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Ecosystem-Based Management Revisited Using Physico-Chemical Factors Interactions with Fish Resources of Lake Malombe, Malawi

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ABSTRACT
Lake Malombe is one of the "hotspot" freshwater ecosystems in Malawi which has attracted both local and international scientists primarily due to changes in fish and ecosystem services. The lake has suffered from overfishing with catches declining from > 12,000 tones in 1980s to 3,820 tons in 2016, creating a gap in fish supply that has affected the livelihoods of many fishers. A concomitant decline in fish taxa was registered from 56 to 28; however, the full ecological impact has only recently been assessed through a series of synchronized studies on the benthos, limnology and fish species. This study shows interactions of how locally induced human activities have been compounded by Global Climate change at interannual scale. An exotic snail from Asia, *Melanoides tuberculata*, is also implicated in the change of fauna to the extent that its population now forms more than 40% of fish by-catches. The phytoplankton concentrations of 2.1-13.4µg/L were recorded while zooplankton varied between cool season (35,387-43,545 individual/m^3) and hot dry season (10,399-171,323 individual/m^3). Carbon fixing in the pelagic zone was estimated at 65.0-873g per m^2 contributing to high carbon sequestration. This has led to need to hatchery-reared introduction of a molluscivorous fish species, *Trematocranus placodon,* tilapias *(Oreochromis karongae)* and *Bathyclarias loweae* to utilize snails and neutralize plankton taking advantage of the high amounts of matter captured in the system. Drawing from examples from other eutrophic systems, "Pen Culture" seems to be an appropriate technique given the shallowness of the water levels and need to utilize rich benthic fauna. Furthermore, this is a carbon sink that should contribute to national carbon units. Since the bulk of national hydropower and irrigation investments are located downstream, *in situ* fish production would maintain required water flow; most importantly, continued monitoring studies should be synchronized with water level controls at the Shire Barrage to mitigate negative downstream impacts. The decline in maximum water depth from 7.0 meters in 1993 to 5.6 meters in 2017, accompanied by changes in shoreline configuration, caused by increased catchment sedimentation. Thus, soil and agriculture conservation, forestry and hydrology studies are critical for sustenance of the Lake Malombe ecosystem. Effective management should be

holistic taking a broader multidisciplinary approach involving all concerned. There is need for some more serious engagement by a cross-section of scientists to assist in resolving the challenges and dilemma that Lake Malombe poses to Malawian society. A mix of fisheries and aquaculture innovations could uplift fish production to more than 6,000 tons annually and serve as test case for application of a series of techniques to similar water bodies. We advocate for the consideration of "Pen Culture" in efforts in restoration of fisheries.

Keywords: Lake Malombe, Ecosystem-based approach, Alien snail, Fish Catch Decline, Benthic Fauna & Flora, Pen Fish Culture, Bio-economic Analysis.

INTRODUCTION

Lake Malombe is located between 14^{o}30'-14^{o}45'S and 35^{o}12'- 35^{o}20E', forming an impoundment which is an outflow of Lake Malawi through the Upper Shire River (Figure 1). The lake is 30km long and about 15km wide. During 2017, the lake covered a total surface area of 314 Km^2 with a maximum depth estimated at 5.6 m and an average of 3-4 meters. It is the third highest source of fish for Malawi, however, since the 1980s major declines have been observed prompting government to institute a co-management regime. In 2003, a conference was held to discuss the possibility of restoring of the "Chambo" fishery (Banda *et al.* 2003). Recommendations from these studies were never implemented and fish catches have continued the downward spiral from a high of over 12,000tones in 1984/5 to less than 4,000 tons in 2017.

The fisheries of the lake are multi-species and multi-gear in nature which commenced being exploited on a commercial scale in the 1960s after the eradication of a large crocodile population (Tweddle 1996). Currently, over 3,964 fishers consisting of 12% fishing gear owners and 88% Crew members who are directly employed in the fishery. Although fisheries are impacted by illegal and unregulated fishing and physico-chemical parameters, the impact of bathymetric factors is little understood. Eccles (1974) reported on the bathymetric factors of Lake Malawi and he was the first to observe a warming effect in the deep zones, forming a thermocline; recently, this has been accentuated by climate change (Msiska *et al.*, 2017). Globally, fisheries have undergone major declines due to unregulated and illegal fishing and Climate Change (Fontana); the latter is largely reflected in the water chemistry.

Through the FAO Project entitled "Increasing resilience to climate change in the fishery sector of southern Lake Malawi and Lake Malombe" baseline studies were conducted on Lake Malombe to determine physical, biological and chemical factors influencing the behavior of Lake Malombe. While many past studies concentrated on fisheries activities (Weyl et al., 2002), physical factors influencing the hydrographic dynamics, benthic and limnology aspects were generally neglected or monitored at different times, lacking synchronization. This project allowed for studies in the various disciplines to be conducted simultaneously giving a more integrated synthesis of the lake. For more than 10 years, a fisheries co-management system was implemented on Lake Malombe, however, its success is being seriously debated as there has been no visible impact on fish stocks which continue to decline, therefore the need for better management approaches of Lake Malombe still exists. For many years, it has been observed that resilience of Lake Malombe has been highly comprised and veered off from its natural state; application of the DPSR and Tobit models show that it has been subjected to more complex driver, pressure, state, impact and response indicators (Kosum et al. 2021). The desire to find a solution has occupied policy makers and managers alike and therefore, a synthesis of the current state of affairs is appropriate.

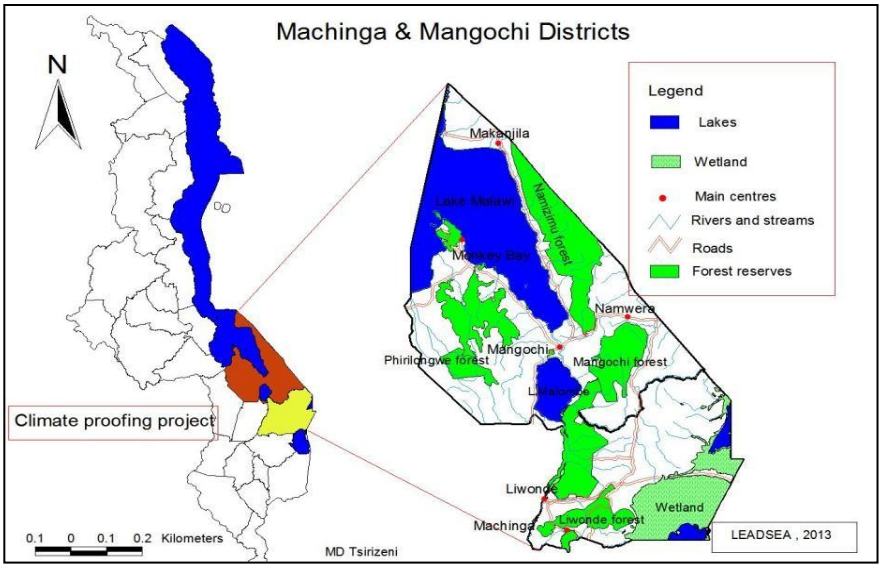

Figure 1: Location of Lake Malombe

OBJECTIVE

Following the general fish catch declines and especially the pre-eminent premium fish like *Oreochromis (Nyasalapia)* species in Malawian waters, this study is aimed:

> *"To demonstrate ecosystem changes in Lake Malombe of Malawi that have contributed to fisheries declines causing disruptions in the socio-economic activities in the area."*

MATERIALS AND METHODS

Limnology

Water samples for physico-chemical parameters for analysis were collected separately from different depths of 0.0 m, 1.5m, 2m, 2.5m, 3m and 3.5m using a Standard grey PVC (RAL 7011) 5L niskin bottle with double sided stopper. A Sea-Bird SBE-19 profiler CTD was cast at each station to maximum depth to collect electronic data and provide *in situ* depth profiles of temperature, dissolved oxygen, oxygen saturation, pH, specific conductivity, chlorophyll fluorescence and salinity. The CTD was connected to a computer using SBE Seasoft V2 with several stand-alone programs including SeatermV2 programs for status, data acquisition setup, data retrieval and diagnostics. The SBE Data Processing program was used to convert, edit, process, and plot data. The HEX file data retrieved from CTD data logger was exported to Windows Microsoft EXCEL for further analysis.

A 30 cm diameter black and white 30 cm Secchi disk was used to determine an average transparency of the lake water in all the sampled stations where CTD was cast.

In the laboratory, the water samples for nutrient determination were immediately filtered through a 47 mm diameter GF/F Whatman filter using air pump vacuum filtration process. The filters were then put in 10ml brown translucent bottle with a mixture of acetone and methanol to extract chlorophyll "a" (Stainton *et al.* 1977). Chlorophyll "an" analysis and absorbance readings were taken from a Turner Designs 10-000 R fluorometer after addition of 2 drops of 2M HCl. The concentration of phosphorus was determined by reaction with a composite reagent of molybdate, ascorbic and antimony using a Jenway 632621 visible Spectrophotometer with a 1cm cuvette following the APHA procedure.

Atomic absorption spectrometer (AAS Buck Scientific, model 200A) was used to determine the concentration of the heavy metal. Samples were preserved according to standard methods as recommended by APHA (1998). The water samples were analysed for major ions within a week of sampling. The results were then compared with standards set by the World Health Organization (Adebayo 2017).

Samples for zooplankton studies were collected using a using a 30 cm mouth diameter Nitex plankon net with 80µm mesh zooplankton net, connected to a 50ml bottle at the base was casted to a required depth and hualed vertically. Water samples (50ml) for zooplankton were immediately transferred into 100ml polypropylene bottles soon after collection and fixed in 70% ethanol concentration before taken to Senga Bay Fisheries Research laboratory for counting.

Five replicates of known volume (5ml) of sub sample of zooplankton water sample was collected to obtain a maximum volume of 25ml (roughly 0.1% of sample). Zooplankton counting was done under a dissecting microscope with magnification ranging between 250 to 400X on a Ward counting wheel. All individuals on the counting wheel were enumerated and the total number of a species in the sample was then calculated using known relationships.

Data Analysis

Data was analyzed using Windows Microsoft Excel 2013. Most of the data were presented in tables and graphs collected to compare the seasons. Some data were presented in form of averages, ranges and percentages. Correlation coefficient (r) was used to relate Secchi depth and Chlorophyll "a" value for the sampling point of the lake.

$$r = \sum(X - \bar{X})(Y - \bar{Y}) / \sqrt{\sum(X - \bar{X})^2} \sqrt{\sum(Y - \bar{Y})^2}$$

Where X and Y are sample means

Shannon diversity Index (H') was used to calculate zooplankton diversity.

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

In the Shannon index, P is the proportion (n/N) of individuals of one species found (n) divided by the total number of individuals found (N), ln is the natural log, Σ is the sum of the calculations, and S is species richness (Shannon, 1949).

Limitations of the Study

The study targeted three seasons (Cool Dry Season: May-August, Hot Dry Season: SeptemberDecember and Rainy season) however rainy season was not included due to limited funding. The study did not identify phytoplankton species of Lake Malombe due to inadequate resources; instead, Chlorophyll “a” was used as a proxy indicator for phytoplankton biomass.

ECOLOGICAL ZONES OF LAKE MALOMBE

Since Lake Malombe is located between Lake Malawi and Middle Shire, it displays both riverine and lacustrine characteristics derived from its connection through Upper Shire to Lake Malawi for a stretch of 13 km, however the Upper, Middle and Lower Shire display riverine conditions.

The Benthic Zone

Materials and Methods:

Bathymetry:

The lake was surveyed for reference points that were established using an RTK GPS using two controls (BMA and BMB) which were fixed near the lake. The rest of the survey was conducted from Mangochi (MARM 3) to Mwalija Fishing Camp at Chawala. Echo soundings were done using a raft, boat and an eco-sounder and RTK GPS. The Eco-sounder was mounted directly below the GPS antenna alongside the survey boat. Horizontal positions obtained in the field were imported onto Excel spread sheet. The Surfer software was used to generate a 3D model for the floor which facilitate to calculate volume of water. The Garmin Etrex 10 GPS was used to locate and locate and record sampling points (Figure 2 & 3).

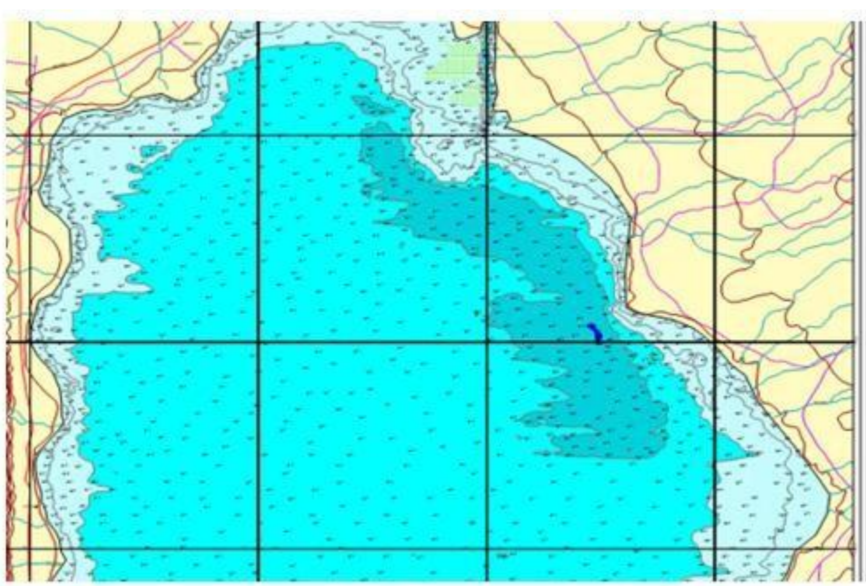

Figure 2: Depth measurements of Lake Malombe showing deep section on the eastern portion.

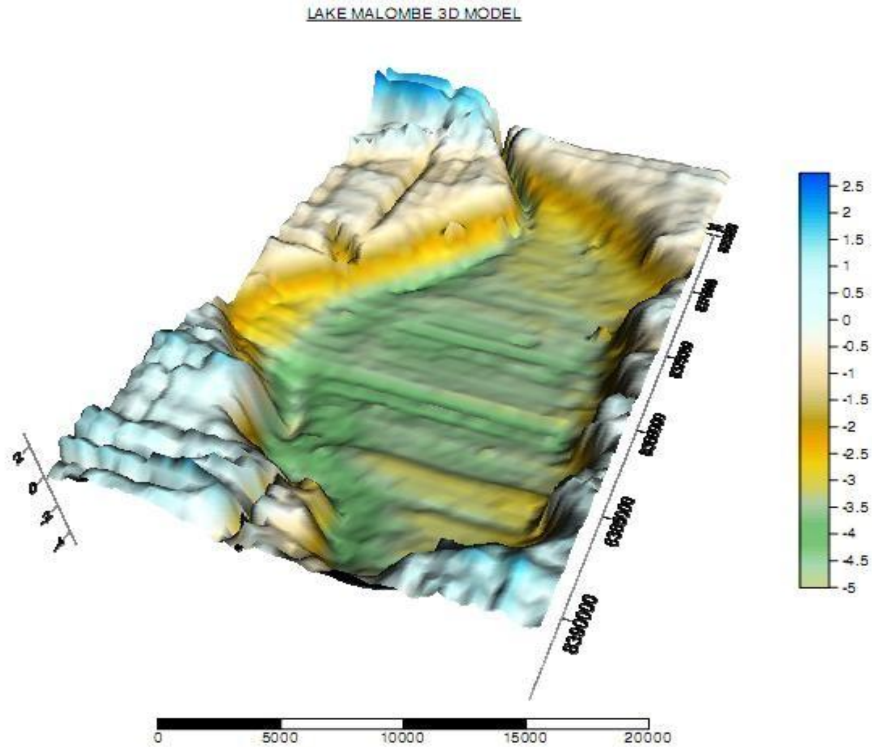

Figure 3: A 3D model of Lake Malombe showing entry and exit points of Upper and Middle Shire (Msiska *et al.*,2021).

Benthic Fauna and Flora

Studies conducted on Lake Malombe in 2017 indicate that the benthic zone is biologically as complex as any other zones of the Lake. It is comprised of a rich source of zoo benthic organisms in the form of bacteria (anaerobic and aerobic), snails and insect life forms that go largely underutilized now (see Table 1 & 2). For the first time, this web compartment has been recognized as an important component of the ecosystem contributing to the energy balance of the Lake. The most striking feature was the dominance of snails in the macro-fauna measuring 177.5, 34.7, 4.3 and 0.1 m^2 mean densities of *Melanoides, Bellamya, Bulinus* and *Lanistes* individuals, respectively (Kamtambe *et al.* 2019). This is a much higher order of magnitude compared to Lake Malawi and Upper Shire. Similarly, bacteria were higher in Lake Malombe (1.4 x 10^7 CFU/g) compared to Lake Malawi (8.9 x 10^3 CFU/g). Therefore, the rate of reaction mechanisms behind the biological processes is much higher in Lake Malombe. This gives room for ecologists to compute models which can lead to informed predictions regarding energy flows through the system according to recommendations advanced by Christensen and Pauly (1993). From a fisheries management view, it is evident that benthic feeders are unavailable or less efficient in utilizing these food resources. Conversely, overfishing might have exhausted fish species that could efficiently convert this food niche. Therefore, if these fish species were identified and reintroduced, fish scavengers and bottom feeders could make the functioning of the system more efficient. Previous studies which were concerned only with fishing pressure on tilapias missed the point that this ecosystem should be treated holistically. The question that needs to be posed now is “Could pen culture using benthivorous species be a suitable proposition for introduction into Lake Malombe?”

RESULTS

The Pelagic System

Physio-chemical Features:

The chemical characteristics of Lake Malombe indicate a relatively high pH regime of 7.7110.19, high conductivity of 255.81-290 µS/cm, soluble reactive phosphorus concentration of 0.01-0.0736 µmolL^{-1} and dissolved Oxygen of 5.67-9.06 mgL^{-1}, low calcium (15mgL^{-1} 19.16mgL^{-1}) and low magnesium (9.09mgL^{-1} to 11.03mgL^{-1}) concentrations were observed. According to Chlorophyll *a* values, Secchi disc depth and phosphorus, Lake Malombe can be classified as eutrophic. It is exposed to strong winds (0.7 and 5.5 ms^{-1}) of northerly origin locally called "Mpoto" as well as strong southeasterly winds locally known as "Mwera". The resulting wind system causes thorough mixing and recycling of nutrients. The water temperature ranges of 22.7-32.5^{0}C and is about 3^{0}C above Lake Malawi.

Table 1: Seasonal variations in Bio-physiochemical characteristics of Lake Malombe

Sampling Site	Season	Secchi depth(m)	Chl-a µg/L	T (°C)	pH	DO (mg/L)	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	CO_3^{2-}	HCO_3^-	SO_4^{2-}	Nitrite	TDS mg/L
A	CDS	1.5	2.10	24	9.07	6.32	17.38	8.64	19.8	6.3	52.95	9.12	126.82	1.67	0.53	131.00
	HDS	1.0	3.15	27.94	8.19	7.82	16.41	9.086	22.02	7.187	39.44	11.52	151.65	ND	0.32	
B	CDS	1.5	3.14	23.5	8.85	6.22	19.19	9.31	19.99	6.42	32.98	10.5	123.95	2.62	0.75	137.00
	HDS	0.6	9.37	27.49	8.02	7.88	18.96	9.518	24.06	7.645	43.13	11.7	150.98	ND	0.39	
C	CDS	2.5	2.10	24.5	9.45	6.2	17.36	8.57	18.91	5.84	18.77	11.7	122.37	1.79	0.91	139.00
	HDS	0.8	8.92	27.64	8.04	7.77	18.32	10.66	25.02	8.144	40.01	23.1	128.41	ND	0.35	
D	CDS	1.8	3.61	23	8.64	6.07	15.39	7.53	16.34	5.02	33.19	5.22	97.60	0.36	0.79	134.00
	HDS	0.6	6.20	27.46	8.36	7.83	17.8	10.55	24.87	7.96	44.27	26.58	137.74	ND	0.46	
E	CDS	1.4	4.54	23	8.96	6.52	9.27	4.78	10.87	3.21	28.93	9.84	138.59	2.02	0.97	139.00
	HDS	0.5	6.56	27.75	8.39	7.82	17.75	10.63	24.9	8.05	50.52	15.78	160.55	ND	0.35	
F	CDS	1.8	2.62	23.1	9.5	6.14	18.15	9.6	19.94	6.27	34.97	11.22	148.35	1.07	0.99	138.00
	HDS	0.7	8.75	27.94	8.18	7.81	17.57	10.36	24.71	8	41.71	21.18	120.41	ND	0.35	
G	CDS	1.7	3.74	23.4	9.23	6.4	18.59	9.7	19.78	6.23	24.69	11.46	150.06	0.60	0.93	137.00
	HDS	1.5	5.25	27.13	8.02	7.92	16.93	9.526	22.48	7.57	42.07	21.06	114.31	ND	0.27	
H	CDS	1.9	3.92	24.3	9.19	6.29	18.43	10.14	20.05	6.44	17.15	14.04	148.66	0.60	0.93	134.00
	HDS	0.5	11.13	27.37	7.72	7.89	17.79	10.37	24.86	8.211	42.49	18.42	123.22	ND	0.27	
I	CDS	1.4	3.11	24	8.94	6.14	19.06	9.63	19.52	6.12	23.11	8.82	150.55	1.43	0.73	135.00
	HDS	1.5	9.18	27.6	8.15	7.72	18.71	10.73	24.72	8.25	51.87	21.66	147.47	ND	0.33	
J	CDS	1.1	4.27	23.3	9.97	5.99	17.93	10.38	19.91	6.31	21.62	8.76	154.15	1.19	1.68	138.00
	HDS	0.3	13.36	28.15	8.21	7.21	19.16	10.77	25.82	8.59	41.32	23.82	126.88	ND	0.38	
K	CDS	1.5	4.51	25	9.31	6.39	18.43	10.76	20.23	6.33	17.79	7.86	90.04	0.60	1.02	139.00
	HDS	0.4	9.46	28.4	8.36	7.73	17.79	11.03	25.42	8.08	41.36	20.94	125.78	ND	0.34	
L	CDS	1.5	3.29	23.2	9.43	55.78	18.01	9.84	19.19	6.52	19.84	9.42	136.76	0.83	0.73	140.00
	HDS	1.0	4.11	28.035	8.12	7.8	15.49	9.529	23.28	7.52	38.94	22.11	111.66	ND	0.30	
M	CDS	2.0	2.47	23	8.98	5.98	18.23	10.28	19.92	6.23	21.55	10.02	127.61	0.95	0.82	140.00
	HDS	0.7	7.51	29.14	8.66	7.65	18.2	10.36	24.18	7.95	53.75	21.78	118.04	ND	0.34	

CDS: Cool Dry Season, HDS: Hot Dry Season, Chl-a: Chlorophyll 'a', T: Temperature, DO: Dissolved Oxygen, ND: Not detected, units for all major ions are mgL^{-1}.

The main ions analyzed included Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, CO_3^{2-}, HCO_3^-, and NO_2^- whose values are summarized in Table 2. During the cool dry season, calcium concentrations ranged from 9.27 mgL^{-1} to 19.19 mgL^{-1}; Mg^{2+} from 4.78mgL^{-1} to 10.76mgL^{-1}; Na^+ values ranged from 10.87 mgL^{-1} to 20.23 mgL^{-1} and K^+ from 3.21mgL^{-1} to 6.52mgL^{-1}, The anion Cl^- registered concentrations were 17.15mgL^{-1}-52.95mgL^{-1}, CO_3^{2-} were 5.22mgL^{-1}-14.04mgL^{-1}, HCO_3^- from 90mgL^{-1}154.147mgL^{-1}, NO_2^- values were 0.53mg/L to 1.67mg/L and SO_4^{2-} had a range of 0.31mg/L to

2.62mg/L and NO_2^- varied from 0.53mgL^{-1} to 1.67mgL^{-1}. Empirically, the buffering effect by bicarbonate and carbonate ions is likely to have a major influence in keeping pH above 7 according to chemical stoichemistry relationships elucidated by Boyd (1982). On the other hand, some nitrite and sulphate (sulphide) values might be responsible for pockets of fish toxicity in this water body causing local fish migrations, especially in low oxygen regimes. Anecdotal reports have observed fish migrations between lake Malawi and Lake Malombe.

During the Hot dry season, Calcium values were 15mgL^{-1} to 19.16mgL^{-1}, Mg^{2+} ranged from 9.09 mgL^{-1} to 11.03 mgL^{-1}, Na^{2+} recorded values of 22.02 mgL^{-1} to 25.82, K^+ values were 7.19mgL^{-1} to 8.59 mgL^{-1}. Records for Cl^- were 38.94 mgL^{-1} to 53.75 mgL^{-1}, CO_3^{2-} was estimated at 11.52mgL^{-1} to 26.58 mgL^{-1}, HCO_3^- recorded 111.66mgL^{-1} to 160.55mgL^{-1}, and NO_2^- values ranged from 0.27 mgL^{-1} to 0.46 mgL^{-1}. Among the major anions, bicarbonates were the most dominant followed by Chlorides, whereas Na^+ dominated cations followed by Ca^{2+}. The effects of climate change are evident between seasons at the chemical level; there was no data to trace chemically what the situation might have been 30 years ago. Lake Malombe can be classified as Eutrophic according to the characteristics shown in the Table 2 below. While it is not known how the system has evolved over time, it seems obvious that climate change is one of the main drivers.

Primary Production:

Table 2: Trophic classification of Lake Malombe compared to other lakes OECD model, Istvanovics, 2009).

Trophic category	Mean total P (µgl^{-1})	Mean (µg.ch-al^{-1})	Max. (µg.ch-al^{-1})	Mean, Secchi depth, meters
Oligotrophic	<10	<2.5	<8	>6
Mesotrophic	10-35	2.5-8	8-25	6-3
Eutrophic	>35	>8	>5	<3
Lake Malombe	**0.31-2.17 mol.L^{-1}(SRP)**	**3.34 -7.92**	**13.36**	**1.1-2.5**

Phytoplankton biomass estimated as chlorophyll 'a' varied greatly with time and season, indicating differences between the cool dry season and hot dry season. Values were substantially different between the cool dry season (3.34µgL^{-1}) and the hot dry season (7.92µgL^{-1}), and a strong Pearson correlation with Secchi depth ($R = -0.778$; $R^2 = 0.6057$). As Chlorophyll "a" concentration increased, Secchi depth values decreased. The observed difference in phytoplanktonic biomass between the two seasons could be attributed to several factors, including availability of nutrients, concentration effects being further influenced by relatively high temperature. The combined effect is increased primary production leading to high Chlorophyll 'a' value. The maximum Chlorophyll 'a' concentration of 13.36 µgL^{-1} observed in Lake Malombe showed higher productivity compared to values recorded in Lake Malawi, the latter fluctuates between oligotrophic and mesotrophic with Secchi depth values of 6.1m and Chlorophyll 'a' of 0.8µgL^{-1} (Macuaine *et al*. 2016). Lake Malombe productivity alternates between mesotrophic in cool dry season and eutrophic in hot dry season. Other studies have shown that Chlorophyll 'a' concentration in Lake Malawi rarely exceeds 1µgL^{-1} while Secchi depth is between 5.5-6.5 meters (Bootsma and Hecky 2003) (see Table 3).

Table 3: Comparative limnology parameters between Lake Malombe and Lake Malawi.

Parameter	Lake Malombe	Lake Malawi (source: Bootsma and Hecky 2003)
pH	7.72-10.16 (9.97)	8.5-8.6
Total Alkalinity, mg/l	102.92-186.38	60.6-85.6
Total Hardness, mg/l	14.1-30.0	11.8-129.0
Calcium, mg/l	9.3-19.2	41.2-49.0
Magnesium, mg/l	4.8-11.0	19.6-36.6
Conductivity µS/l	255.8-290.0	210-220
Total Dissolved Solids mg/l	131.0-140.0	134.8-140.0
Secchi depth, meters	0.3-2.5	5.7-6.10
Chlorophyll "a", µg/l	2.1-13.36	0.80-0.91 (Macuiane *et al* 2016)
Surface water temperature ^{0}C	22.7-32.5	24-29 Stauffer and Madsen, 2012)

Secondary Production: Zooplankton:

The secondary food chain of Lake Malombe is generally represented by zooplankton species which share close affinity to those of Lake Malawi (Figure 3).

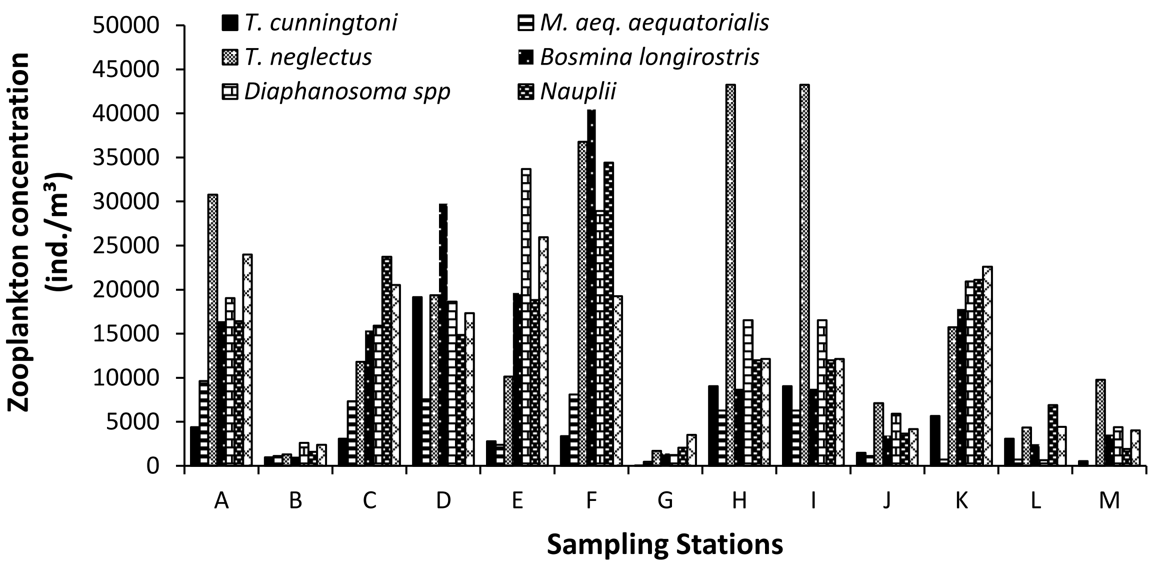

Figure 3: Zooplankton density of Lake Malombe by station during the Cool Dry Season.

During the cool dry season which lasts from May to August, zooplankton concentrations vary greatly between 13 sampling stations, the highest being 43, 544.79 ind/m^3 and lowest was 35, 386.63 ind/m^3. The species mix was dominated by Cladoceran and *Bosmina longirostris* at seven stations. The rest of the 4 stations were dominated by *Thermocylops neglecctus.* During the hot dry season which lasts from August to December, high populations of zooplankton of 171,332.77 ind/m^3 on the east of the lake followed by the mid-south station which recorded a density of 126, 637.37 ind/m^3. The least concentration was observed midway of the lake where a density of 10, 399. 07 in/m^3 was recorded.

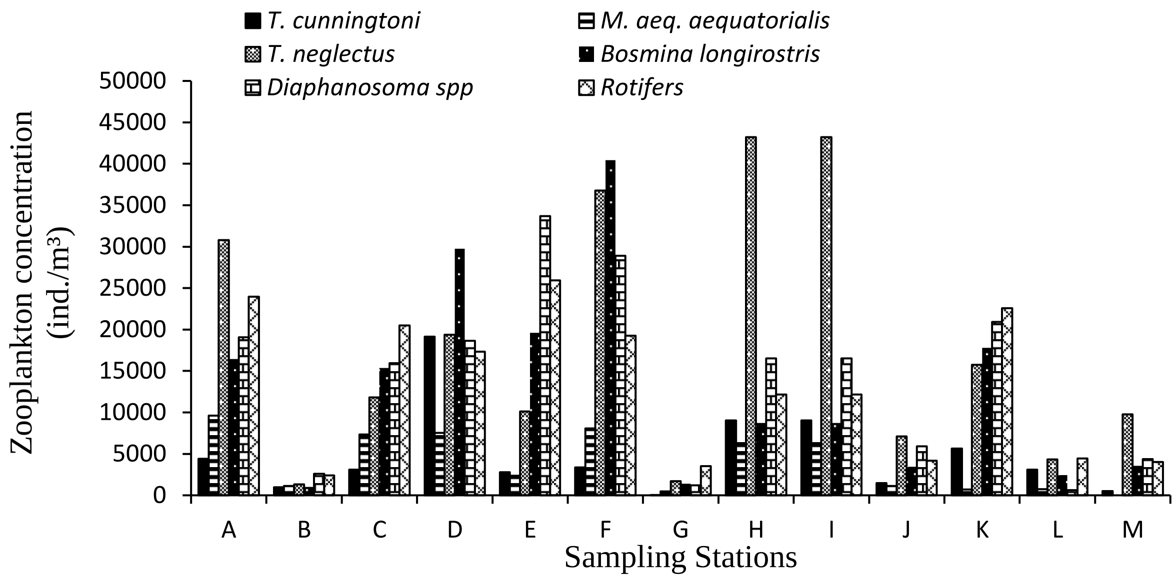

Figure 4: Zooplankton species density of Lake Malombe by station in the Hot Dry Season.

From the zooplankton species mix, it is apparent that the lake provides ample natural food for fry ad juvenile for most of the fish species and thus, it is an ideal nursery ground. Therefore, the introduction of hatchery bred phytoplankton feeders would be ideal. A good example of such tilapia fishery thriving under such a eutrophic ecosystem is to be found in Laguna de Bay in the Philippines (Beveridge 1984).

STATUS OF FISHERIES

Methods

Data on fisheries has since 1976 consistently collected using the CASS (Catch Assessment Statistics), where specific beaches are visited 4 days in month to collect fish catches from fishermen including the type of gears employed. Fish catches are sampled and weighed and recorded for further processing at Monkey Bay Fisheries Research Station in Mangochi. However, since 1992, the Malawi Traditional Fisheries method has been operational after observing biases where exaggeration was observed to be inherent when raising catch and effort data from small beaches. Raising factors on gear-based data are converted into total catches per given area, segregated by family, genus and species.

Results

Since records started to be collected, the fisheries of Lake Malombe have experienced the greatest decline in the past three decades from about 12, 000 tons in 1981-91 to 3, 820 tons in 2016 (Figure 5). This prompted a series of studies on the fishery to understand the dynamics behind such reductions and their impacts. First to experience the decline were tilapias especially those belonging to the "Chambo" (*Oreochromis Nyasalapia*) family. After observing that a top-down management system was ineffective, having created much conflict between government enforcement officials and fishers, it was decided to introduce a new comanagement system, which operated for more than 10 years from 1993, however, this too did not yield desired results. The fisheries of Lake Malombe have attracted seven fishing gear types from Kandwindwi, Nkhacha seine, Gillnet Fish trap, Handline, Mosquito seine nets and

Longline, which are very effective and distractive in that juvenile fish were also captured. Due to the unprecedented exploitation rate that Lake Malombe has undergone, there has been a reduction of fish taxa in Nkhacha fishery from 56 in 2004 (Weyl *et al,* 2004) to the current 28, the majority of the catch were made of four cichlids (*Nyassachromis argrosoma (31.8%)*, *Otopharynx argyrosoma* stripe (17.6%), *Lethrinops lethrinus* (6.5%) and *Copadichromis (*4.8%) and one cyprinid *Engraulicypris sardella* (16.3%), making up 75% of the total. The latter fish species has only recently made intrusion from Lake Malawi into Lake Malombe and it was recorded for the first time in this study. What has prevented this fish species from entering Lake Malombe in the past is a puzzle to be investigated, and being a fast-growing pelagic species, this opens the lure of it stocking large dams. Apart from the impact of unselective gears, the Lake experienced decreasing water levels due to complex interaction of siltation and climate change. Sedimentation in the catchment area is high, estimated at 30 tons of soil per hectare per annum. Temperature increased by 0.9^{0}C annually from 1960 to 2006 (FAO & GEF 2017). Since then, hot days have increased by 30.5 per year while hot nights have risen by 41 days according to the General Circulation Model by the Intergovernmental Panel on Climate Change (IPCC). The opposing scenarios of ENSO where rainfall is influenced by the Eastern Equatorial Africa receives above average rainfall during EL Nino while Southeastern Africa experiences below average rainfall. These conditions make Lake Malombe a deserving “hotspot” for studying climate change effects on water resources and fisheries.

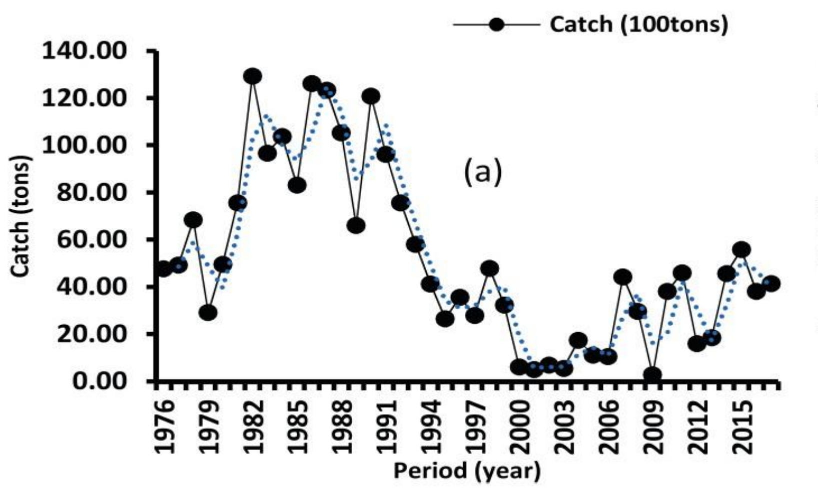

Figure 5: Fish Catches from Lake Malombe, 1976-2015

As recommended elsewhere, once you are fishing below **spawning biomass**, fishing has to stop until recovery has been attained.

TROPHIC CHANGES

Trophic relationships in Lake Malombe need to be studied using modern technology so that any remediation of the its environment should be based on a full understanding of how the system functions. Furthermore, fish species niches should be better articulated to take advantage of over- subscribed, especially at the primary production level. Among the snail eating fish species, *Trematocranus placodon* has been touted to be the most efficient snail cracker (Jere *et al.* 2016). Of course, there will be other species which could be considered even if they might not be as efficient; *Clarias gariepinus* might also qualify. Both primary and secondary trophic levels show that there are enough food resources to support tilapias provided they are protected from early capture and "pen culture" appear to provide such an environment. However, this will require ownership rights to be established in a new regulatory framework.

CLIMATE CHANGE AND CARBON UNITS

When investigating and considering national carbon credits, it is obvious that the aquatic system provides an ideal medium for capturing carbon dioxide; what would be ideal is to enhance the production process that enhances human nutrition through fish production. A recent study by Ngochera and Bootsma (2020) have elucidated further on this by showing that Lake Malawi is a carbon sink. Given the evidence provided by this study, Lake Malombe is an even better carbon sink and should not be sidestepped when considering computations of carbon units for Malawi. This means that aquatic scientists should work together with climate experts to optimize the potential of both these lakes.

Table 4: Estimates of Carbon fixing in the Pelagic Zone in Lake Malombe.

	Percent Carbon	Area in m^2	Concentration mg/L	% Carbon	Carbon (fixed per m^2)
H_2CO_3	N.A.	3.1×10^7	2.1-13.4 μg/L	1%	0.7-8.8g/m^2
HCO_3^-	0.200	3.1×10^7	2.1-13.4 μg/L	92%	65.1-872.3g/m^2
CO_{32-}	0.196	3.1×10^7	2.1-13.4 μg/L	7%	4.95-66.40 g/m^2

$$CO_2 + 2H_2O = H_2CO_3 + 2HO_3^+ \quad (1)$$

$$H_2CO_3 = H_+ + HCO_{3-} \qquad K\,a_1 = 10_{-6.35} \quad (2)$$

$$HCO_{3-} = H_+ + CO_{32-} \qquad Ka_2 = 10_{-10.33} \quad (3)$$

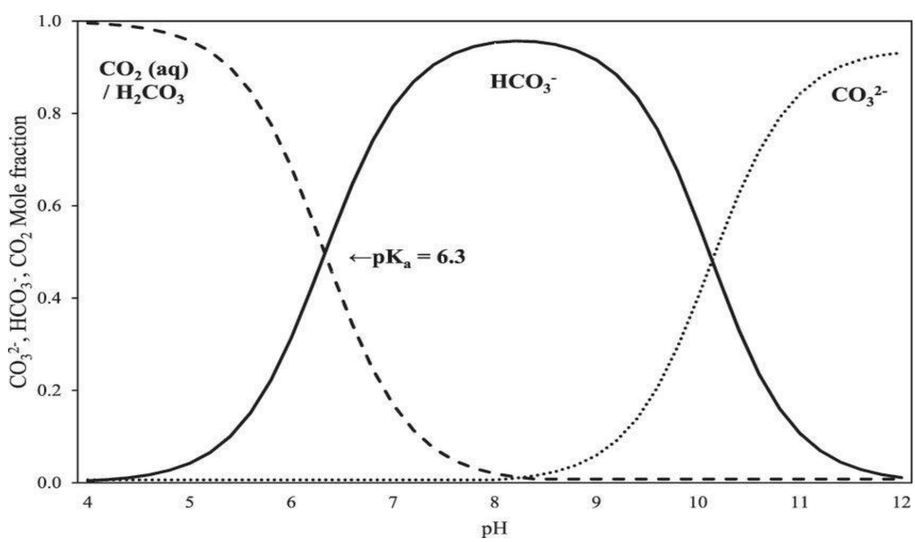

Figure 6: Agreement between measured bicarbonates, carbonates and empirical trends.

The values of pH, bicarbonates and carbonates obtained from measurements in Lake Malombe tally with the cycle shown in Figure 6.

FISHERIES BIOECONOMICS

Given the dynamic nature of the fishery, the surplus model of Verhust Schaefer did not offer a solution to sustainably utilization of both the tilapia and *Haplochromine c*ichlid fisheries. Instead, this model was used along with the biological growth model to develop a bioeconomic models more befitting the nature of the fishery (Singini *et al* 2012). Some of the results from these studies are shown in the Table 4 below:

Table 5: Estimates of MSY, MEY and OAY, costs, revenues and economic rents.

Variable	MSY	MEY	OAY
Catch (tons)	2326. 02	1464. 08	1217
Effort (pulls)	38364	37490	276730
Cost (million MK)	62.112	13.493	
Revenue (million MK)	62.827	15.666	
Rent	0.715	2.172	

Where MSY is maximum sustainable yield; MEY is maximum economic yield and OAY is Open Access Yield.

While these reference points were derived in 2012, results of the 2016 landed catches were 3820 tons, just above predicted MSY levels but certainly pointing to a downward trend. Hence the hybrid model developed by Singini (*et al.* 2012) provided an accurate estimate of the scenario. Being an open access fishery means that stability cannot be reached and need not be the aim of management. The fishery of Lake Malombe will continue to provide challenges for theory and practice of conventional fisheries management, neither will ecosystem management provide the necessary respite. Meanwhile, affected communities still wait for solutions to their lost livelihoods. Their willingness to participate in any intervention is borne by the dire need for redress is not doubted but practical solutions to their livelihood suggest that capture fisheries need to be augmented by aquaculture.

The forecasting techniques advanced by Makwinja *et al*. (2021) have shown that even with the best management techniques, fish catches between 2014 to 2032 would only reach a maximum of 5, 620 tons and are likely to fluctuate between 3000 -4000 tones. On the other hand, the same ecosystem achieved more than 12, 000 tons in 1970-80s showing that the potential exists to upgrade fish production. Management regimes which have been employed do not optimise production and combining capture and culture-based fisheries is the best route to increasing fish production. Both Singini *et al.* (2012) and Makwinja *et al*. (2021) reached the same magnitude of prediction; these studies were 10 years apart.

DILEMMA FACING FISHERIES MANAGEMENT

When both local governing agencies and central government interventions fail, some introspection needs to be done jointly so that solutions can be discussed and agreed upon. Going forward, roles must be spelled out, and good scientific evidence should lead to management decisions regarding policy and regulatory procedures. Many organizations seem to have shunned Lake Malombe but given the current extremities of climate change, this water body offers opportunities for enhanced fish production and computation of carbon units, showing that the benefits go into nutrition. However, bringing together experts in soil, forestry, water, fisheries and agriculture conservation could be key to bringing hope to the fishers. Going forward, it is advisable to combine capture fisheries management techniques with culture based fisheries with due attention given to the selection of appropriate species. Several candidate fish species have been tested in ponds to utilize plankton (*Oreochromis karongae* and *Bathyclarias loweae*) and snails (*Trematocramus placodon)* and pond breeding studies have been conducted at research stations at LUANAR, Domasi and among fish farmers throughout Malawi (Msiska OV 1999, Jere *et al* 2020 and Msiska *et al* 1991), attesting to their suitability.

NEED TO REVISIT ECOSYSTEM-BASED MANAGEMENT

While the fisher-folk fishing expectations have evolved and matured into accepting innovations that would enhance their livelihoods, previously, they had placed undue danger on the lives of fisheries extension staff, hence the introduction of a co-management regime whose results have not born meaningful results. The mistrust between the community and government ran very deep, therefore, community mobilization has not been fully rolled out. The next management might want to try a rights-based approach which could suit introduction of a "Pen Culture". A broadbased ecosystem management needs to be supported by strong political will, where a ban on fishing should be instituted first for a specific period, otherwise, any fishing activities will nullify piloting efforts to resuscitate the fish resource. One of the best success studies of Pen Culture has been recorded in Philippines (Beveridge 1984).

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