of the sheltered bays in Lake Victoria have cage fish farming as a recent introduction (Aura et al., 2018). The cages are medium sized floating types with typical dimensions of 7 x 8 x 9 m. The main cultured species in the lake is the Nile tilapia (*Oreochromis niloticus*) and the culture practice is mainly semi-intensive (Njiru et al., 2018). The fish are fed with commercial pellets supplemented with farmer-formulated feeds comprising of the fresh water shrimp (*Caridina spp.*).

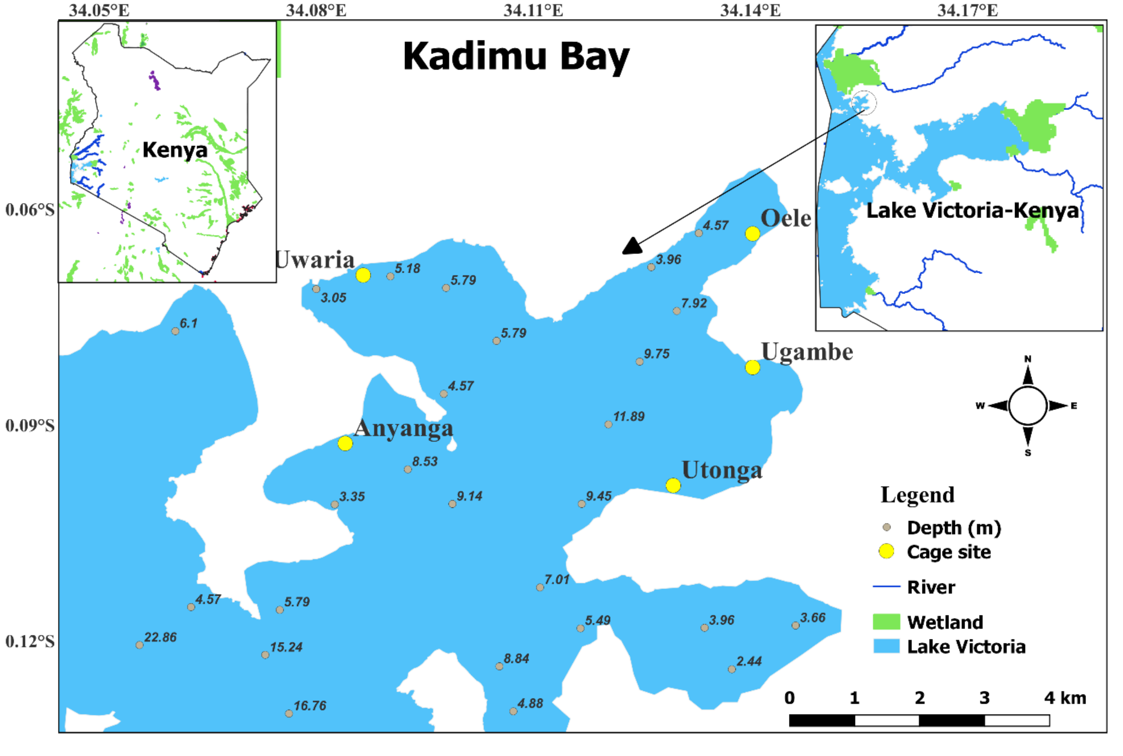

Figure 1: Map of Lake Victoria showing sampling sites: Anyanga, Uwaria, Oele, ugambe and, Utonga in the Kadimu Bay of Winam Gulf, Lake Victoria, Kenya. (Modified from KMFRI).

Sampling

Sampling for physico-chemical parameters and nutrient load was conducted at five fish cage sites (Anyanga, Uwaria, Oele, Ugambe and Utonga) within the Kadimu Bay (Figure. 1). The five cage sites have an average depth of 7.098 m and are separated by an average distance of 0.5 Km. Each cage site is managed under a different beach management group. The sites were selected because they had on-going cage fish farming activities, were easily accessible and met most of the site selection criteria (Pillay, 2005). Sampling for water quality variables was conducted at a frequency of three-times in a month for a period of ten months extending from January to October, 2021. On each sampling occasion, three replicates of water samples were collected randomly at the sites using labeled water bottles. The samples were placed in a cooler box at a temperature of approximately 4°C and transported to the Kenya Marine and Fisheries Research Institute (KMFRI) laboratory for analysis of total phosphorus concentrations. Water transparency was measured *in situ* with a Secchi disk of about 20 cm diameter (Bartram and Balance, 1996).

Analytical procedures

The UV Spectrophotometer (Genesys 10S Vis SN- 2F1N308001), was used for analysis of chlorophyll-a, total phosphorus (TP), and total nitrogen (TN) following the methods in APHA (2005). The partitioning of chlorophyll-a was done by the sonication technique (APHA, 2005) and the concentration determined by the Lorenzen equation (APHA, 2005) through the application of absorbance readings from the UV Spectrophotometer. The ascorbic reduction technique and the diazotization procedure were used to determine TP and TN concentrations using unfiltered water samples (APHA, 2005). A total of eighteen water samples were analyzed per site.

Calculation of Phosphorus-based carrying capacity

Phosphorus is a critical element needed by fish for optimum growth and development (Pillay, 2005). It is often a limiting nutrient in freshwater bodies that controls phytoplankton production and together with light, optimizes the productivity of aquatic ecosystems (Beveridge, 2004). Over supply of phosphorus leads to non-linear feedbacks those results into negative responses like eutrophication and water quality deterioration (Volleinweider, 1998; Beveridge, 2004; Pillay, 2005). Phosphorus-based carrying capacity (mg m^3) is the TP assimilation potential of an area that will not disrupt the ecological functioning of the area (Beveridge, 2004). Total phosphorus load of a site is simply quantified by multiplying the site area by unit concentration of TP in the water. The TP assimilation load of the five cage sites within the study area were estimated following the mass-balance equation modified from Dillon and Rigler (1975) and as applied by Beveridge (2004) and Pulatsu (2003) as:

$$\text{Lfish} = \frac{\Delta[P]Z\O}{1-Rfish} \quad \text{..............................(1)}$$

Where:

Lfish = Cage site carrying capacity (maximum assimilation load) of total phosphorus (mg m^3 year^{-1}).

Δ [P] (mg m^{-3}) = Total phosphorus allocation load, obtained from the difference between measured phosphorus $[P]_c$ and the maximum allowable phosphorus load $[P]_i$ for fish culture as:

$$\Delta[P] = [P]i - [P]c \quad \text{........................(2)}$$

Z (m) = Average depth of a cage site

Ø (year^{-1}) =Flushing coefficient, a measure of the water replacement rate at a site.

Estimated from average water debit (Q, m^3 year^{-1}) and water volume at sites (V, m^3) as:

$$Ø = Q/V \quad (3)$$

Where,
R_{fish} = Proportion of total phosphorus left in sediments as a result of feeding fish in the cages and from fish waste matter estimated according to Beveridge (2004) and Pulatsu (2003) as:

$$Rfish = X + [(1 - X)]R \quad (4)$$

Where,
X: the net proportion of total phosphorus lost permanently to the sediments as a result of solid deposition and is estimated to be ranging between 0.4-0.5 (Pulatsu, 2003).

R: Phosphorus retention coefficient given by:

$$R = \frac{1}{1 + 0.747Ø^{0.507}} \quad (5)$$

The effective quantity of total phosphorus discharged in the environment from fish aquaculture waste (Pe) is directly proportional to fish production and is given by the equation (Beveridge, 2004):

$$Pe = (Pfeed \ x \ FCR) - Pfish \quad (6)$$

Where:
Pe = TP released into the environment from a ton of fish produced (kg of TP per ton of fish production).

FCR = Feed conversion ratio generated from the ratio of feed given and the amount of fish produced.

P_{feed} = TP in fish feeds (kg ton^{-1})

P_{fish} = TP incorporated into the body of whole fish (kg ton^{-1})

Data sources for calculation of Phosphorus-based carrying capacity

The variables for the estimation of phosphorus-based carrying capacity per site using the mass-balanced model (equation 1) were derived through fieldwork activities and from the published and grey literature. The surface area and water volume at each cage site were estimated by KMFRI using the planimetry method. The average depth (Z, m) of cage sites were estimated using a depth finder. The average water debit (Q, m^3 year^{-1}) for the cage sites used to derived the flushing rate (Ø) in equation 3 was determined from the average of published data on the lake's water balance parameters for comparable sites and included; long-term average inflow from catchment surface runoff (Ad..r), cage site surface area (A), Precipitation into the lake (Pr), and Evaporation from the lake (Ev) (Table 1). The variables were incorporated in the equation below as (Dillon and Rigler, 1975; Shoji, 2009);

$$Q = Ad.r + A\,(Pr - Ev) \quad (7)$$

Analysis of TP in feed (Pfeed) and TP in the body of whole fish (Pfish) (equation 6) was done at the KMFRI laboratory. Consequently, the TP in feed used by cage fish farmers was estimated to be about 21.75 kg ton^{-1}, while TP in the body of whole tilapia was estimated at about 3.5 kg ton^{-1}.

Table 1: Published estimates of the mean annual water balance parameters of Lake Victoria, and their reference sources. Adopted from Xungang and Nicholson (1998)

Period	Rainfall Over lake (mm/year)	Evaporation (mm/year)	Tributary inflow (mm/year)	Reference source
	1420	1350	230	Hurst (1952)
	1145	1130	237.5	
1925-1959	1630	1523	260	de Baulny and Baker (1970)
	1650	1500	250	Hastenrath and Kutzbach(1983)
	1636	1459.5	238	WMO (1974, 1981)
	1450	1370	260	Spigel and Coulter (1996)
1956-1978	1810	1593	343	Howell et al (1988)
1945-1984	1645	1470	0	Flohn and Burkhardt (1985)
1950-1979	1660	1590	420	Kite (1982)
1970-1974	1850	1595	343	Piper et al (1986)
1956-1978	1476	1401	241	Balek (1977)
Mean	1579.27	1452.86	256.59	

Results

Phosphorus-based carrying capacity

The mass-balanced model in equation (1) was applied to derive the total phosphorus (TP) assimilation capacity for the five sites. An example of how TP assimilation capacity was derived for each of the five cage sites in Kadimu Bay is shown for Anyanga site (Figure. 1) as follows:

For Anyanga site, the TP assimilation carrying capacity (amount of TP the area can hold as a result of cage fish farming), L fish, in equation (1) was derived from the following steps:

Table 2: Datasets for calculation of total phosphorus assimilation carrying capacity for cage sites in the Kadimu Bay, Lake Victoria, Kenya

Site	Surface area (m^2)	Depth (m)	Volume (V) (m^3)	Water Debit (Q) (m^3/year)	Flushing rate (Ø=Q/V) ($year^{-1}$)
Anyanga	617509	7.01	4328738.09	78059569.28	18.03
Oele	22458	4.27	95895.66	2839172.37	29.61
Ugambe	9250	8.84	81770	1169549.09	14.30
Utonga	29122	10.67	310731.74	3681568.61	11.85
Uwaria	137022	4.7	644003.4	173321207.61	26.89

The TP allocation load Δ [P] was derived as 13.44 mg m^{-3} from the difference between maximum allowable TP allocation load of 100 mg m^{-3} recommended for Lake Victoria (Kenya) cage aquaculture by the Kenyan Marine and Fisheries Research Institute (Aura, 2020), and the highest measured field value of 86.56 mg m^{-3} at the site. The highest field values of TP at sites were used in order to provide precautionary estimates of TP assimilation carrying capacities.

Given the average depth (Z) of 7.01 m for Anyanga site (Table 2) and flushing rate (Ø, Equation 3) of 18.03 $year^{-1}$ derived from water debit (Q) of 78 059 569.28 m^3 $year^{-1}$ from equation (3) and water volume (V) of 4 328 738.09 m^3 (Tables 1 and 2), the phosphorus retention coefficient (R) was derived as 0.24 from equation (5).

Consequently, R_{fish} (equation 4), the proportion of TP left in sediment was derived as 0.62 taking X as 0.5. Therefore, the amount of TP that can be carried by the lake at Anyanga site (Lfish) was estimated by substituting the above variables into equation (1) as 4.47 g m^{-2} $year^{-1}$ (Table 3). This was multiplied by the cage site surface area of 617 509 m^2 to derived the site overall TP assimilation carrying capacity as 2 760 265.23 g $year^{-1}$ or equivalent to 2 760.27 kg $year^{-1}$ (Table 4).

Table 3: Total Phosphorus (TP) assimilation carrying capacity, fish production carrying capacity and hydrological parameters of cage sites within Kadimu Bay, Lake Victoria, Kenya

Site	TPmax (mg/m^3)	ΔP(mg m^{-3})	Z(m)	Ø($year^{-1}$)	R	R_{Fish}	Lfish ($g/m^2/year$)
Anyanga	86.56	13.44	7.01	18.03	0.24	0.62	4.47
Oele	96.61	3.39	4.27	29.61	0.19	0.595	1.058
Ugambe	97.38	2.62	8.84	14.3	0.26	0.63	0.895
Utonga	82.93	17.07	10.67	11.85	0.28	0.64	5.995
Uwaria	55.16	44.84	4.7	26.87	0.2	0.6	14.167
Kadimu Bay	83.73	16.27	7.098	20.132	0.234	0.617	6.07

All notations are as explained in the text.

Following equation (6) for the amount of TP generated per ton of fish produced, and given the TP in feed (P_{feed}) as 21.75 kg ton^{-1}, FCR value of 1.4 and TP in the body of whole fish (P_{fish}) as 3.5 kg ton^{-1} the TP released in the environment per ton of fish produced (Pe) at the site was estimated at 26.95 kg ton^{-1}. Consequently, the total carrying capacity for Anyanga site based on fish production is derived as 102 421.72 kg $year^{-1}$ (102.42 MT $year^{-1}$ Table 4) from the ratio of TP assimilation capacity for the site (2 760.27 kg $year^{-1}$) and the quantity of phosphorus released per ton of fish produced (26.95 kg).

From consultations and the literature (Orina et al., 2018), the annual cage fish production at Anyanga site averages 6 320 MT $year^{-1}$ (Table 4). This production therefore releases 170 324 kg $year^{-1}$ (Pe x fish production) of TP to the environment at the site. This value is several magnitudes higher than the estimated TP carrying capacity at Anyanga site of 2 760.27 kg $year^{-1}$

The TP assimilation capacity for each of the other four sites, the TP released by current fish production at sites, the current fish production at sites and the maximum potential fish production at sites were calculated in the same computational procedure and are shown in Table 4.

Table 4: TP carrying capacity, TP release by current fish production, Maximum potential fish production and current fish production by cage site in the Kadimu Bay, Lake Victoria, Kenya.

Site	TP carrying capacity (kg/year)	TP released by current fish production (kg/year)	Maximum potential fish production (ton/year)	Current fish production (ton/year)
Anyanga	2,760.270	170,324	102.420	6,320
Oele	23.761	113,190	0.882	4,200
Ugambe	8.279	32,340	0.307	1,200
Utonga	174.586	6,468	6.478	240
Uwaria	1,941.191	21,560	72.029	800
Kadimu Bay	4,949.241	343,882	183.645	12,760

The estimated cage site fish production potential within the studied bay (Table 4) ranged from a minimum of 0.307 MT year^{-1} at the Ugambe site to a maximum of 102.42 MT year^{-1} at the Anyanga site showing variations in production potential at small spatial-scales. The other sites also had variable fish production potential in the bay that varied from a relatively high yield at Uwaria (72.03 MT year^{-1}), low values for Utonga (6.48 MT year^{-1}), Ugambe (0.31 MT year^{-1}), and Oele (0.88 MT year^{-1}). The estimated potential maximum fish yield for all the five cage sites were orders of magnitude lower than the current harvests by the farmers (Table 4).

The estimated TP released to the environment by current fish production (Pe x current fish production) is greater than the TP that can be accommodated by sites (Lfish) for all the sites, indicating that the TP assimilation capacity at the cage sites has been exceeded (Table 4). Hence, the potential for more fish production at the cage sites in the Kadimu Bay, including the TP that can be accommodated by these cages sites (Lfish), indicates that both the maximum potential fish production and TP carrying capacity for the bay have been exceeded (Table 4). The TP released by current fish production in the Kadimu Bay (Table 4) is a lot more than the TP that can be accommodated by the bay. The current cage fish production in the Kadimu Bay (Table 4) is above the estimated maximum potential cage fish production of the bay following the mass-balanced model used in this paper.

Discussions

This paper pioneers the use of nutrient analysis, especially TP, in setting the limit of aquaculture production in African lakes and reservoirs. The mass-balance method can provide a useful tool for managing cage aquaculture in lakes and reservoirs (David et al., 2015; Pulatsu, 2003). However, the accuracy of the TP based mass-balanced model applied in this study, will depend on the availability of accurate and recent data on the water balance parameters of aquatic systems, something which is lacking for most African lakes and reservoirs (Roberts and Zohary, 2018; Plisnier et al., 2022). In this study, we relied on historical water balance data for the Winam Gulf of Lake Victoria due to the unavailability of recent datasets. The estimates provided in this paper will therefore require validation as more physical and limnological data become available on Lake Victoria. Nonetheless, the paper has delved into methodological and computational details to allow replication of the method as a policy tool for managing aquaculture in the African Great lakes and reservoirs.

The estimated allowable TP level for the studied bay is exceeded by the current TP released into the environment as a result of aquaculture activities. Excess TP can lead into increased algal biomass production through eutrophication (Pillay, 2008) and water quality deterioration. Some studies on the Winam Gulf have found TP levels not to have reached the eutrophication thresholds (Gikumu-Njuru et al., 2021) save for occasional seasonal increases in TP loading caused by agricultural run-off leading to localized eutrophication (Ledang et al., 2020). TP levels in this study ranged between 85.11 and 140.02 mg m^{-3} and are comparable to those of other studies in Lake Victoria (Gikuma-Njuru et al., 2021) and provided a moderate Eutrophic state (Sellu unpublished data). However, human activities including deforestation, urbanization and agricultural production have the potential to increase nutrient load into Lake Victoria (Ogutu-Ohwayo, 1990; Roberts and Zohary, 2018) and could exacerbate the enrichment caused by aquaculture in the lake.

The maximum TP assimilation load for the studied sites has a direct correlation with the depth, flushing rates and allowable TP as per the mass-balanced model (*sensu* Dillon and Rigler, 1975). Except for the depth variable, the other parameters will require more validation in future studies. For example, the accuracy of TP allocation load (Δ [P]) based on maximum TP concentration of 100 mg m^{-3} (Aura, 2020) will affect the maximum TP an area can hold from aquaculture and the potential fish production based on the model. The maximum allowable TP value in lakes varies between jurisdictions with a recorded maximum of 300 mg m^{-3} in some waters (Pulatsu, 2003) and low values of up to 30 mg m^{-3} in reservoirs (David et al., 2015). There is no clear policy on the maximum allowable TP values in Lake Victoria and hence requiring more validation of the proposals by KMFRI (Aura, 2020) in future studies.

The TP based mass-balanced model used in this study suggests the TP and Nile tilapia carrying capacity for the sites in the bay have been surpassed by the current fish production by farmers in the bay. These estimates are based on a precautionary approach but are useful starting guidelines for the management of Lake Vitoria cage aquaculture. There has not been a clear policy guideline on the number of cages allowed in Lake Victoria, leading to conflict between the farmers and wild stock fisheries (Njiru et al., 2018). Determination of carrying capacities for fish production and TP loads in the lake's shallow bays is important for a planned cage aquaculture enterprise including the setting up of sites for "aquaculture parks" (*sensu* David et al., 2015). TP addition by the cage aquaculture in the lake is likely to synergize with run-off inputs from agricultural activities around the lake hence the novelty of precautionary approach used to estimate TP allocation levels in this study and others (David et al., 2015; Mahamudi, 2019).

Conclusions and recommendations

This study provides a pioneering policy tool for managing aquaculture development in Lake Victoria and other African water bodies for sustainable livelihoods and ecosystem functioning. The mass-balanced model outputs used in this study will require re-parameterization as more data become available but are an important starting guideline for science-based management of aquaculture in the lake. Scientific effort is therefore required in order to generate recent data on water balance parameters for the lake, in addition to other limnological variables necessary to fit the model.

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