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Lake Malawi/Niassa/Nyasa basin: Status, challenges, and research needs

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ABSTRACT

Lake Malawi/Niassa/Nyasa (LMNN) is one of the most important and third-largest African Great Lakes. It has the largest number of freshwater fish species in the world, most of which are endemic. Current estimates put the number of fish species in the range of 800–1000. The riparian countries of Malawi, Mozambique and Tanzania enjoy enormous benefits that accrue from the ecosystem services that the lake provides. However, LMNN is experiencing severe adverse impacts resulting from anthropogenic and climatic stressors, leading to increased sediment and nutrient loading. This observation motivated this study to identify existing research gaps to enhance the lake's sustainable management. Specifically, the assessment focused on three key issues identified and prioritised by the LMNN Basin Fisheries and Aquaculture Network (LMNNBFAN), namely: fishery health, invasive species, and climate change. Data collection involved stakeholder consultations, field surveys, and desk reviews. Recommendations from study findings, that would create a conducive environment for the sustainable management of the lake, have been grouped into four main categories: research needs, infrastructure development, human capacity building and funding.

1. Introduction

Lake Malawi/Niassa /Nyasa (LMNN) is the third largest lake by area in the African Great Lakes System. It is shared by three countries: Malawi, Mozambique, and Tanzania (Fig. 1). The lake is called Lake Malawi in Malawi, Lake Nyasa in Tanzania and Lake Niassa in Mozambique. The catchment area of the lake is 97,740 km^2, of which 64,373 km^2 lies in Malawi, 26,600 km^2 in Tanzania, and 6,768 km^2 in Mozambique (Bootsma and Hecky, 1999). The lake is estimated to be over 5 million years old (Ivory et al., 2016). LMNN is younger than Lake Tanganyika which is between 9 and 12 million years old, but older than Lake Victoria with about 400,000 years (Sturmbauer, et al., 2001) (see Table 1).

The largest tributary of LMNN is the Ruhuhu River in Tanzania, with a catchment area of 14,070 km^2 while the second largest is South Rukuru in Malawi with a catchment area of 12,110 km^2. Other major tributaries include the Bua, Dwangwa, Dwambazi, Lweya, Linthipe, Songwe, Kiwira, Mbaka, Lufilya and North Rukuru. The LMNN is

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Fig. 1. Lake Malawi /Nyasa/Niassa Basin (Source: Bootsma and Jorgensen (2004)).

drained at its southern end by the Shire River, a tributary of the Zambezi River. The Shire River flows approximately 410 km from Mangochi to Ziu Ziu in Mozambique, where it drains into the Zambezi. The annual and seasonal variability of LMNN levels highly affects discharge in the Shire River which requires a firm river flow of >170 $m^3 s^{-1}$ for sufficient operation of the hydropower plants in the lower part of Malawi (Mtilatila et al., 2020; Shela, 2000).

As stated by Chavula (2008), LMNN is important for a number of reasons. In addition to supporting the fishery industry (which is the main source of animal protein for millions of people in the three riparian countries), the lake's outflow is harnessed for hydroelectric power genertation in the middle reach of the Shire River. LMNN is also used as a source of domestic water supply and irrigated agriculture for coastal areas while ships that ply on LMNN are used to ferry passengers and cargo to various destinations. In spite of its basically oligotrophic character, the lake is renowned for its rich biological diversity. It contains the largest number of freshwater fish species in the world, providing habitat to 800–1,000 fish species, most of which are endemic, and dominated by cichlids. And in recognition of its unique biological diversity, in 1984 LMNN was declared a World Heritage Site by UNESCO.

Table 1
Descriptive Summary of Morphometry and Hydrological Data for Lake Malawi/ Nyasa/Niassa (Bootsma and Hecky, 1999).

Characteristic	
Area	29,500 km^2
Depth	700 m; mean 294 m
Maximum length	570 km
Mean width	48 km (but ranges from 25 to 75 km)
Shoreline length	1,500 km
Altitude	471 m
Volume	8,300 km^3
Total catchment	126,500 km^2
Major inflowing rivers	9
Outflow rivers	1
Precipitation over the lake	41 $km^3 yr^{-1}$
Inflow	29 $km^3 yr^{-1}$
Evaporation	54 $km^3 yr^{-1}$
Outflow	12 $km^3 yr^{-1}$
Annual lake level fluctuation	0.4–1.8 m
Residence time	114 y
Flushing rate	750 y
Secchi depth	1–5 m (shallow area); 12–20 m (open water)
pH	7.9–9.1 at surface and 7.8 at 300 m
Depth of oxygenated water	170–220 m

Notwithstanding the above-mentioned positive economic benefits derived from LMNN, it is worth noting that during periods of heavy storms and rainfall, rising lake levels trigger floods that wreak havoc in coastal areas and the Lower Shire Valley (Shela, 2000). Lake levels are, however, being managed through an automated water regulation system at Kamuzu Barrage in Liwonde, Machinga District, Malawi. An increase in water level has some benefits to aquatic organisms through nutrient richness that come along with eroded soils (Bootsma and Hecky, 1999). When lake levels go down and become too low, hydropower generation is greatly affected which in the end impacts the electricity supply in Malawi. Low lake levels also reduce breeding sites of fish species, especially the chambo, native tilapia, which prefers to breed in very shallow areas.

LMNN faces a number of challenges that range from loss of biodiversity, proliferation of invasive species, climate change and variability, and insufficient funds to carry out meaningful research, just to mention a few (Chavula, 2008). These issues have the potential to mask the effort for sustainable fisheries management. A better understanding of these issues and how they impact the fisheries resources of the LMNN catchment is key for the formuation and implementation of streamlined interventions. Without such information, decision and policy makers lack tangible scientific evidence of the current status of the LMNN catchment. It is with this in mind that this paper seeks to highlight the status of LMNN by recognising key issues surrounding the fishery health, invasive species, land use/habitat destruction, and climate change. Research needs that can positively contribute towards the sustainable management of the lake based on the identified key issues have also been discussed.

2. Methods

A three-pronged qualitative approach was adopted for collecting data that were used in writing this paper, namely, stakeholder consultations, field surveys and desk reviews. Details of the three approaches are discussed below:

2.1. Stakeholder consultations

The stakeholders' consultative process involved experts who attended the Entebbe (Uganda) African Centre of Aquatic Research and Education (ACARE) workshop held in November 2019. The workshop led to the establishment of six African Great Lakes Advisory Groups, namely: Lake Malawi/Nyasa/Niassa Basin Fisheries and Aquaculture Network; Lake Edward/Albert Advisory Group; Lake Kivu Advisory Group; Lake Tanganyika Scientific Advisory Group; Lake Turkana Advisory Group and Lake Victoria Advisory Group. In breakout group discussions, stakeholders drawn from the three riparian countries (Tanzania, Malawi and Mozambique) and professionals from other countries, namely: the USA, Canada, and Norway discussed research needs for the LMNN. The workshop further established national committees in the respective riparian countries that would oversee the implementation of various research activities intended to improve the management of the lake and enhance collaboration among the three countries. Later on, more participants were co-opted in the national committees in order to ensure a well-balanced representation and scope of expertise. After the initial meeting at Entebbe, LMNNBFAN members conducted several virtual meetings which further clarified the research agenda "*Strengthening Capacity in Research, Policy and Management Through the Development of a Network of African Great Lakes Basin Stakeholders*." About 34 virtual meetings were arranged which among other things discussed key issues identified during the online field survey (described below).

2.2. Online surveys

LMNNBFAN members of the respective riparian countries conducted field surveys which were facilitated by ACARE. A questionnaire containing 32 questions was administered virtually to seven respondents with afisheries research background. Respondents included LMNNBFAN members, ACARE board of directors and other fisheries experts. The questionnaire asked each respondent to identify and prioritise key issues and generate potential research priorities for their respective LMNN catchment. The questionnaire was also administered to other five ACARE great lakes advisory groups. The other advisory groups were consulted in order to understand and compare issues affecting the African Great Lakes. Five key issues including climate changes, fishery health, biodiversity decline, invasive species, and insufficient skills and knowledge were identified in LMNN. These issues were ranked according to their importance and the top three (fishery health, invasive species and climate change) were prioritisred for the desk study. Ranking was achieved through codes (Blue = First Priority, Red = Second Priority and Yellow = Third Priority). Where the number of respondents tied, a consideration of the priority ranking was applied. The top three for all the great lakes were fishery health, biodiversity decline, land use/habitat destruction.

2.3. The desk reviews

Desk reviews which comprised peer review papers and grey literature were conducted based on the three key issues identified by members of the LMNNBFAN. The study reviewed technical reports and peer-reviewed papers on LMNN fisheries, invasive species and climate change. The grey literature consisted of many documents and reports, key among which were the International Union for Conservation of Nature (IUCN) of 2021; Malawi's Third National Communication to the Conference of the Parties (COP); and 2016 Country Reports for Malawi, Mozambique, and Tanzania for the Building River Dialogues and Governance (BRIDGE) Project.

This paper was written by members of LMNNBFAN through virtual interactions. The first draft of the manuscript was shared on Google Doc and that enabled all co-authors to make their contributions online. The process was spearheaded by the Chairperson of LMNNBFAN with technical support from the Program Manager for the ACARE-African Great Lakes Advisory Groups.

3. Results and discussion

3.1. Results of the survey

A total of seven (7) survey respondents participated and all of them were scientists/researchers. For priority issues, some respondents listed multiple 1st, 2nd and 3rd priorities; in some cases, there was no clear "top 3" ranking. As such, other aspects were considered, particularly the score priority. The survey respondents ranked the top three key issues as (1) Fishery Health, (2) Invasive Species, and (3) Climate Change (Fig. 2). Climate change was selected over land use because it had a score of 1st priority. This section, therefore, discusses the three key issues that will lead to the identification of the key research priorities.

(1) Fisheries Health

Specific issues pertaining to fisheries health are presented in three categories: (a) limnological status, (b) macrophyte and plankton communities, and (c) fisheries status.

(a) Limnological status and land use

According to Bootsma and Jorgensen (2004), LMNN is meromictic, thermally and permanently stratified into three layers: epilimnion (0—100 m), metalimnion (100–220 m) and hypolimnion (220–0700 m). These three layers are separated by differences in water density. The thicknesses of these layers vary with the season and the strength of the wind blowing over the lake (Bootsma and Jorgensen, 2004). It is further affected by heat gain and loss processes, including solar radiation and evaporative cooling. LMNN is an oligotrophic lake with a maximum depth of 700 m which results in vertical variations in water temperature and density that restrict mixing (Bootsma and Jorgensen, 2004). Fig. 3 depicts the variation of temperature, chlorophyll concentration, and dissolved oxygen variations with the depth of the lake. Generally, surface temperature varies throughout the year. The data in Fig. 3 indicate a surface temperature of around 28 degrees, but during the cool, windy season it can down to 23 degrees. Vollmer et al. (2002), reviewed long-term changes in temperature in LMNN for over 60 years where an increase of about 0.18 degrees was noted in the deeper part of LMNN while in the shallow waters, the temperature increased by 0.7 degrees. The chlorophyll *a* concentration profile shows a depth of chlorophyll maximum (DCM) at around 35 to 40 m while anoxic waters (no dissolved oxygen) are observed from 180 m and below.

Secchi disk depths of 11–20 m and light extinction coefficients for photosynthetically active radiation (PAR) of 0.07 to 0.13 m were reported by Patterson and Kachinjika (1995), Bootsma and Hecky (1999)

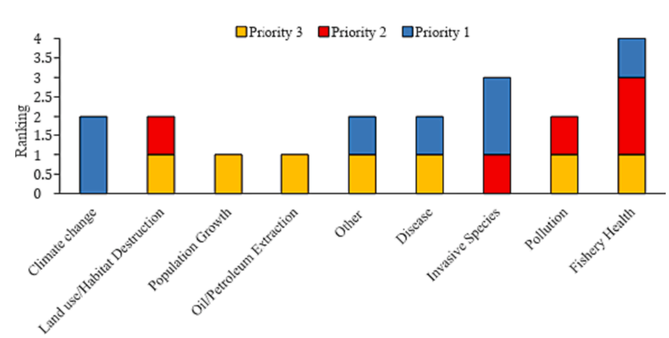

Fig. 2. Graph of critical issues and their rankings on Lake Malawi/Niassa/Nyasa Basin.

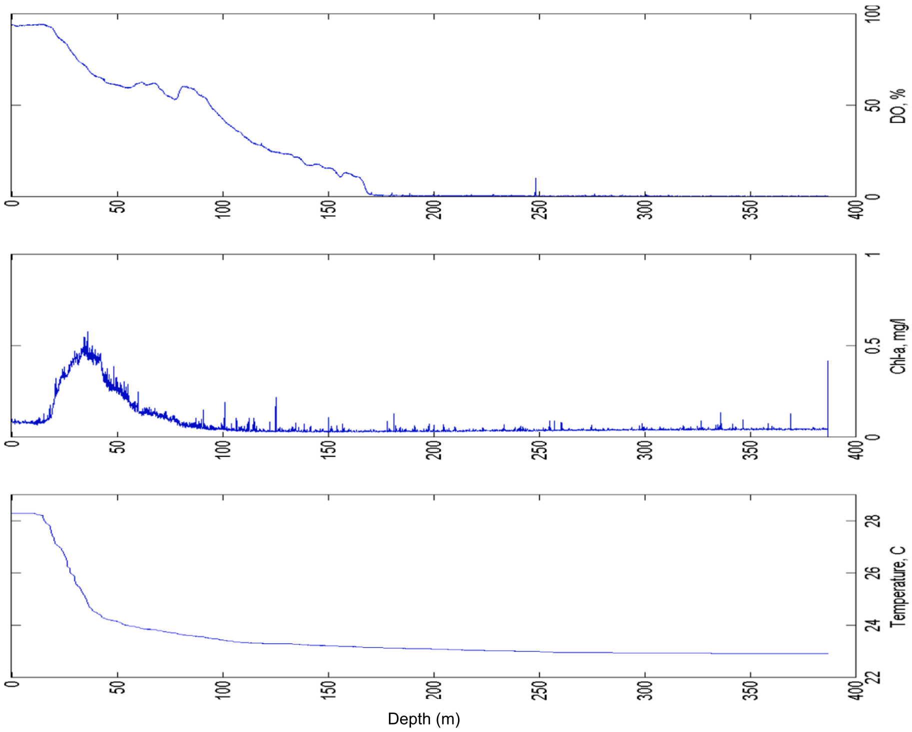

Fig. 3. Variation of temperature, chlorophyll concentration, and dissolved oxygen with depth in LMNN (BRIDGE, 2016).

and Guildford et al. (2003). These values typify optically clear water of oligotrophic lakes and oceans. High water clarity values over most of the lake are an indicator of low concentrations of colour-dissolved organic matter (CDOM), suspended mineral sediments, and phytoplankton (Guildford et al., 2003). The lake does show some seasonal patterns in water clarity. Guildford et al. (2000, 2003) reported that during the deep mixed (May-August) and deep stratified (December to May) periods, the mean water column light intensity was about one-third of the water column light intensity in the early stratified period, showing that light is an important control on the lake's phytoplankton production during deep stratification and deep mixing.

Because the temperature in LMNN is generally high throughout the year (~22–28 °C) and falls within a narrow range, its effect on phytoplankton growth probably does not vary substantially with the seasons. However, temperature variations do affect nutrient supply by controlling vertical mixing (Bootsma and Hecky, 1999). Exchange rates between the epilimnion and metalimnion, and between the metalimnion and the hypolimnion are in the order of 3.7 and 18.5 years, respectively (Bootsma and Hecky, 1999). Although this accounts for some of the nutrient delivery to the photic zone, atmospheric deposition and river discharge play important roles in determining nutrient concentration in the upper mixed layer. Bootsma and Hecky (1999) identified three major factors that control the nutrient chemistry of the productive mixed layer (above 100 m depth), namely: river flows, wet and dry deposition from the atmosphere, and mixing with deeper nutrient-rich waters. Each of these sources contributes significant amounts of nutrients to sustain algal productivity in the upper mixed layer. The authors further asserted that the sources differ in the proportion of different nutrients and contaminants they contribute to the mixed layer, and they differ in their sensitivity to anthropogenic activities. Of particular interest nutrients are nitrogen, phosphorus, silica, and iron because of their critical role in promoting phytoplankton growth. However, prolonged southerly winds (locally known as Mwera) produce upwelling in the southern part of the lake (Bootsma and Hecky, 1999; Hamblin et al., 2003), which dominates vertical water exchange and introduces nutrient-rich deeper water into surface waters. The nutrient loading provided by upwelling enhances phytoplankton production and sustains higher rates of fish production in the southern part of LMNN. Bootsma and Hecky (1999) and Patterson and Kachinjika (1995) reported that the "Mwera"winds, in addition to driving the upwelling, also cause a horizontal density disequilibrium, which resulted in internal seiches in the lake. This leads to higher rates of primary production in the southern part of the lake until the seiches dissipate.

Bootsma and Hecky (1999) observed that the annual yield of sediments and nutrients brought into LMNN by tributary rivers depends on flow conditions in a given year. More nutrients are washed into the lake during the rainy season (November to April) than during the dry season (May to October). Hecky et al., (2003) also noted that sediment and nutrient concentrations, loads, and yields are sensitive to the degree of agricultural land in the sub-basins, with the lowest sediments transported from small steep forested watersheds and highest amounts carried by tributaries in densely settled catchments with extensive agricultural activity. During the period over which Bootsma and Hecky (1999) conducted their study, they noted that rivers supplied 0.26–0.40 g P m^{-2} per year and 2.0–4.5 g N m^{-2} per year to LMNN. They also observed that rivers were the largest source of total P to the lake, and those rivers carried higher concentrations of sediments and nutrients early in the rainy season than did similar flows late in the rainy season. This was explained as resulting from the flushing of debris from the prolonged dry season and soil loss from cultivated and planted fields prepared for the beginning of the rains. Nutrient richness in waterbodies has been reported to lead to algal blooms which have significant negative effects to the aquatic resources and human beings, raising concern about continued increases in nutrients from agricultural catchments (Hecky et al., 2003).

According to Bootsma and Jorgensen (2004), phytoplankton species composition in LMNN varies with season and location, with diatoms dominating during the windy season (May to August), cyanobacteria (blue-green algae) dominating during September to November, and a mixture of small diatoms, blue-green algae, and green algae occurring from December to April. Bootsma (1993) reported an unusual distribution of *Scenedesmus* bloom and the *Aulacoseira* in LMNN between March 1990 to March 1991. Because phosphorus is an important nutrient controlling phytoplankton growth in the lake, increased inputs of this nutrient should result in increased phytoplankton abundance (Bootsma and Jorgensen, 2004). Land use change was identified as one cause of an increase in phosphorus concentration noted in sediment cores from LMNN (Bootsma and Jorgensen, 2004). The current Malawi government's policy to subsidise fertiliser to rural farmers in Malawi needs to be closely monitored while it is reducing food insecurity in the country. Atmospheric deposition is another important source of nitrogen and phosphorus for LMNN. Considering that nearly 60 % of the total input of water is derived from direct rainfall over the lake surface and that the surface area of the lake is large, it is not surprising that nutrient input into the lake from atmospheric deposition is prominent (Bootsma and Hecky, 1999; Bootsma and Jorgensen, 2004). A study by Bootsma et al., (1996) reported a significant difference in annual dry deposition rates of nitrogen and phosphorus over wet deposition rates highlighting the seasonal variations regarding the nutrient deposition. A global comparison indicates that atmospheric deposition rates of nitrogen and phosphorus in the LMNN region are among the highest in the literature (Bootsma et al., 1996; Bootsma and Jorgensen, 2004). These authors stated that the sources of atmospherically derived nutrients are biomass burning, increased exposure of soil to wind erosion promoted by burning, deforestation, and overgrazing of land. They also stated that the region around LMNN was among the most frequently burned regions in Africa. Reasons for the burning include preparation of fields for cultivation, burning of woodlands to open up agricultural areas, promotion of early growth of grass for livestock, hunting, accidental fires and tradition.

(b) Macrophytes and plankton communities

The abundance and distribution of macrophytes around the lake are poorly understood, but they are particularly vulnerable to removal by seine netting, agriculture and shoreline development (Ngochera, 2016). Macrophytes are confined to shallow areas along the lake shore, rivers and swamps. Macrophytes as categorised by Ngochera (2016) are of conservation interest because of the threats they pose to the ecosystem and other species particularly when they colonise the aquatic environment. Two known macrophyte species that pose a threat to the aquatic ecosystem are water hyacinth (*Eichhornia crassipes*) and Kariba weed (*Salvinia molesta*) which are alien and have the potential to grow rapidly in response to nutrient enrichment.

Phytoplankton species composition, abundance and seasonal variations in LMNN have been documented (Bootsma 1993; Guildford et al., 2007). Of major importance is that phytoplankton species composition, abundance and seasonality are driven by nutrient availability, water temperature, light availability, wind mixing, water column stability, grazing pressure, and the impacts of climate warming (Patterson et al., 2000; Ndebele-Murisa et al., 2020). This change results in degradation of water quality. According to Guildford et al. (1999), degradation of water quality can result in the proliferation of toxin-producing algal species such as *Microcystis, Anabaena, Aphanizomenon*, and *Cylindrospermopsis* as these are favoured in water characterised by elevated inputs of phosphorus. A study by Bootsma (1993) recorded a cyanobacteria bloom of *Chroococcus limneticus* in LMNN particularly the southern part. Phytoplankton blooms have previously been detected at this time of the year in the northern part of the lake (Hecky and Kling, 1981). The increase in phytoplankton, which coincides with the onset of the rain and nutrient inflows through surface run-off, indicate higher nutrient input to the system.

The zooplankton community of LMNN is species-poor (Ngochera, 2016). It comprises two species of calanoid (*Tropodiaptomus cunningtoni* and *Thermodiaptomus mixtus*), two species of cyclopoids (*Mesocyclops aequatorialis aequatorialis* and *Thermocyclops neglectus*), two species of cladocera *(Diaphanosoma excisum* and *Bosmina longirostris*), and the midge *Chaoborus edulis*. While zooplankton species are observed throughout the year, short-term fluctuations in abundance and population sizes are observed in the Southeast Arm (SEA) of the lake and their biomass ranges from 16 and 46 mg m^{-3}.

(c) Fisheries status

LMNN has the highest number of freshwater fish species in the world (Konings, 2016), providing over 800 species of fish which accounts for 15 % of the global freshwater fish biodiversity (Kapute, 2008). According to Konings (2016), over 500 species have been formally described; and the vast majority of cichlids are endemic. Eleven (11) families are represented in the lake, with the Cichlidae family being dominant in species richness. Table 2 shows a comprehensive list of riverine (R) and lacustrine (L) fishes of the LMNN system, and the percentage of endemicity (Weyl et al., 2010).

The Cichlidae family in LMNN is represented by two principal phylogenetic lineages, namely: the tilapiines and the haplochromines (Konings, 2016; Shaw et al., 2000; Turner, 1996). The tilapiines consist of the genera *Oreochromis*, *Tilapia* and *Coptodon*. The *Oreochromis* spp. are represented by a small, endemic species-flock comprising four members that are collectively referred to as chambo, and a fifth non-chambo species, *Oreochromis shiranus* (Konings, 2016; Turner, 1996). The only representative member of the genus *Tilapia* is a non-endemic species *Tilapia sparrmanii* and the genus *Coptodon* is represented by the *Coptodon rendalli*. Haplochromines species belong to fish species numbering between 700 and 800 (Konings, 2016). Most of the haplochromines are endemic to LMNN, except for *Pseudocrenilabrus philander* commonly found in peripheral lagoons; *Astatotilapia calliptera* and *Serranochromis robustus*, formerly regarded as non-endemic and are now recognised as distinct lineages (Seehausen, 2002). The origin and age of the endemic cichlid fauna currently form the focus of much research and debate (Genner et al., 2007; Genner and Michel, 2003) but other, more conservative (in terms of speciation) fish families and genera provide clear evidence for the history of fish colonisation of the lake and its inflowing rivers. The lake's fish fauna reflects its complex geomorphological history which has an East Coast and Upper Zambezi system affinity (Seehausen, 2002).

It is worth noting that the LMNN fisheries sector comprises capture fisheries and aquaculture, with the former being the dominant type in terms of production and employment. Capture fisheries include small-scale, large-scale (trawling) and export trade fisheries (Banda, 2001; Malawi Government, 2021). The small-scale fisheries are "open entry and exit" (van Zwieten et al., 2016; van Zwieten et al., 2003). and contribute over 90 % of the total catch landings in Malawi. From the Malawian side, over 1,600,000 people are involved in fisheries-related activities such as processing, marketing, fishing gear production, boat building, net mending and maintenance, engine repair and other

Table 2
Riverine and lacustrine fishes of Lake Malawi/Nyasa/ and their percentage endemicity (adapted from Ribbink 2001). Endemicity is lower in rivers than in the lake. All families in the lake also have riverine representatives, but not all riverine families have representatives in the lake. *Introduced alien fishes (after Ribbink, 2001).

	R or L Fishes	Genera	Endemic	Species	Endemic
Protopteridae*	R	1	0	1	0
Anguillidae	RandL	1	0	1	0
Mormyridae	RandL	6	0	7	0
Salmonidae	R	1	0	1	0
Alestidae	RandL	2	0	2	0
Cyprinidae	RandL	5	1	26	35
Bagridae	RandL	1	0	1	100
Amphiliidae	R	2	0	4	40
Clariidae	RandL	2	1	17	71
Mochokidae	RandL	2	0	3	33
Cyprinodontidae	RandL	1	0	1	0
Aplocheilidae	R	1	0	2	50
Mastacembilidae	RandL	1	0	1	100
Cichlidae	RandL	56	51	Ca750	99.5

activities (Malawi Government, 2021; Torell et al., 2020). A total of 74,222 people are directly employed by the fisheries sector as fishers in Malawi (Malawi Government, 2021). However, the majority of this is made up of crew members (82 %) while gear owners make up 18 %. The fishery industry is dominated by male gear owners, who account for 98 % of the total population while 2 % are female gear owners (Malawi Government, 2021).

The predominant large-scale fishery is known for trawling which commenced in Malawi in 1968 after successful trawling experiments in 1965 (Tarbit, 1972; Turner et al., 2005). At the time, only nine pair trawl units were in operation. The fishery then, involved small, 38 Hp open decked boats, which were relatively cheaper as they were made of wooden planks. By 1984, 20 units were recorded but by 2001 only 8 units were active (Banda, 2001). According to Banda (2001), stern demersal trawlers were introduced into the fishery in 1972 while mid-water trawlers were introduced four years later (Turner, 1977b). By 2001, six stern trawlers were in operation in the southern part of the lake with only three being capable to trawl beyond the 80 m water depth. The decline in the number of commercial fishing units between 1985 and 2001 is attributed to lack of proper maintenance resulting from low profit margins due to frequent breakdowns. The peak in the numbers from 2002 to 2019 was attributed to the government's tariff exemption on all marine engines, coupled with a proliferation of cheaper engines from China (Ngochera, Pers. Comm.). According to the 2021 census of commercial trawling, about 350 people are employed directly by the industry as gear owners and crew members, and female gear owners account for about 15 % of trawler owners (Malawi Government, 2022). At present, there are 48 large-scale licensed trawl units in Malawi, most of which operate in the southern and central part of the lake (Malawi Department of Fisheries, Unpublished data). The trawl fishery which previously targeted chambo, is currently targeting ndunduma (*Diplotaxodon* spp.) and utaka (*Copadichromis* spp.).

Due to the great diversity of fish species, LMNN attracts international tourists and researchers (Weyl et al., 2010) who are mostly attracted by the most popular and abundant, rock-dwelling cichlids, locally known as mbuna (Malawi Government, 2021; Kapute, 2008; Msukwa et al., 2021a). The fishery which is currently dominated by the ornamental fish, is practiced in Malawi and Tanzania (Msukwa et al., 2021b). Exploitation of export fish is allowed in all waters of LMNN except in National Parks although cases of poaching have widely been reported (Msukwa et al., 2021a). The operations of fishing for the export fish trade are currently confined to four licensees in Malawi and three in Tanzania that commonly target mbuna fish species (Msukwa et al., 2021b). The export fish trade thrives on the exploitation and exportation of these coloured cichlids, mostly to Europe, Asia and North America (Malawi Government, 2021). In 2020, a total of 23,985 units of fish worth USD137,600 was exported to Europe, Japan, the USA and South Africa (Malawi Government, 2021). This was, however, a huge drop when compared with 66,461 live fish in 2019, which generated a total income of USD295,090. The drop was attributed to the impact of COVID-19-restricted exports (Malawi Government, 2021).

LMNN fisheries resources are managed through many approaches and one of such approaches is the use of catch and effort statistics. The catch and effort data collection system established and introduced in Malawi by the Food and Agriculture Organization (FAO) reveals that catches in trawl fishery have had a decreasing trend since the late 1980s and currently the fishery reports about 3,000 tonnes (Fig. 4). Furthermore, the composition of catch landings from large-scale fisheries has changed over time and Turner et al. (2005) blames it on the introduction of commercial trawling. Between 1976 and the early 1990s, the fishery was dominated by *Oreochromis* spp. (chambo) and *Lethrinops* spp. (chisawasawa) (Fig. 4). These two species groups were later replaced by *Diplotaxodon* spp. (ndunduma) while *Copadichromis* spp. (utaka) has had a rather stable trend over the years. The dominance of *Engraulicypris sardella* (usipa) catches in the small-scale fisheries (estimated to account for over 60 % of the total catch) has been observed from 2000 to date (Malawi Government, 2021) and can be observed in Fig. 5. Similar trends of smaller pelagic fish dominance have been reported in many African great lakes (Kolding et al., 2018). Fish catches in 2020 were estimated at around 170,844 tons (Malawi Government, 2021). Despite the general increase in the trend of fish catches, catches of some of the larger species, such as chambo, have declined (Fig. 4). During the late 1970s, production of chambo was about 9,000 tons annually but landings declined since 2010 and have remained at those low levels with current estimates of about 4,000 tons (Malawi Government, 2021).

LMNN is facing several challenges that impact the sustainable management of fisheries resources. One of such challenges is the increased rate of post-harvest fish losses despite recent efforts like the development of post-harvest fish loss reduction technologies such as solar tent dryers and improved smoking kilns. Over 54 % of fish processed in Malawi continue to undergo physical and quality losses (Torell et al., 2020). As a result, fish reaches consumers in less quantities leading to low levels of per capita fish consumption and an increase in demand for fish thereby promoting overfishing (Torell et al., 2020). Siltation is also causing a lot of challenges to the LMNN by destroying fish habitats and causing nutrient loading Bootsma and Hecky (1999). Non-compliance to fisheries rules and regulations is another concern. The fisheries in Malawi are controlled through technical restrictions, i.

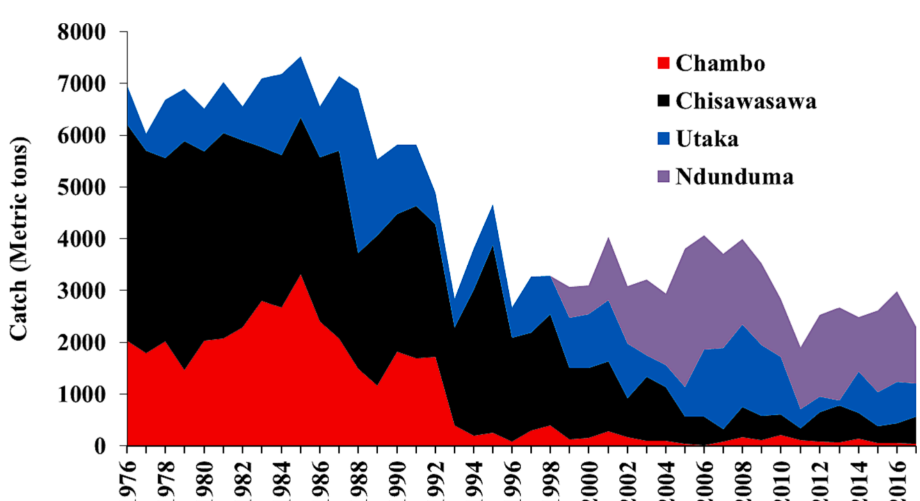

Fig. 4. Fish production from large-scale trawlers showing trends in the commercially important fisheries. source (Malawi Government, 2021). Chambo (*Oreochromis* spp.), Chisawasawa (*Lethrinops* spp.), Utaka (*Copadichromis* spp.), Ndunduma (*Diplotaxodon* spp.),

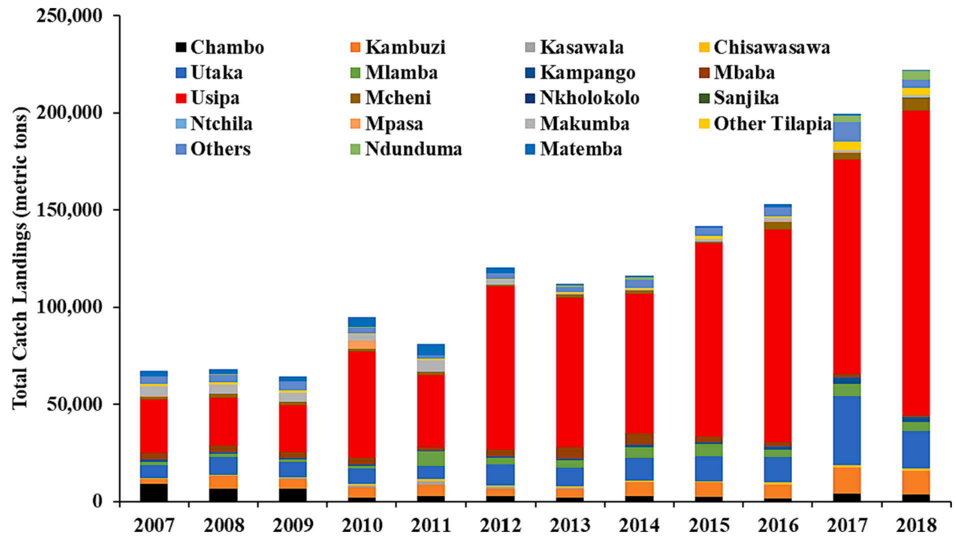

Fig. 5. Fish production from the major water bodies of Malawi. Source (Government, 2021). Chambo (*Oreochromis* spp), Utaka (*Copadichromis* spp), Usipa (*Engraulicypris sardella*), Ntchila (*Labeobarbus* spp), Kambuzi (Haplochromine spp), Mlamba (*Clarias* spp), Mcheni (*hamphochromiss pp*), Mpasa (*Opsaridium microlepis*), Ndunduma (*Diplotaxodon* spp), Kasawala (Small *Oreochromis* spp), Kampango (*Bagrus* spp), Nkholokolo (*Synodontis* njassae), Makumba (*Oreochromis shiranus*), Matemba (*Enteromius* spp), Chisawasawa (Lethrinops spp), Mbaba (Shallow water large cichlids), Sanjika (*Opsaridium microcephalum*).

e., closed season, fishing effort control through licensing, minimum mesh sizes, time of fishing and minimum takeable size of fish. However, there have been challenges in enforcing these restrictions. Scientists have faulted the approach as it is considered a top-down fisheries management system, hence local compliance becomes a challenge (Jul-Larsen et al., 2003).

Despite the challenges, several initiatives are being taken to resolve them and one of them is to do with governance and regulatory framework. There is, therefore, a need to enhance and embrace co-management which has proven to produce positive results notably in Lake Chiuta (Njaya, 2007). For its part, the Malawi Government has brought in the latest interventions to ensure sustainable management of the fisheries resources through the installation of a vessel monitoring system (VMS) on trawling boats. The introduction of the closed season and the ban on the importation of monofilament gillnets are some of such initiatives.

In summary, the fisheries resources in LMNN require urgent actions that are holistic in nature (combining ecology, social and regulatory frameworks) to reverse some of the critical issues currently being experienced. Community engagement in fisheries resources management will be critical as this has proven to be cost-effective and sustainable. Communities should be encouraged to identify potential sites for fish sanctuary establishment. Not only that, the fisheries departments of the three countries should put extra effort into capacity-building efforts, aiming at addressing issues of fish postharvest losses, targeting the fishermen, fish processors, fish distributors and fish marketers.

(2) Invasive species

The LMNN has been reported to face threats from invasive introductions thereby threatening its rich fish diversity. Biological invasions as they are commonly known, are human-mediated events where humans intentionally and/or unintentionally introduce species into new areas (Moore, 2005; Cucherousset and Olden, 2011). The introductions occur for many reasons and some of which are to do with land use changes; economics and trade; climate change; tourism; conflict; regulatory regimes; biological control of pests and public health (Moore, 2005). Not all introductions cause problems (Holcik, 1991). As previously observed by Wittmann et al. (2013), biological invasions follow two phases, establishment phase and invasion phase. Hence, before the alien gets to the point of causing problems, it has to establish itself successfully, and this is impacted by several factors (Wittmann, et al., 2013). It is, however, widely accepted that only one-tenth of the introduced species get established and only one-tenth of the established species cause problems. This scenario is known as the “tens rule” as described by Vander Zanden (2005) which demonstrates only a low probability of an exotic organism successfully get introduced and cause problems. Otherwise 90 % of them fail. In addition, species that are known to be invasive elsewhere may not necessarily become invasive in a new environment. Sayer et al. (2019) point out that the level of threat of invasion to the lake’s fish species is significantly lower than that for Africa as a whole, and much lower than that for Lake Victoria. Hence, relative to most lakes around the world, LMNN still has a relatively intact biological community with a moderately small number of non-indigenous species.

In Africa and many other parts of the world, cases of introductions have had mixed results (Riedmiller, 1994; Cucherousset and Olden, 2011; Aloo, et al., 2017). The introduction of two invasive tilapiines, *Oreochromis niloticus* and *Oreochromis leucostictus* in the LMNN catchment, was an initiative to develop aquaculture and new capture fisheries (Genner et al., 2013; Weyl et al., 2010). It was, however, noted that the introduction of *O. leucostictus* was accidental as it was misidentified for *O. niloticus*. The initiatives to develop aquaculture have been identified as primary drivers for the spread of invasive species in freshwaters (Genner et al., 2013; Gozlan et al., 2010). Currently, there is no evidence that native species in the LMNN catchment have been impacted by invasive species, but the situation is likely to change (Sayer et al., 2019). The Third National Communication of the Republic of Malawi to the Conference of the Parties (COP) report highlighted that the aquaculture initiatives posed very little threat to the fish community in the catchment, but there is a likelihood that *O. niloticus* can compete and hybridise with native species (Government of Malawi, 2021). *Oreochromis niloticus* and *O. leuco*stictus have not yet been reported/observed in LMNN. However, Genner et al. (2013) indicated evidence of translocation within the LMNN catchment. *O. niloticus* is present in Lake Itamba, a small satellite lake just north of the LMNN catchment and its introduction took place as an attempt to start a new fishery in the lake in 2010. In 2012, this species was reported to be grown in some ponds in Songea, Tanzania near the north end lf LMNN. However, there is an indication that natural escape from Itamba is low due to a lack of natural outflow (Genner et al., 2013). But there is a higher risk of escape from the ponds in Songea because of the direct connection to Ruhuhu River, one of the largest tributaries to LMNN (Third National Communication of the Republic of Malawi to the Conference of the Parties (COP)), and this can have potential consequences on the native species of LMNN.

A notable introduction to the LMNN catchment was the piscivorous *Oncorhynchus mykiss* in Nyika plateau and *Protopterus annectens* in LMNN seasonal wetlands near Salima (Genner et al., 2013). Malawi's Third National Communication of the Republic of Malawi to the Conference of the Parties (COP) of 2021 reported the risk of accidental introduction of tiger fish (*Hydrocynus* sp.) through the canals of the proposed lower Shire irrigation scheme. The concerns were heightened following the large cyclone and heavy rains in January 2022, which could have allowed the fish to swim over Murchison cataracts on the Shire River. Preliminary study that was conducted revealed that tiger fish distribution did not go beyond where it used to be. These fears should encourage a precautionary approach regarding the potential for disastrous effects with the introduction of new species in an existing water body, after noting the devastating effects on the haplochromines reported in Lake Victoria with the introduction of *Lates niloticus* and the subsequent elimination of many native species (Ogutu-Ohwayo and Hecky, 1991: Witte et al., 1992).

Melanoides tuberculata, an invasive gastropod, was introduced in LMNN from Asia. Since its invasion, it has obtained high abundance and dominance in shallow waters (Genner et al., 2004). Studies by Van Bocxlaer and Albrecht (2014, 2015) indicate a remarkable shift in communities towards the dominance of non-endemic taxon. The decline in abundance of endemic *Melanoides* is attributed to altered benthic ecosystem due to sedimentation and eutrophication, and interaction between alien and endemic *Melanoides*. However, detailed studies on the benthic ecosystem are recommended to understand the interaction between the invasive and endemic *Melanoides*. It is understood that invasive *Melanoides* may play an important role in reshaping communities and diversity in LMNN.

The water hyacinth (*Eichornia crassipes*), another invasive species has massively terrorised the Shire River. The invasion is attributed to increased interaction between an increase in nutrients in the LMNN catchment and lack of biological control agents (Mellhorn, 2014). A study by Otu et al. (2011) provided evidence that the southern part of LMNN receives abnormally and significant heavier amount of nutrients through sedimentation in comparison with the northern part. A direct measurement in sediment traps revealed significant quantities of dry weight and nutrients than the northern part. The rich nutrients are therefore blamed for the proliferation of the water hyacinth particularly in the outflowing Shire River system and similar reasons were reported in Lake Victoria (Mailu et al., 1999, Gichuki et al., 2001). In Lake Victoria, water hyacinth has caused serious and varying impacts ranging from restricting access to shore for fishing, transportation challenges, hydroelectric power generation challenges, blocking water intake for water supply and disrupting native aquatic plant communities (Mailu et al., 1999, Gichuki et al., 2001). However, such detailed information about the impact of the water hyacinth on biodiversity in LMNN is limited and wide covering multidisciplinary research is required.

(3) Climate Change impacts in Lake Malawi/Niassa /Nyasa

A study by Limuwa et al. (2018) revealed that increasing temperatures and decreased rainfall have led to a decline in fish catches, which has negatively affected the livelihoods of fishing communities around the LMNN. The study also noted that climate change has led to a shift in the composition of fish species, with some species becoming more dominant while others are declining. Of late, the LMNN has had a number of reported cases of mass fish kills, particularly in the southern part of the lake. This scenario may be explained using two theories, namely: increased temperature with climate change that enhance algal blooms which consume huge columes of oxygen when they die, and increased speeds of *Mwera* winds which blow over the lake thereby enhancing water circulation and extrude anoxic bottom waters to the lake surface, causing fish kills in the process. The study by Cohen et al. (2016) reported a significant drop in the pelagic fish species of Lake Tanganyika and attributed this decline to the temperatures that have been increasing over the years. The study further noted a warm-induced shift in ecosystem productivity which negatively affected the production of the pelagic fishes… Atudy was done by Makwinja and M'balaka (2017) where the impact of rainfall and temperature on the catches of chambo was inferred. The study revealed that unlike the air temperature, rainfall fluctuations had a significant impact on the total catches of chambo. The study urges decision makers to take an immediate climate change mitigation measure to reduce the impact.

3.2. Climate change vulnerability assessment and potential adaptation strategies

Although the major threat to the sustenance of the fishery industry in the LMNN catchment is overfishing, impacts of climate change resulting from increased temperatures (which fuel algal blooms) and increased speeds of *Mwera* winds only help to exacerbate these threats.

Malawi's Third National Communication Report submitted to the Conference of the Parties (COP) of the UNFCCC proposed a number of adatptation strategies for the fisheries sector (COP literature, 2021). These include: establishment of protected areas; enforcement of buffer zones for lakes and rivers; development of infrastructure to control invasive plants and adoption of climate-resilient fisheries management. The following section presents details of these strategies.

(a) Establishment of Protected Areas

Since the establishment of Lake Malawi National Park as a World Heritage in 1982 by the United Nations Educational, Scientific and Cultural Organization (UNESCO), this LMNN section has been well managed though cases of poaching have been reported. Elsewhere, the fisheries resources have benefited from such restoration programmes, and the establishment of protected areas or parks has become a common practice (Erisman, et al., 2017). In Malawi, there has been noticeable increase in the adoption of the protected areas especially by various fishing communities in Malawi (FISH, 2018). These community-owned protected areas have revealed their effectiveness in restoring aquatic biodiversity (FISH, 2016). On a large-scale, marine protected areas (MPAs) have been hailed for improving degraded and overexploited ecosystems (Erisman, et al., 2017; Rife et al., 2013) while Ban et al. (2017) added social benefits to large marine protected areas.

(b) Enforcement of buffer zones for lakes and rivers

While regulations exist for the conservation of buffer zones for both rivers and lakes, enforcing the regulations has been a very big challenge. The Department of Irrigation in Malawi has a 10 m buffer zone regulation for which farmers are supposed to observe (Third National Communication of the Republic of Malawi to the Conference of the Parties (COP) of 2020). However, in many lakes and rivers, cultivation in marginal and river banks is the order of the day. The problem with not leaving a pristine buffer zone is that when the first rains come, most of the loose soil and organic matter are transported into the rivers, ending up getting dumped in the lakes (Third National Communication of the Republic of Malawi to the Conference of the Parties (COP) of 2020).

(c) Development of Infrastructure to Control Invasive Plants

Given the undesirable effects of invasive aquatic weeds like water hyacinth on the fishery, appropriate mitigation effects such as construction of barriers along the Shire River must be implemented. The construction of these barriers would play an essential role in controlling the weeds and improving the efficiency of the weeds' disposal. Such barriers have already been fixed at Liwonde Barrage to control water hyacinth from going downstream to affect electricity power generation (COP, 2020). However, to ensure practical outputs, systems would have to be in place to ensure the availability of human capacity with the technical know-how on operation and maintenance of the equipment underuse. Furthermore, plans would have to be in place for sustainable financial resources to maintain the equipment.

(d) Adoption of Climate-Resilient Fisheries Management

The LMNN has been subject to several governance arrangements such as traditional fisheries management, centralised, and co-management (Njaya, 2007). However, despite the current co-management governance arrangements, the fishery faces challenges through climate change impacts and overfishing. In this paper we suggest the continued need for establishing meaningful processes with fishing communities, integration with existing structures, and improvement of the current co-management arrangement. The commitment to governance arrangements should be reflected in all policy design, implementation, and evaluation stages. Pittman et al. (2019) noted that co-management can strengthen relationships and trust among fisheries stakeholders, empower fishers, and foster more outstanding collective actions for sustainable fisheries and effective adaptation options to climate change. Adoption of community-owned fish protected areas could also cushion the climate change impacts to the fishing communities as highlighted by FISH (2018).

4. Conclusion

Lake Malawi/Niassa/Nyasa continues to provide essential ecosystem services to people in Malawi, Tanzania and Mozambique. The fishery industry however, faces a number of challenges that need to be addressed in order to ensure improved and sustained benefits to the riparian countries and the world at large. A number of key challenges currently being faced by LMNN have been discussed which ranges from fisheries resource decline, invasive species to climate change impacts. Despite the challenges, the sector recognises a number of opportunities and some of them are that the sector is well recognized and supported by both state and non-state actors, including donor partners. There are both new and old infrastructure across the three countries that can support investments including research and development into the sector. There is also a strong linkage between national policies which guide national development and the fisheries policy which ensures that the sector is kept abreast of both local, regional and international developments and obligations. It is therefore believed that with proper monitoring of the ecosystem, well-coordinated support and swift reaction to events such as invasive species and climate change that pose threat to the catchment, the people around the catchment will continue to benefit from the ecosystem services provided by the LMNN.

5. Recommendation

Based on the above findings, we make the following recommendations that are identified as research and development needs.

(a) Research needs

The study recognises the current and previous projects that have worked on LMNN and have developed the catchment in number of ways. Some of the notable fisheries projects were UK/SADC Pelagic Resources Assessment (1991–1994); Lake Malawi/Nyasa/Niassa Biodiversity Conservation (1994–1999); The Demersal Ecology (1998–2002) International Union of Conservation of Nature (IUCN) (2019–2022) and Songwe River Transboundary Catchment Management Project (2015). Based on the previous interventions, the following are the potential research needs for the LMNN built on the key issues discussed above:

- Assessment of plankton and invertebrates' species biodiversity and abundance along the littoral waters
- Identification and mapping of breeding and nursery areas of commercially important fish species
- Dedicated field studies for biodiversity surveys to inventory fish species and their distribution, identifying critical habitats and biodiversity areas in the lake, produce a map of breeding and nursery areas of commercially important fish species
- Studies on the taxonomy, ecology, and distribution of the cichlid species.
- There is an increased need for assessment of species diversity using high throughput genetic methods such as metabarcoding, especially for macroinvertebrates.
- Resource-dependent and independent surveys, especially for fishery assessments, are a must. In addition, informed conservation status assessments, such as the red listing for key taxa, would help gauge the region's biodiversity status.

A study by Plisnier et al. (2023) recommends that monitoring of fisheries resources be instituted on the African Great Lakes particularly the catch assessment surveys, frame surveys, fish size distribution while making biomass assessment surveys as occasional and optional. For limnology and water quality, Plisnier et al. (2023) make monitoring recommendations for all African great lakes which includes temperature, pelagic specific conductivity, water transparency, water level monitoring and systematic sampling of the water and planktonic blooms.

(b) Infrastructure Development

There is a need for the following infrastructure development to support the research dimension in LMNN:

- Modest rehabilitation of the Monkey Bay Capture Fisheries Centre in Malawi, the Kyela Centre Fisheries Research Station in Tanzania, and the Metangula Fisheries Research Station in Mozambique is also required. These research stations need to be equipped with important basic molecular and water quality monitoring laboratory equipment to help research scientists conduct research in LMNN.
- Key infrastructure such as platforms, vessels, data-basing infrastructure, basic molecular labs are required to support the research dimension of the LMNN, in each of the three countries.
- establishing well-equipped field stations right at the lakes, where existing structures could be rehabilitated to support the research needs.
- One research vessel equipped with a multi-frequency split beam hydro acoustic echo sounder for fish acoustics and bathymetry studies, sediment grab for collecting sediment samples, and zooplankton and plankton nets

(c) Human capacity building.

Considering the number of challenes being faced by the researchers in the LMNN catchment, there is a great need for building capacities of the scientists in the following areas:

- stock assessments
- biodiversity monitoring
- climate change modelling, genomics
- plankton taxonomy
- biogeochemistry

These skills will ensure that the fisheries resources in the LMNN are properly managed based on adequate and comprehensive research findings conducted by the local researchers.

(d) Funding

Funding is a cross-cutting issue across the priority areas discussed above. For most developing countries, such as the three LMNN countries, limited financial support greatly affects the implementation of projects and programs. Funding for the LMNN should be drawn from both internal and external resources. There is a need for increased engagement with policymakers to make a case for increased funding for the basin, which can also be drawn from other relevant ministries. Secondly, there is a need to establish an authority for the lake that will be responsible for seeking and coordination external funding for the work on the lake.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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