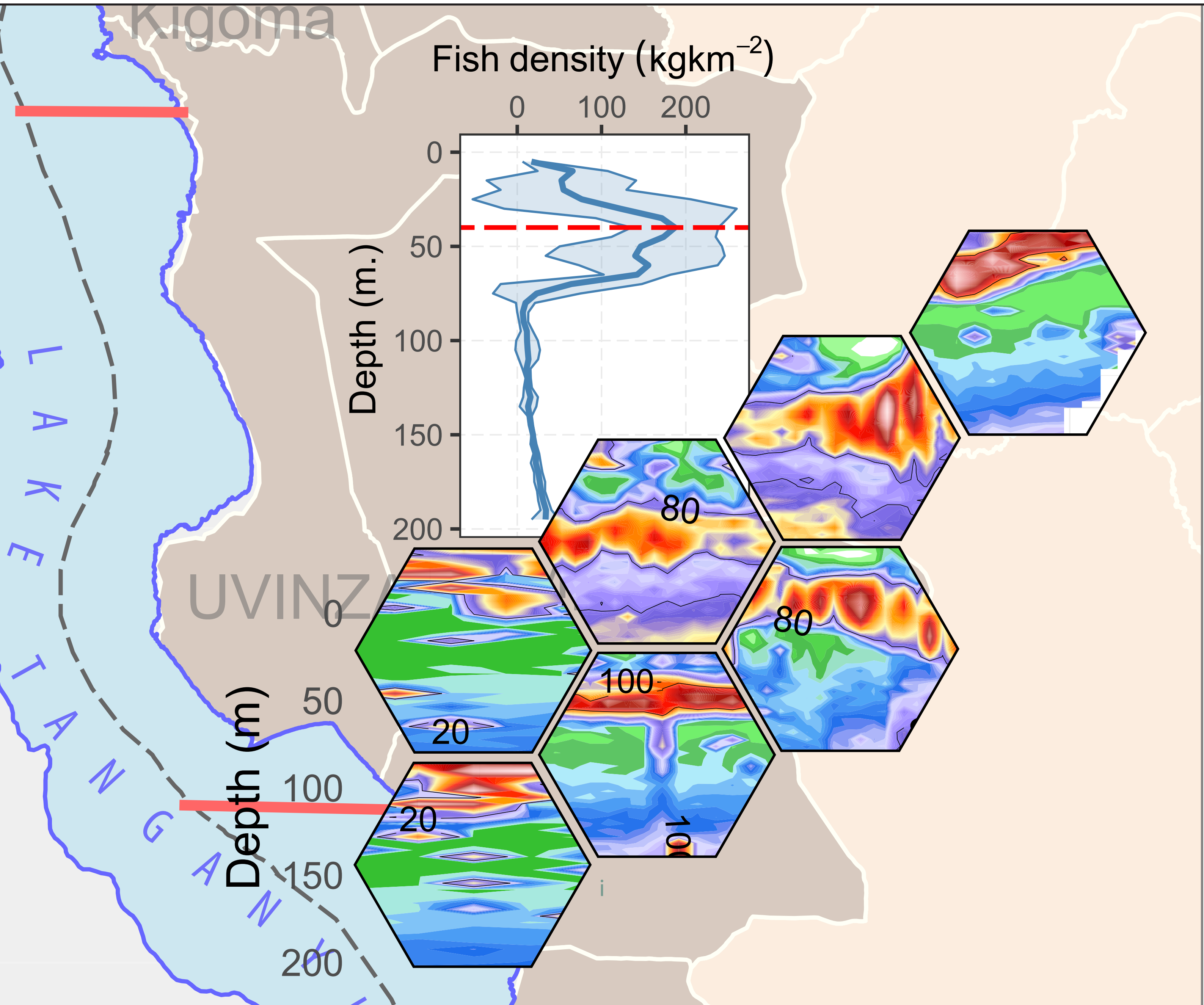
UNITED REPUBLIC OF TANZANIA
MINISTRY OF LIVESTOCK AND FISHERIES

FISH STOCK ASSESSMENT USING HYDROACOUSTIC SURVEY IN LAKE TANGANYIKA, TANZANIA



A REPORT ON FISH STOCK ASSESSMENT USING HYDROACOUSTIC SURVEY IN LAKE TANGANYIKA, TANZANIA

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EXECUTIVE SUMMARY

This report presents the result of an hydroacoustic survey to determine the standing stock biomass of the pelagic fish species in the Tanzanian waters of Lake Tanganyika. The report also, presents the first biomass estimates after nearly 30 years since the last survey was conducted in 1995. The survey was conducted from 23rd February to 19th March 2022 from the northern-most to the southern-most points of the Tanzanian waters. Acoustic data were collected alongside limnological and biological parameters in a predefined transects spanning the entire shoreline in Tanzania. Both the acoustic and environmental and biological data were analyzed according to the three major basins of the lake, that is the Northern, Central and Southern basins, respectively. The acoustic data were processed using the Echoview 12 software (Myriax, Hobart, Australia) and data analysis was done in excel, Sigma plot and R language.

The results showed that the total biomass of the pelagic fish species in the Tanzanian waters of Lake Tanganyika was estimated to be 144,690 tonnes, from an area of 13,495 km^2 which was surveyed. The highest biomass was recorded from the Central basins, which was 60,796 tonnes. The southern and northern basins recorded 52,928 and 30,966 tonnes, respectively. The total biomass has declined by 8% compared to biomass estimates of the 1995 survey, which was 157,493 tonnes. Similarly, fish densities were highest in the central basin where 14.52 ton/km^2 was recorded, followed by the southern and northern basin where 11.56 and 6.55 ton/km^2 were recorded, respectively. Like in the previous survey, it was not possible to apportion the biomass into different biomass estimates by fish species due to limited number fish samples and lack of specific target strengths (TS) of fish of interest: i.e., *Stolothrissa tanganicae*, *Limnothrissa miodon* and *Lates stappersii*.

Furthermore, differences in water temperature, water visibility (turbidity), dissolved oxygen concentration, and primary productivity (fluorescence, Chl-a) among the three basins were found to optimally explain variations in fish biomass and densities among the basins. Water temperature that explained higher fish densities and, therefore, biomass, was found to be 27°C. Dissolved oxygen as high as 4 mg/l in waters deeper than 120m, high Chl-a and fluorescence were recorded in the central basin where, also a significant layer of deep chlorophyll maxima was observed. All these parameters support the existence of high biomass and fish densities in the central and southern basin of the lake. Finally, there was an observation of declining mean fish sizes where use of undersized nets and fishing in inshore waters, especially by ringnets was identified as threat to sustainable use, development, and management of the Lake Tanganyika pelagic fish resources.

According to these results it is recommended that:

i. While the findings of the current survey should be considered preliminary, we recommend a precautionary approach of harvesting not more than 70% of the standing biomass to ensure sustainability. That is, harvesting should not exceed 101,283 tonnes annually. Measuring this however, will need employment of hidden harvesting methods and controlling all illegal fish trade and transportation.

ii. This survey is an attempt to understand the stocks of the pelagic fish species in the lake from almost 30 years after the last survey in 1995 – 1998. During thing time, fishing effort has nearly tripled (LTA – Secretariat, 2012), and environmental changes have worsened. It is needed, therefore, to have regular stock assessment surveys in Lake Tanganyika in different seasons as a basis for determining a sustainable fishing policy.

iii. The lake is shared by four countries Burundi, Democratic Republic of Congo, Tanzania, and Zambia. It is important to aim for a Lake-wide enforcement of fisheries regulations.

Thus, efforts being taken by the Lake Tanganyika Authority should be embraced and supported by all member states.

iv. In order to maximize the possibility of correctly estimating the biomass of the various pelagic species in Lake Tanganyika, and as a way forward, it is recommended to conduct an experiment to determine acoustic target strength (TS) or the different pelagic species of interest. This will help in future estimations both at a country and regional levels.

MUHTASARI ANDAMIZI

Taarifa hii inatoa matokeo ya utafiti wa tathmini ya wingi na mtawanyiko wa samaki wa tabaka la juu (pelagic species) katika maji ya Tanzania ya Ziwa Tanganyika. Pia, taarifa hii inawasilisha makadirio ya kwanza ya wingi wa samaki baada ya karibu miaka 30 tangu utafiti wa mwisho ulipofanyika mwaka 1995. Utafiti huu ulifanyika kuanzia tarehe 23 Februari hadi tarehe 19 Machi 2022 kutoka kaskazini hadi kusini kabisa katika maji ya Tanzania ya Ziwa Tanganyika. Takwimu za mwangi (acoustic) zilikusanywa pamoja na viashiria kilimnolojia na kibaiolojia katika maeneo yote ya maji ya Tanzania. Takwimu hizi za mwangwi na mazingira na kibaiolojia zilichambuliwa kulingana na mabonde/sehemu kuu tatu za ziwa (major basins), ambayo ni Sehemu ya Kaskazini, Kati na Kusini, mtawalia. Takwimu za mwangwi (hydroacoustic) zilichakatwa kwa kutumia programu ya Echoview 12 (Myriax, Hobart, Australia) na uchambuzi wa takwimu ulifanywa katika excel, SigmaPlot na programu ya R.

Matokeo ya tathmini ya wingi na mtawanyiko wa samaki katika maji ya Tanzania ya Ziwa Tanganyika yanaonyekwa kuwa kuna tani 144,690 za samaki wa kwenye tabaka la juu (pelagic species), katika eneo la kilomita za mrada 13,495 lililofanyiwa utafiti. Biomasi ya juu zaidi ilirekodiwa kutoka sehemu ya Kati (central basin), ambayo ilikuwa na tani 60,796 za samaki. Sehemu ya Kusini na Kaskazini zilikuwa na tani 52,928 na 30,966, mtawalia. Wingi wa samaki (biomass) umepungua kwa asilimia 8 ikilinganishwa na makadirio ya wingi wa samaki ya utafiti wa mwaka 1995 ambao ulipata tani 157,493. Vivyo hivyo, mkusanyiko wa samaki (fish density) ulikuwa mkubwa zaidi katika sehemu ya kati ambapo kiasi cha tani 14.52 za samaki kwa kilimeta moja ya mraba ilirekodiwa, ikifuatiwa na sehemu ya kusini na ya kaskazini ambapo tani 11.56 na 6.55 za samaki kwa kilometa moja ya mraba zilirekodiwa, mtawaliwa. Aidha, kama ilivyokuwa katika utafiti uliopita, haikuwezekana kuidhinisha wingi (biomass) wa samaki kwa spishi za samaki kutokana na sampuli ndogo za samaki na ukosefu wa 'acoustic target strength' (TS) za aina za samaki lengwa: yaani, dagaa (*Stolothrissa tanganicae*), lumbu (*Limnothrissa miodon*) na mgebuka (*Lates stappersii*).

Aidha, tofauti katika joto la maji, uangavu wa maji (turbidity/transparency), kiwango cha hewa ya oksijeni, na kiwango cha umbijani (fluorescence, Chl-a) kati ya mabonde (basins)/ sehemu tatu za ziwa vilieleza tofauti katika wingi (biomass) cha samaki na mkusanyiko (densities) wa samaki kati ya mabonde hayo. Joto la maji ambalo lilielezea mkusanyiko mkubwa na, kwa hivyo, wingi wa samaki, lilikuwa ni nyuzijoto 27 (27^{o}C), kiwango cha hewa ya oksijeni kwenye maji cha miligramu nne kwa lita moja ya maji (4 mg/l) katika maji zaidi ya 120m, na ubijani jingi vilirekodiwa katika bonde la kati (central basin). Vigezo hivi vyote vinasaidia kuwepo kwa wingi na mkusanyiko mkubwa wa samaki katika bonde la kati (central) na kusini (southern) ya ziwa. Hatimaye, utafiti unaonyesha kuwa ukubwa wa samaki aina zote (yaani dagaa na migebuka) umekuwa ukipungua ikionyesha kuwa kuna matumizi ya nyavu zisizozingatia ukubwa wa macho yaliyoruhusiwa na uvuvi katika maji ya karibu na nchikavu (nearshore), hasa uvuvi wa ringineti ambavyo ni tishio kwa uvunaji, uendelezaji, na usimamizi endelevu wa rasilimali za samaki wa Ziwa Tanganyika.

Kwa mujibu wa matokeo haya inashauriwa kuwa:

i. Wakati matokeo ya utafiti wa sasa yanapaswa kuzingatiwa kama ya awali, tunapendekeza njia ya tahadhari ya kuvuna sio zaidi ya asilimia 70 ya samaki wote (biomass) ili kuhakikisha kuwa uendelevu wa rasilimali hii unazingatiwa. Yaani, uvunaji haupaswi kuzidi tani 101,283 kwa mwaka. Ili kuhakikisha kuwa lengo hili linafikiwa, tunashauri njia za kutambua mavuvi yasiyotolewa taarifa au yaliyofichika (hidden harvest) zitumike, pamoja na kudhibiti biashara na utoroshaji wa samaki nje ya nchi bila kunukuliwa kwenye vitabu vya takwimu za mavuvi.

ii. Utafiti huu ulilenga kutambua kiasi/wingi wa samaki wa tabaka la juu (pelagic species) katika Ziwa Tanganyika ukilinganishwa na wingi wa samaki ulioripotiwa takribani miaka 30 iliyopita, katika utafiti wa mwaka 1995. Katika kipindi hiki, nguvu ya uvuvi imeongezeka karibu mara tatu (LTA - Sekretarieti, 2012) ya ile ya mwaka 1995, na hali ya mabadiliko ya tabia nchi yamezidi kuwa mabaya. Hivyo basi, tunapendekeza kuwa tafiti za mara kwa mara za tathmini ya wingi wa samaki katika Ziwa Tanganyika zifanyike katika misimu tofauti ili kuwezesha uvunaji, uendelezaji na usimamizi endelevu wa uvuvi katika Ziwa Tanganyika.

iii. Ziwa Tanganyika linapakana na nchi nne za Burundi, Jamhuri ya Kidemokrasia ya Kongo, Tanzania na Zambia. Tunapendekeza kuwa jitihada za makusudi za kuweka sheria na kanuni za usimamizi wa wa uvuvi kwenye ziwa hili. Hivyo, juhudi zinazochukuliwa na Mamlaka ya Ziwa Tanganyika (LTA) zinapaswa kuungwa mkono na nchi zote wanachama.

iv. Ili kuongeza uwezekano wa kukadiria kwa usahihi biomasi ya aina mbalimbali za samaki katika Ziwa Tanganyika, tunashauri kufanya jaribio la kutambua jinsi aina mbalimbali za samaki wanaoelea wanavyohusiana na mwangwi wa sauti (acoustic Target Strength). Hii itasaidia katika makadirio wingi wa samaki ya baadaye ili tuweze kuchambua kiwango cha samaki kwa kila aina ya samaki hawa ambayo itatumika kwenye ukadiriaji wa wingi wa samaki katika tafiti zinazofuata hapa nchini na kikanda.

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ABBREVIATION

Chl-a	Chlorophyll-a
CTD	Conductivity-Temperature-Depth
DCM	deep chlorophyll maximum
DO	Dissolved Oxygen
EDSU	Elementary Distance Sampling Unit
GAM	Generalized Additive Models
GPT	General Purpose Transceiver
KMFRI	Kenya Marine and Fisheries Research Institute
LED	Light emiting diode
LTA	Lake Tanganyika Authority
LVFO	Lake Victoria Fisheries Organization
NBS	National Bureau of Statistics
NM-AIST	Nelson Mandela African Institution of Science and Technology
NTU	Nephelometric Turbidity Units
SRP	Soluble Reactive Phosphorus
TAFIRI	Tanzania Fisheries Research Institute
TN	Total Nitrogen
TNC	The Nature Conservancy
TP	Total phosphorus
TS	Target strength
TSS	total suspended solids
UV	Utra violet
WBT	Wide Band Transceiver

1. INTRODUCTION

Lake Tanganyika is among the Great Lakes of Africa, which is the second deepest lake in the World and contains about 17% of the World's freshwater (Molsa et al. 2005). The lake harbours hundreds of endemic fish species, snails, crabs, shrimps, sponges, and many other faunal species, most of which are endemic to the lake. According to the latest population and housing census, the catchment of Lake Tanganyika encompasses four regions with a total of 8,556,123 people (NBS, 2022). These regions include Kigoma, Katavi, Rukwa and Tabora. People who reside in the four regions, as well as those who live in distant regions, benefit from the lake basin in terms of fish protein which ensures food security, employment and other ecosystem services. It is, thus, crucial to ascertain basic information on the lake's current pelagic fish stock, since fishers, investors, planners and managers need it to guide sustainable use, development, and management of the fish recourses. One of the most precise techniques for collecting this type of data, which includes estimates of fish population and their distribution on a broad scale, is the use of hydroacoustic method which has advantages of wide coverage and generation of high-resolution data among others.

The lake`s fishery can be divided into two components - littoral and pelagic sections. Littoral fishing focuses on cichlid and several non-cichlid demersal species and operates in the shallow inshore waters using gillnets, and there is no aggregation during fishing. The second type is the pelagic fishery which contributes significantly to the livelihood of many people who have been directly and indirectly employed by the fishery. The fishery is composed of six indigenous species, three of which are fished using light aggregation using kerosene and LED light as sources of light. The main species caught in this pelagic zone are the two sardines: Stolothrissa tanganicae and Limnothrissa miodon, and one latid species—*Lates stappersii*. The other latid species which are incidental in the catches include *Lates mariae*, *Lates microlepis*, and *Lates angustifrons* (Kimirei et al. 2008). Three of the pelagic species *Stolothrissa tanganicae*, *Limnothrissa miodon*, and *Lates stappersii* are exploited on a commercial level, making a significant contribution to the economies of the fishers and the respective districts and regions, and the nation at large. The main fishing gears in this area are lift- and ring-nets and a small number of subsistence fishers also use handlines for catching the four *lates* species.

Sardines are among the most fecund and short-lived of all the pelagic species. Their counterparts, which are all *Lates* species, have higher fertility and longer lifespans. The biology, distribution, and abundance of all these pelagic species are influenced by environmental, biological, and physical variables of the lake (Coulter 1991; Kimirei and Mgaya 2007; Plisnier et al. 2009). These parameters have an influence on food availability and distribution in the water column. Temperature provides optimal temperature for their metabolism as well as for the primary production processes within an ecosystem. The lake is deep, and an oxic layer that sustains life extends about 200 metres (m) below the water's surface. This layer's depth changes depending on the time of year and location. Additionally, the lake is noted for being sizable, meromictic, and oligotrophic (Plisnier et al., 1999). The amount of limiting nutrients increases with increasing water depth, forming a high vertical gradient over the thermocline (Edmond et al., 1993). As a result, the hypolimnion is nutrient-rich and the epilimnion has low nutrient concentration. In Lake Tanganyika basin, there are two main seasons: dry and wet (Naithani et al., 2002, 2003; Plisnier et al., 1999). The nutrient profiles fluctuate with these two main seasons, and secondary producers follow the same pattern since they depend on the changes that occur in the lake.

Despite its significant contribution to the local community and nation as source of income and food, the Information on the stock of the lake is very old as the last assessment of the lake's stock was conducted in the 1990s. The lack of comprehensive long-term studies has resulted in the limited availability of information about fish stock status in the lake. Although historical data exist as a result of research projects carried out by universities, institutes and organisations, it is scarce and, in practice, the state of the Lake's Tanganyika fish stock is poorly known. Taking all the aforementioned into account, the current state of fisheries stock in Lake Tanganyika must be dtermined using methods already in use. Fisheries acoustics is one of the widely used methods to estimate stock abundance in marine and freshwater systems. The method involves the use of underwater sound(s) to detect, enumerate, and measure the distribution of fish and other living marine and freshwater resources and describe their habitat.

This approach is preferable because of its ability to collect data directly from the population and measure the distribution of organisms over large spatial scales. In addition, hydroacoustics can also cover a much greater area per unit of time, allowing large spatial scales to be studied which may be necessary to sample highly mobile species. The overaching goal of this study was to use hydroacoustic techniques to estimate pelagic fish stock biomass in Lake Tanganyika and determine fish density in relation to biotic and abiotic conditions.

2. MATERIAL AND METHODS

2.1. STUDY AREA

The survey was conducted in the Tanzanian waters of Lake Tanganyika. The lake has a total length on 650 km and maximum depth of 1470 m, which makes it the deepest lake in Africa and second deepest in the world. The lake covers a surface area of about 32,900 km^2. The survey covered a total of 13,495 km^2 on the Tanzania side, which is about 41% of the area under the jurisdiction of Tanzania. The lake area was partitioned into three sections corresponding to the three main basins of the lake, that is, the Northern, Central and Southern basins (Figure 1).

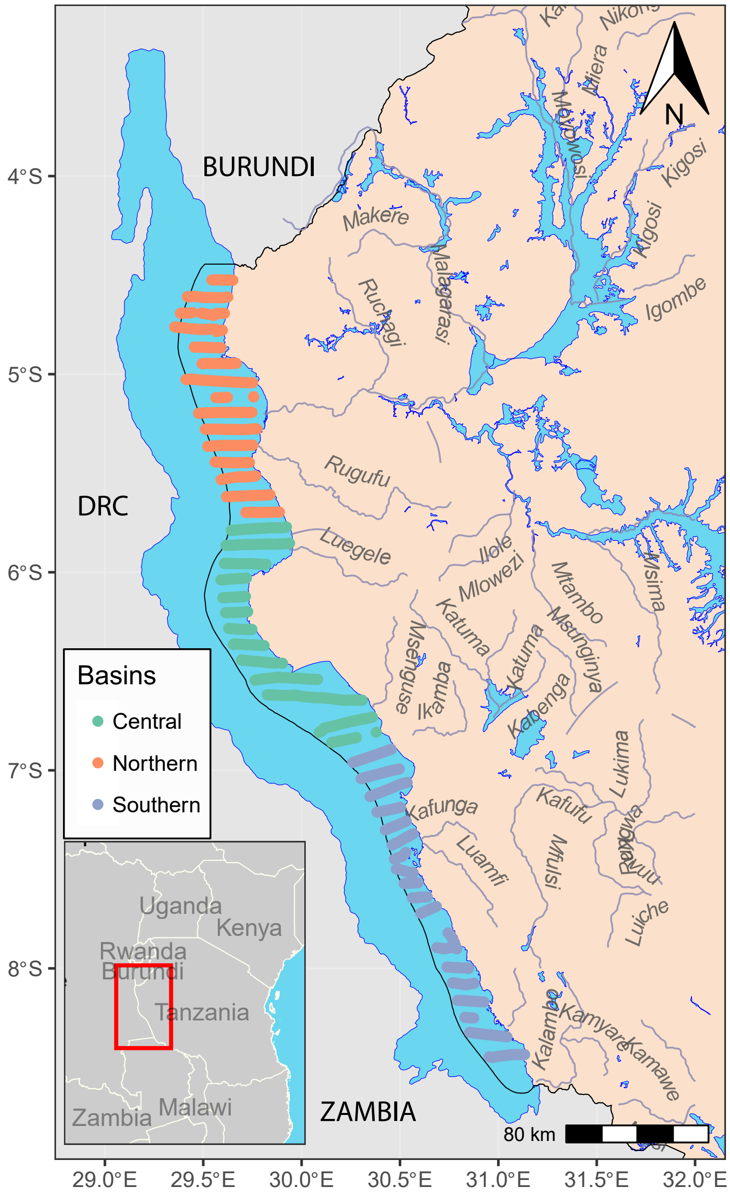

Figure 1: Map of Lake Tanganyika showing the hydroacoustic survey transects color-coded by basin. An inset map shows the location of the lake in the region.

2.2. STUDY DESIGN

Acoustic and fishing were done on predetermined transects that were about 10 km apart, running from the northern basin of the lake to the south. A 10 km apart distance was chosen as the best width between the transects considering resources availability during the execution of the survey. The transects were running perpendicular to the lake shoreline. Calibration of the echo sounder system, CTD, and YSI multiprobe Sonde was done in Kigoma Bay prior to commencement of the sampling campaign. The survey was conducted using a fibreglass Research Vessel (RV ECHO), which is 12.5 m long, 3.5 m wide, with a draft of 1.4 m and powered with an in-board engine of 300HP. Two echo sounder systems, the Simrad EK80 Wide Band Transceiver (WBT) with 120kHz as a central frequency operating in FM mode to collect broadband data and EK60 General Purpose Transceiver (GPT) operating at 70kHz frequency were used to collect the acoustic data.

Both transducers were mounted on a pole with a shoe of about 70 cm long to enhance beam overlap on the portside of the RV ECHO. Concurrently, fishing activities were performed using a separate wooden boat that was operating a ringnet during daytime and at night. Limnological parameters such as water temperature, conductivity, fluorescence, turbidity, DO, nutrients, and chlorophyll a were collected by a team of researchers that were on board another fibre boat, which was propelled by an out-board engine. Samplings of limnological parameters were done along the transects and close to the fishing areas (*See* Figure 3).

2.2.1. Calibration of echosounders

Calibration of the equipments was conducted using the standard target method for both systems (Demer et al. 2015). The FM calibration was carried out on 22nd February 2022 between 1700 and 2000 hours local time in Kigoma Bay, near the TAFIRI Kigoma Centre Offices (4. 0.8847167°S, 29. 0.6156 °E). The EK60 system was also calibrated after the EK80 WBT system in the same location. In both cases, a tungsten carbide sphere (38.1 mm) with target strength (TS) of -40.4 dB was used to calibrate the two systems. The calibration settings are given in Table 1. Measurements of the calibration environment (e.g., water temperature) were made using a YSI multi-probe sonde and sound speed was calculated using the EK80 software. The water temperature and mean sound speed at calibration was 27.1 °C and 1,502.14 m/s, respectively. Both calibrations were successful based on RMS values, where the 120kHz gave better calibration results than the 70kHz frequency transducer, and therefore, the 120kHz was used.

Table 1: Echo sounder specifications and calibration settings before the survey

Centre frequency (kHz)	**70**	**120**
Transducer type	ES70-7C	ES120-7C
Mode	CW	FM
Power (W)	225	200
Pulse duration (ms)	0.256	0.256
Ping rate(s)	Max	Max
Transducer depth (m)	2	2
Calibration results		
RMS error	0.3810	0.0529

Centre frequency (kHz)	70	120
Gain (dB)	23.5	26.53
Sa correction	-0.7638	-0.1448
Beam width alongship (deg)	7.27	6.63
Beam width athwartship (deg)	7.27	6.63
Angle offset alongship	0.05	-0.08
Angle offset athwartship	0.03	0.09

2.2.2. Survey Transects

The survey followed parallel predefined transects spaced at about 10 km intervals (Figure 2). Sampling was restricted to daylight hours to minimize interference from taxa other than fish. The parallel lines were considered as Transects where the vessel was heading in the same nominal direction at constant speed (about 6 knots). The distance travelled between the two nearby transects was called Deadhead and was not considered for analysis. The transects were designed to start and end at about 5 nm from the shore for safety reasons, particularly, because there was no current bathymetric chart for the lake.

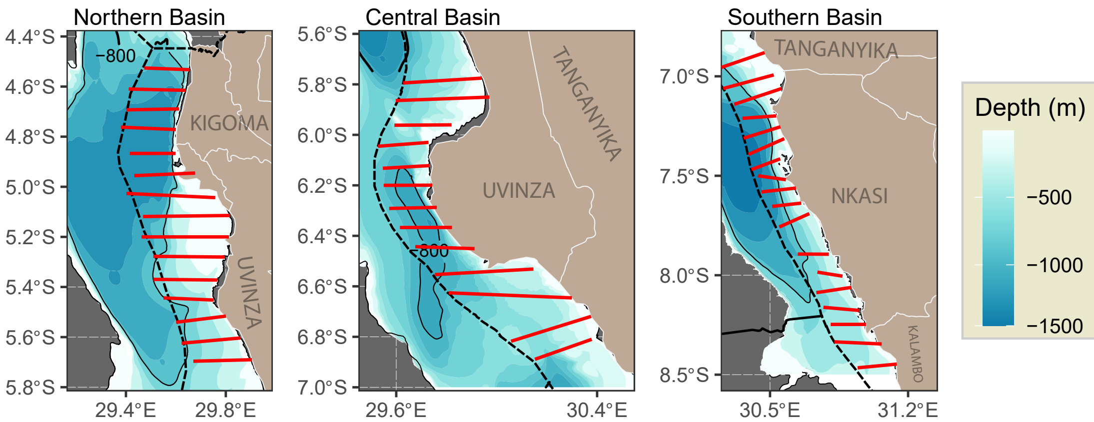

Figure 2: The Lake Tanganyika bathymetry overlaid on hydroacoustic survey transects (red lines) for the northern, central, and southern basins. The thick-black-dotted line is the international boundary.

2.2.3. Data logging, storage, and preparation

Acoustic data was logged in 100MB files and stored to external SSD disk drives. After the survey, raw acoustic data files were loaded into Echoview (v. 12.0 Myriax, Hobart, Australia) software using a standardized template to ensure consistency, specifically for selected exports and analysis telegrams and saved as EV files.

2.2.4. Acoustic data analysis

Data collected from regions designated as 'Transect' were used for analysis of standing stock. Depth layers were binned to standard depth with 5m depth intervals and one-kilometre horizontal interval (Elementary Distance Sampling Unit – EDSU). Estimates of the standing stock of fish were done using echo integration. The mean transect density for each EDSU was calculated as the mean of all EDSUs within the respective transect (Jolly and Hampton 1990). Integration was done between the top line (fixed at 2m depth from the surface) and analysis line (fixed at 200 m depth). Data was exported by region and by cell. Since this survey obtained poor fish catch due to gear limitations, Sv values were converted to density using TS per kg of -30.47 dB (Szczucka, 1998). The TS has previously been used for *Stolothrissa tanganicae*, *Limnothrissa miodon* and *Lates stappersii*, which are reported to occur in mixed aggregations and their acoustic properties are similar (Szczucka, 1998). Therefore, during this survey, only the total abundance of the mixture could be estimated on the assumption that one unit weight of all the species reflected the same proportion of acoustic energy. Thus, fish density was calculated with following formula:

$$Density = (1000 * 10^{2}\ (Sv\text{-}TS/10)\ *2$$

Whereby: S = echo signals
TS = target strength per kg of fish

A longitudinal cross section of fish density for each transect was computed. A total of 45 longitudinal cross-section were mapped and compared for density difference for northern, central and southern basins. Along the transect, longitudinal cross section analysis was computed using fish density binned in the five metres depth interval from the surface to 200 metres deep. Furthermore, a latitudinal cross-correlation analysis was performed by averaging fish density at five metre depth intervals from the surface to 200 metres in one-kilometre horizontal surface of latitudinal gradient from the northern transect to the southern transect of the lake. Fish density was explored for spatial distribution differences, while it was also colour-mapped both along transect and depth-wise, in the West-East direction, to visualise the variation in both dimensions at the same time, where transect distances aligned to standard depth. Finally, in each bin, a total fish density was computed and interpolated spatially to create cross-section variations both in latitudinal and longitudinal gradients for northern, central, and southern basins of the Lake Tanganyika.

2.3. BIOLOGICAL AND ENVIRONMENTAL DATA ACQUISITION

2.3.1. Biological data

Two fishing boats with dimensions of 11 and 15 m long, 1.2 and 2.0 m wide and 1.45 and 2.5 deep for the first and second boats, respectively, were used to collect biological data. These boats were fitted with ring nets which were used to catch fish and estimate catch rates and composition of each species. The fishing nets had a mesh size of 10mm and height of about 30m and 50m (from surface to bottom), respectively. The length of these nets was 100 and 150m, respectively. The duration for each haul was generally one hour during daytime, while light aggregation for night fishing was about two hours. In total, 42 hauls were done using the two fishing boats, which were hired from local fishers.

The total catch was weighed with a digital spring balance (Kg) and then sorted between large Lates and smaller individuals (sardines and juveniles of *Lates* spp.) for biological and composition analyses from each haul. A proportion factor was then developed out of the grab sample to estimate catch composition and biometric data of the respective haul for *S. tanganicae* and *L. miodon*. Other fish species caught along with the target species, such as cichlids and non-cichlids were sorted and identified to their respective groups.

The majority of the net hauls were done within predetermined hydroacoustic transects as guided by the acoustic team after observing fish schools. This was done by sharing geographic coordinates of the location where fish were observed to be abundant through the acoustic signals. Sharing of the coordinates made sure that fishing was done at the desired area. This was done both during the day and night depending on how fast the fishing boat could arrive at the identified fishing ground. For the northern and part of the middle section of the lake (from Kagunga to Ikola), fishing was done during the daytime while in the remaining part of the central and southern sections (Ikola to Kasanga), net hauls were done during the night to increase the chances of catching fish. Ringnet was selected because it is the largest fishing gear being operated in the pelagic area of the lake. It can also be operated during day and night, due to its large size and high chances of catching fish, compared to lift nets that are prominent in the lake, but used during night-time.

Fish individuals were measured for length (mm) and weight (grams), and their sex and gonadal maturity stages determined (Kimirei 2005; see Table 2), and gut content and stomach fullness were determined after gutting. This was done after sorting fish catches from each haul into species levels for the six targeted species (*L. stappersii, L. mariae, L. angustifrons, L. microlepis, S. tanganicae and L. miodon*). Cichlids and non-cichlids were sorted into a genus/group level and no biometric data were collected. For small catches, every individual fish in the catch was measured while large catches biometrics were drawn from a sub-sample. Historical length and weight data of the three species was also used in supplementing the smaller number of individuals that were caught during this survey. This data was used in calculating growth parameter 'a', 'b', and calculating the length frequencies of the three species.

Table 2: Description of the five-point maturity stage key (modified from Kimirei, 2005)

Stage	Description
Stage 1: Immature (juvenile)	Young individuals, which are not yet able to reproduce. Gonads are exceedingly small, translucent, and thread-like. Sexes not identifiable by naked eyes, thus grouped together.
Stage 2: Maturation	Eggs are opaque and distinguishable to the naked eye. A very rapid increase in weight of the gonad is in progress. Testes change from transparent to a pale pinkish colour.
Stage 3: Maturity	Sexual products are ripe. Gonads have achieved their maximum weight, but the sexual
Stage 4: Reproduction (spawning)	Sexual products are extruded in response to light pressure on the belly. Eggs easily detachable and ovarian membrane easily punctured. Weight of the gonads decreases rapidly from the start of spawning to its completion.
Stage 5: Spent	Gonads are translucent and flaccid, and with small opaque residual eggs in the distal part of the ovary.

2.3.2. Environmental data

Limnological sampling was conducted from the northern part (Kigoma region) to the middle section of the lake (Kigoma-Katavi border). Activities for limnological sampling included measurements of the physical-chemical parameters such as dissolved oxygen (DO) using YSI EXO2 Multi-Parameter Water Quality Sonde (Yellow Spring Instrument Inc., USA). Water samples for YSI parameters were collected from the surface to 120 m at an interval of 20 m, and were measured onboard a fibre boat. Discrete water samples for nutrients and chlorophyll a (Chl-a) analyses were collected from the surface to 120 m at an interval of 20 m, using a Niskin Water Sampling Bottles with a capacity of 30 L.

Water samples for analysis of dissolved nutrients, that is, nitrate (NO3-) and soluble reactive phosphorus (SRP) were filtered on-board through a 0.45 μm nucleopore membrane immediately after collection. Water samples for analysis of total nitrogen (TN) and total phosphorus (TP) were collected and stored unfiltered. To determine chlorophyll a concentration, 4 L of water per each depth were filtered on-board through a 0.7 μm glass fibre filter (Whatman GFF), and filters were placed in glass tubes containing 10 mL of 90% (v/v) acetone. All collected samples were stored on ice and taken to the laboratory at TAFIRI-Kigoma Centre for analysis.

Nitrate was analysed by using the ultra-violet (UV) colorimetric methods (APHA 1998), while TN was analysed by using similar UV colorimetric methods following the peroxydisulfate oxidation process. SRP was analysed by using the ascorbic acid method. TP was analysed by peroxydisulfate oxidation followed by molybdenum antimony spectrophotometric method (APHA 1998). Chl-a was extracted with 90% (v/v) acetone after first disrupting the cells for 15 min in a Branson Sonicator. The samples were then kept at 4°C overnight and re-sonicated the following day before analysis. Chl-a was then analysed spectrophotometrically in unacidified form at 665 nm wavelength.

2.3.3. Hydrographic Data

To complement the hydroacoustic data, the hydrographic data collection was conducted using CTD and other water quality parameters including Chl-a, total suspended solids (TSS), salinity, dissolved oxygen (DO), and pH. Hydrographic profiles were collected using a SBE 19plus V 2.2d instrument (Sea-Bird Scientific, USA), which is configured with an internal Digiquartz pressure sensor and a pair of external temperature and conductivity sensors. The instrument configuration also included additional sensors for oxygen, fluorescence, photosynthetic active radiation (PAR), Nitrogen saturation, Oxygen saturation and turbidity. The casts were deployed along each hydroacoustic transects and the maximum depth at each location was determined. The CTD was mounted in a vertical position to a 750 m rope from the lower part of a vessel. The deployment procedure involved lowering a CTD instrument to about 2 meters below the surface and waiting for a minute to stabilise the CTD pumps and raise it near the surface before lowering a CTD for profiling. The time and position of each cast was recorded using a handheld GPS device. The profiles were sectioned into the different basins as presented in Figure 4.

2.3.4. Processing Hydrographic Data

The first part of standard processing of the CTD data was to convert raw data stored on a computer as binary number in `.hex` format into engineering units. Both up-cast and down-cast were processed and exported as ASCII file in `.cnv` format, which was further binned to standard depth of 5-meter interval from the surface to the maximum depth of each profile. Then the standardised profiles were filtered with a low pass filter to remove spikes of CTD measurements caused by tow and roll of a boat. Profiles of temperature, conductivity, oxygen, fluorescence, and PAR were aligned to standard pressure of 5 metre interval.

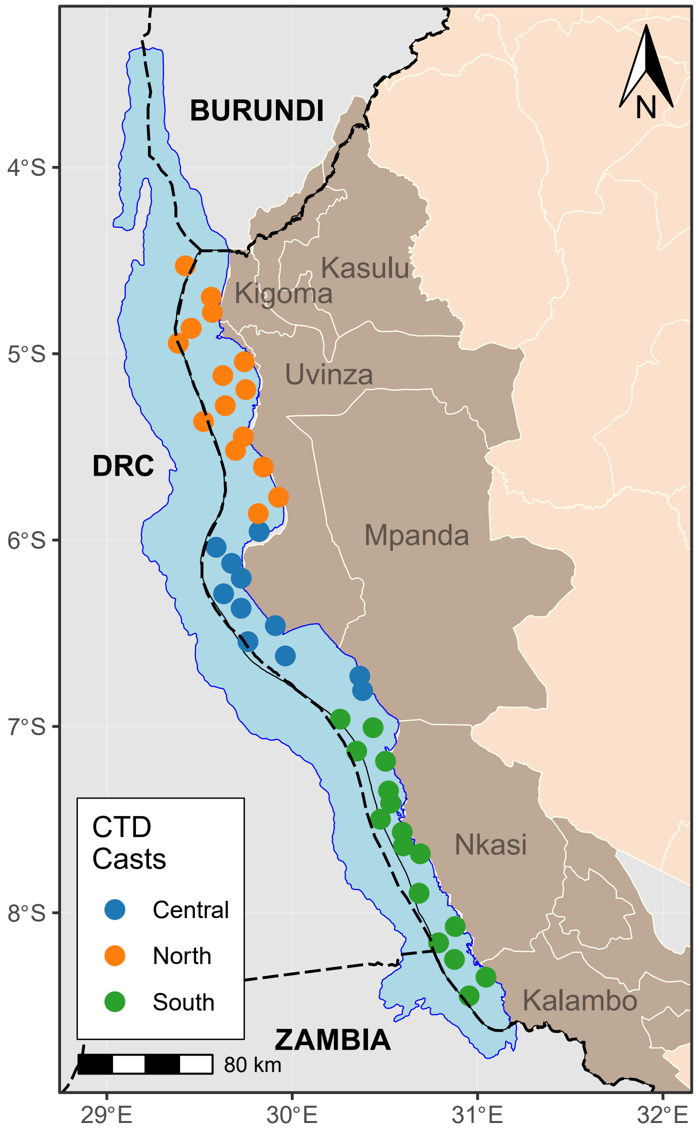

Figure 3: The CTD locations in Lake Tanganyika where hydrographic profiles were deployed during the survey. The color-coded bullions represent the cast based on the lake's basins

2.3.5. Data Analyses

For environmental parameters, comparisons between the three basins were calculated from the mean values of data that were collected in the respective basins. Furthermore, the water column of the lake was divided into two layers, the upper and bottom layer. For the purpose of this analysis, the upper layer is considered to be more productive in terms of primary production and represents a water depths from the surface to 50 m. Likewise, the bottom layer is considered less productive in primary productivity and represents a water depths below 50 m.

The functional relationship between vertical distribution of fish density and hydrographic variables was assessed using a Generalised Additive Models (GAMs). GAM was chosen because it handles linear and non-linear relationships between response and predictor variables (Zhao et al. 2014). GAM models were developed using the gam function in mgcv package (Wood, 2017). The vertical gradient of fish was used as response variable and temperature, fluorescence, turbidity, conductivity, and depth as independent variables. The fish density was converted from gram per square meter to kilogram per square kilometre.

The non-linear components of the GAM were fitted with locally weighted polynomial loess smoother to replace least-square fits in regression. Because the span or neighbourhood sizes of loess smoother determine the fraction of the datasets used in smoothing at each point, the best smooth was chosen through a series of steps. First smoothing was done with 10% (mul = 0.1) of fish density, but some of the responses were poorly represented and used 1% (mul = 0.01). Furthermore, it was noticed that fish density contains values that are relatively higher and were considered outliers. Fortunately, a span of 0.1 was able to smooth the either longitude or latitude as function of depth in the sampled transects. The profile plots were created using SigmaPlot 10.0 (Systat Software Inc, USA), whereas maps and cross-section plots and statistical charts were created using R language version 4.2.

3. RESULTS AND DISCUSSION

3.1. PELAGIC FISH STANDING STOCK

The current biomass of pelagic fish in the Tanzanian part of Lake Tanganyika was estimated to be 144,690 tonnes with an average density of 11.13t/km2. The highest biomass was recorded from the Central region (60,796 tonnes), followed by the southern region (52,928 tonnes) and the least biomass, that is 30,966 tonnes, was recorded in the Northern basin (Table 3). The overall biomass of 144,690 tonnes reported in this survey is lower by 12,803 tonnes (about 8%) from the total biomass of 157,493 tonnes which was recorded by Szczucka, (1998) for the Tanzanian side of the lake. The decline in biomass may be associated with the increase in fishing effort and changes in environmental factors, especially lake warming. It was not possible to discriminate between fish species and provide estimates of biomass by fish species due to limited number fish samples and lack of target strengths of fish of interest. The pelagic fish species, that is *Stolothrissa tanganicae, Limnothrissa miodon* and *Lates stappersii*, normally occur in mixed aggregations and their acoustical parameters have been previously reported to be almost the same (Szczucka, 1998). Similarly, previous surveys were not able to apportion biomass estimates by species for the same reasons.

Table 2: Biomass estimates of pelagic fish by basin in Lake Tanganyika, Tanzania.
CV = coefficient of variance of mean density of the survey region.

Basins	Area (km^2)	Biomass (tonnes)	Mean Density (t/km^2)	CV
Northern	4,729	30,966	6.55	0.19
Central	4,188	60,796	14.52	0.21
Southern	4,578	52,928	11.56	0.32
Total	13,495	144,690		

3.1.1. Density distribution

Mean (±SD) fish density distribution per basin/region and depth strata are presented in Figure 4. High densities were recorded at the lower and upper portions/sections of the central and the southern basin of the lake, respectively, while the northern basin recorded low densities (6.55 ±0.19). Most fish densities were recorded in the upper 80 m of the water column for all basins. The northern basin had relatively high densities in waters not more than 80 m. In addition, the central basin and the northern portion of the southern basin recorded high fish densities in waters deeper than 80 m, indicating that the environmental conditions in the central basin was conducive enough to allow fish to aggregate in waters as deep as 200 m (Figure 4).

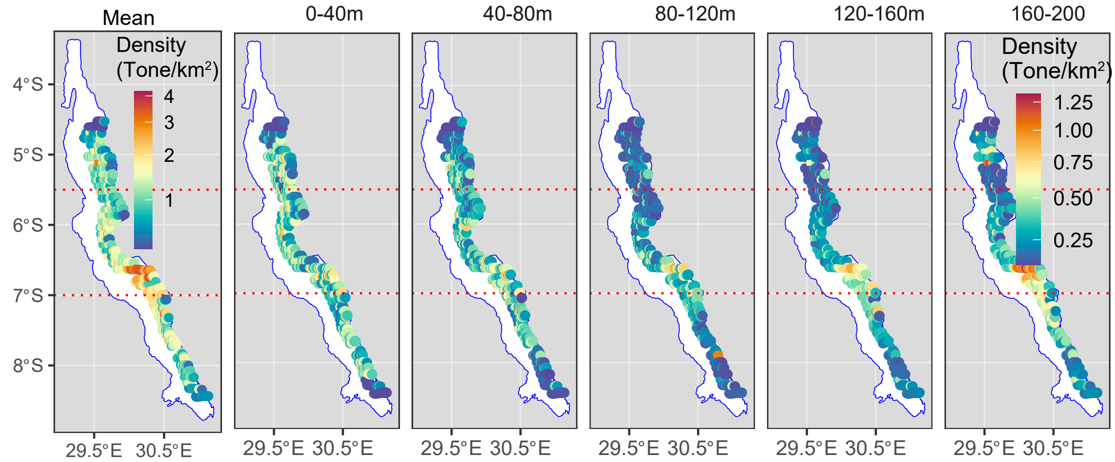

Figure 4: Spatial distribution of fish density divided into five water column strata

Figure 5 shows the latitude-depth cross section of fish density from the northern-most to the southern-most tip of the Tanzanian side of Lake Tanganyika. It indicates that fish densities varied both at latitudinal and depth gradients. The high density of fish above 150 kg/km^2 were recorded in surface waters between latitude 7°S and 4.8°S, which form the southern part of the northern basin, the whole central basin, and the north part of the southern basin. This latitudinal band of high density is visible from the surface to around 80 metres deep (Figure 5). The southern tip of the south basin at latitude 7°S and above and the northern basin from latitude 5 are characterised with low fish densities across the section (Figure 5).

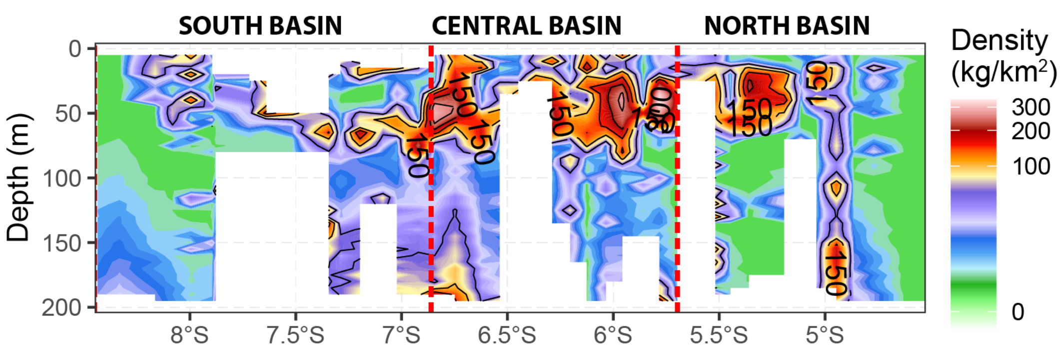

Figure 5: Latitudinal cross-section of fish density in Lake Tanganyika with gridded colour scale overlaid with contour of fish density. The red-dotted line marks the boundary of the northern, central, and southern basins of Lake Tanganyika

Furthermore, fish densities varied longitudinally with depth (Figure 6). The high fish density along the longitudinal gradient in the northern and southern basins are limited in the upper water column from the surface to about 60 metres and low fish density in the deep-water layer (Figure 6). The central basin of the lake had the lowest fish density in the upper water column and higher densities in depth between 80 and 120 metres, which span about 32 km from the centre of the lake to the eastern shoreline in Tanzania (Figure 6).

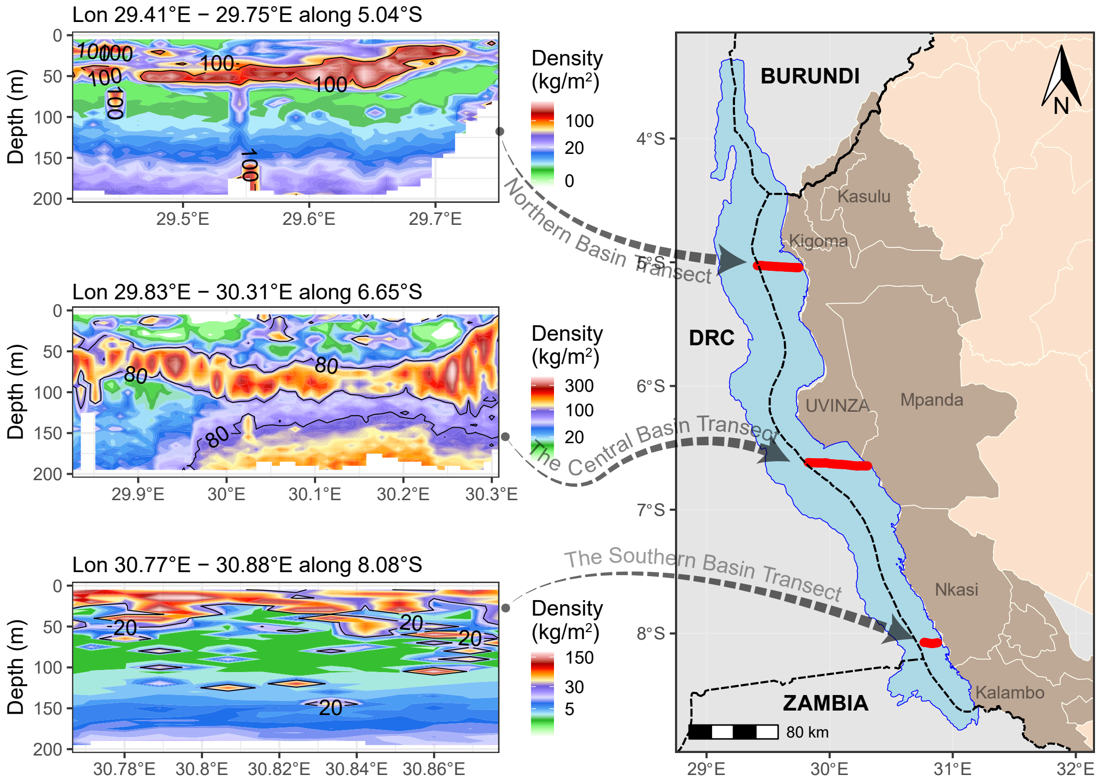

Figure 6: Longitudinal sections of fish density from the selected transects in the northern basin (top panel), central basin (middle panel) and southern basin (bottom panel). The transects are shown with red dots on the map (right panel)

3.2. BIOLOGICAL AND ENVIRONMENTAL VARIABLES

3.2.1. Catch rates

Figure 7 presents a map with locations where fishing was conducted during the survey, and data of whether hauls had or had no fish caught. It was observed that nearly 54% of all the hauls had fish caught while the remaining hauls (46%) had no catch at all. It was observed further that most hauls with catch were concentrated in the central and southern basins of the lake. It is, therefore, not surprising that the central and southern basins had higher catch rates than the northern basin (Figure 7). Lack of fish catches in the northern sites does not necessarily indicate absence of fish. This may be reflective of the deficiency of the fishing gear used. The survey employed ringnet fishers during the day, who were given coordinates of schools of fish observed by the hydroacoustic team. It was observed that the ringnet used by the fishers was not deep enough to reach the depths at which schools of fish were observed. This, also, calls into question the validity of fishers wanting to fish for dagaa during the day.

Nonetheless, the catch rate results agree with the findings of Beard et al (1997) that catch rates are directly related to fish densities, and that fish population data can be used to predict catch rates. This seem to have been the case for the central and southern basins where catch rates followed fish densities collected from the hydroacoustic survey (see Figure 4 & Figure 5). Generally, the pelagic fish catches from the lake in recent years have declined (Kimirei et al. 2008; Mgana et al. unpublished manuscript). The decline of fish catches in the offshore waters is thought to have caused fishers to fish in the inshore as an adaptation to reducing the running cost of their vessels by using less gasoline. Fishing in the inshore is resulting in catching even the undersized individuals of dagaa. Our findings proves that any alteration in fishing gears, location and time could have an impact on sizes and composition of the individuals caught.

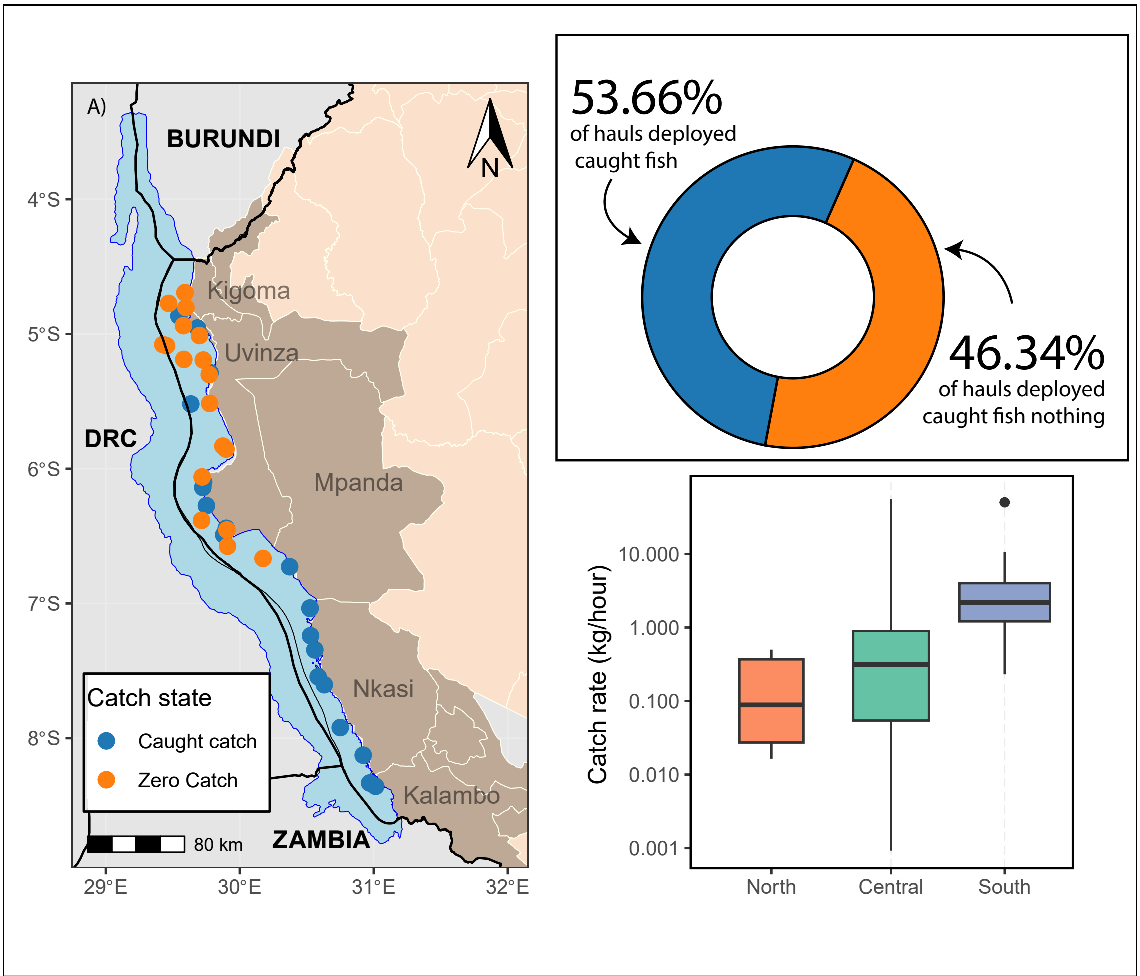

Figure 7: Location of fish haul and points indicate state of haul with or without catch. The donut plot indicates the percentage of haul with and without catches and boxplot presents catch rates (kg/hour) by basins

3.2.2. Length-frequency Distribution

Figure 8 presents length frequency distribution for *Lates stappersii, Limnothrissa miodon*, and *Stolothrissa tanganicae* obtained from the current hydroacoustic survey report and historical data. The historical data were collected from landing sites while the 2022 data are from fishing operations during the survey. The data indicates a bimodal distribution for *L. stappersii* in 2022 with peaks at 30 and 300 mm. Individuals with 30 mm are uncommon as can be deduced from historical data and is reflective of recruitment. The length frequency data for *L. stappersii* indicate that between 1994 and 2011, individuals of *L. stappersii* were about 300 mm, while most fish caught between 2011 and 2022 are relatively small with average total length of about 200mm. These findings reflect a shift in the size structure of *L. stappersii* which represents the current situation at the landing sites where majority of catches are juveniles.

The shift towards smaller sizes of *L. stappersii* in recent years can be explained by the shift in fishing gears, fishing behaviour and activities, fishing effort, and climate change (Mgana et al. unpublished manuscript; O'Reilly et al. 2003). These reasons include: i) the use of non-selective gears that have been introduced in the fishery, such as the Freemaya nets, some of which are undersized, for fishing Migebuka and the fishers' use of a 40% hanging ratio of these nets is allowing the catching of a wide range of fish sizes and may not be sustainable in a long run (TAFIRI 2020); ii) change in fishing practice, where fishing activities in Lake Tanganyika is done throughout the year, which allows fishers to catch small individuals during spawning and recruitment periods of the year; iii) change in fishing pressure, where the number of fishing efforts (vessels and gears) in Lake Tanganyika have increased over time which has inflated the fishing pressure, thus, stressing further the fish resources. Therefore, reduction in sizes is an adaptation strategy to maintain their capability to reproduce and recruit to the pelagic fishery. The increase in sizes starting in 2020 may reflect selectivity of the Freemaya net, which may occasionally be selective; iv) Climate change that is causing lake water warming, may also be contributing to the reduction in sizes since it causes reduction in natural fish food and causing fish to invest into regulation of body temperature rather than invest into growth of somatic tissue.

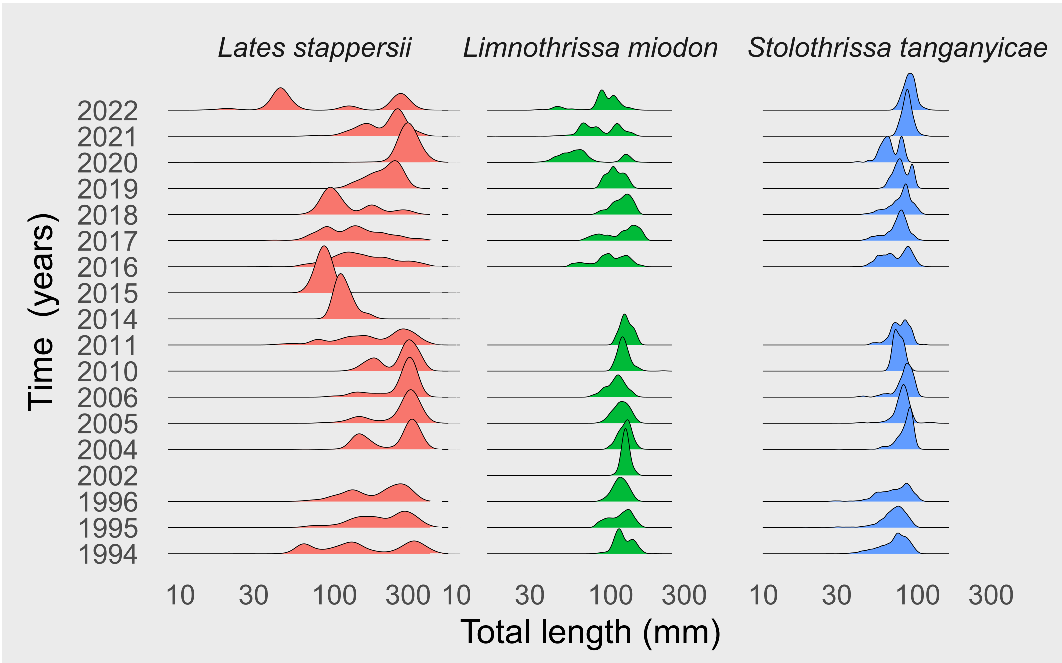

Figure 8: Length frequency distribution for *Lates stappersii, Limnothrissa miodon* and *Stolothrissa tanganicae* during 1994 through 2022.

The size frequency data for *L. miodon* indicate a general reduction in mean size since 2016, where a bimodal size distribution pattern appears, indicating presence of fishing of undersized individuals. Before 2016, *L. miodon* catches were of the same size ranging at 120mm and 160mm. Based on the ecology of this species, the fact that small-sized individuals are landed, indicates that fishers are fishing in putative nursery habitats. *L. miodon* is known to spend most of its life in inshore waters, migrating to deep offshore waters for spawning, where they are caught by the liftnet fishery. After spawning, the larvae migrate to inshore nursery habitats to restart the cycle. While most of the catches during the current survey came from sites that were close to shore, fishing was done both in the inshore and offshore waters. It is, therefore, plausible that the pattern observed since 2016 is caused by fishers fishing in nearshore nursery grounds, and most probably using undersized meshes.

Similarly, the length frequency distribution of *S. tanganicae* species indicates bimodal distribution during 2019 and 2020, signifying, in this case, the rampant use of small mesh liftnet or ringnets in nearshore waters. The predominance of *S. tanganicae* individuals with sizes ranging from 80 to 95mm and displaying single modal class in the years before 2016 indicates that fishers were mostly fishing from offshore locations and probably abiding to the mesh size regulations. Bimodality in length frequency distribution of *S. tanganicae* started showing in 2016 and may be related to the introduction of ringnets which are fishing in nearshore waters and sometimes using undersized meshes (Mgana *et al*. unpublished manuscript).

3.2.3. Environmental variables

Water temperature did not vary much between the basins. It was highest in the upper layer of the lake relative to the bottom layer (Figure 9). Water temperatures were 25.17 ±1.09, 25.30 ±1.11, and 25.48 ±1.14 °C in the north, central, and south basins, respectively. It ranged between 23.53 - 27.39, 23.79 - 27.24 and 23.97 - 27.79 °C in the same basins, respectively (Table 3). The thermocline was situated around 50 m in the north and relatively deeper in the central and southern basins (Figure 10). The high surface water temperatures observed during the survey may be attributed to low wind speeds and warm weather conditions existing in the lake region during the wet season. The wet season is characterized by an existence of weak north-easterly monsoon winds (Coulter and Spigel 1991) and presence of cloud cover especially during the rainy days. Cloud cover insulates the environment and prevents evaporative cooling thereby reducing heat loss, resulting in more heat energy being retained in the environment.

Although fluorescence measurements in all basins did not differ significantly, the maximum values were higher in central and southern basins. Fluorescence ranged between 0.03 – 0.23, 0.03 – 0.33, and 0.03 – 0.27 for northern, central, and southern basins, respectively (Table 3). Moreover, the high fluorescence values measured in the central basin occurred deeper at around 40 - 50 m (Figure 9). The fluorescence values reflected the variations in turbidity with high values recorded in the central basin. The upper layer of the lake was more turbid compared to the bottom layer of all the three basins, with the northern basin being more turbid followed by the central and south basins (Figure 9). High turbidity levels measured in the northern basin may be explained by the inflows and runoffs from the major and smaller rivers such as Malagarasi, Lugufu and Luiche, and storm water discharge from the Kigoma Municipality. The Malagarasi River comprises the largest catchment in the lake basin representing about 50% of the lake's total catchment area (Edmond et al., 1993), and contributes about 60% of all water flowing into the lake. Turbidity levels were also in agreement with Secchi depth transparency readings which were low in the northern basin (ranging between 6.5 – 15 m) followed by the central (ranging between 8 - 19.5 m) and southern basin (ranging between 8.5 – 21.5 m). Turbidity is a measurement of the amount of light that is scattered by organic and inorganic particles in the water (Lloyd et al., 1987). High turbid water prevents light penetration deeper in the water column and leads to a reduced phytoplankton photosynthesis and primary production. Electrical conductivity was higher in the upper layer of all the three basins compared to the bottom layer (Figure 10). Its values in the water column did not vary much between basins where the northern, central, and southern basins had mean (±SD) values of 684.62 ±2.86, 685.06 ±4.88, and 684.94 ±6.6, respectively (Table 3).

Table 3: Descriptive statistics of conductivity, fluorescence, water temperature and turbidity

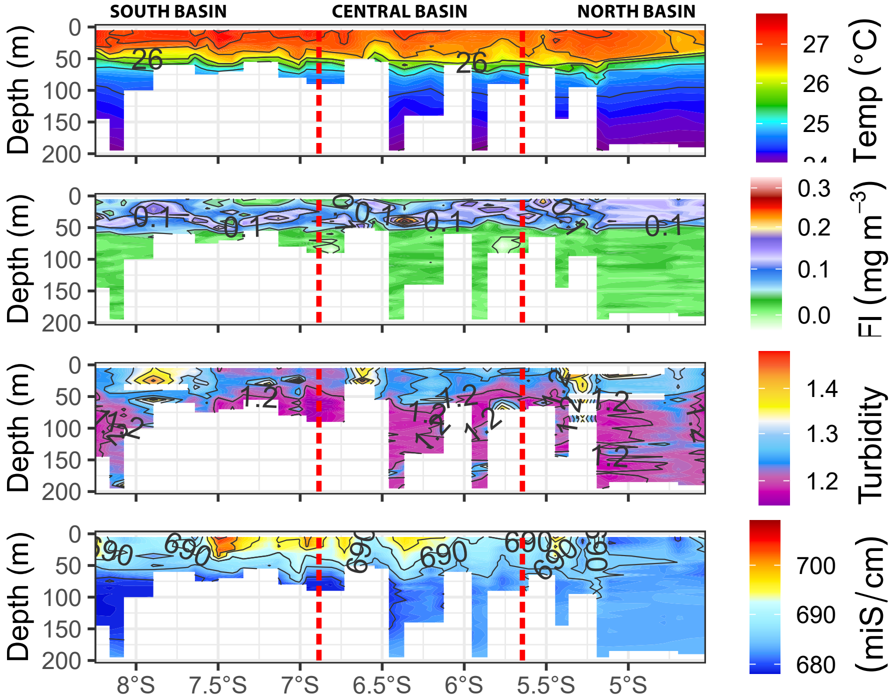

Figure 9: Cross-sectional area of water temperature, fluorescence, turbidity and electric conductivity from north, central, and south basins of Lake Tanganyika, Tanzania

from the north, central, and south basins of Lake Tanganyika, Tanzania. Min = minimum; Max = maximum; SD = standard deviation

Basin	Variable	Min	Max	Median	Mean	SD
North	Temperature (°C)	23.53	27.39	24.71	25.17	1.09
	Fluorescence (mg/m^3)	0.03	0.23	0.02	0.04	0.05
	Turbidity (NTU)	1.16	2.17	1.21	1.24	0.1
	Conductivity (µS/cm)	676.92	702.39	683.81	684.62	2.86
Central	Temperature (°C)	23.79	27.24	24.78	25.3	1.11
	Fluorescence (mg/m^3)	0.03	0.33	0.03	0.04	0.05
	Turbidity (NTU)	1.16	12.62	1.2	1.3	0.86
	Conductivity (µS/cm)	678.29	698.26	683.55	685.08	4.88
South	Temperature (°C)	23.97	27.79	25.07	25.48	1.14
	Fluorescence (mg/m3)	0.03	0.27	0.03	0.05	0.05

Basin	Variable	Min	Max	Median	Mean	SD
	Turbidity (NTU)	1.15	1.57	1.21	1.22	0.05
	Conductivity (µS/cm)	678.03	709.12	682.42	684.94	6.6

The surface water of the lake was generally well aerated, with oxygen values decreasing with increasing depth. Dissolved oxygen was high between 0 - 40 m and decreased abruptly with depth from 60 m to 120 m, after which in the north basin DO was almost zero. While dissolved oxygen in the north and central basins were comparable between 0 - 60 m, the central basin recorded comparatively higher DO values 80 and 120 m, with DO values as high as 4 mg/l (Figure 10). The presence of high oxygen at greater depth in the central basin indicates that both upper and bottom layers of this basin can support life, and may explain why there were high fish densities in the deep waters than in the northern basin (see Figure 5 & Figure 6).

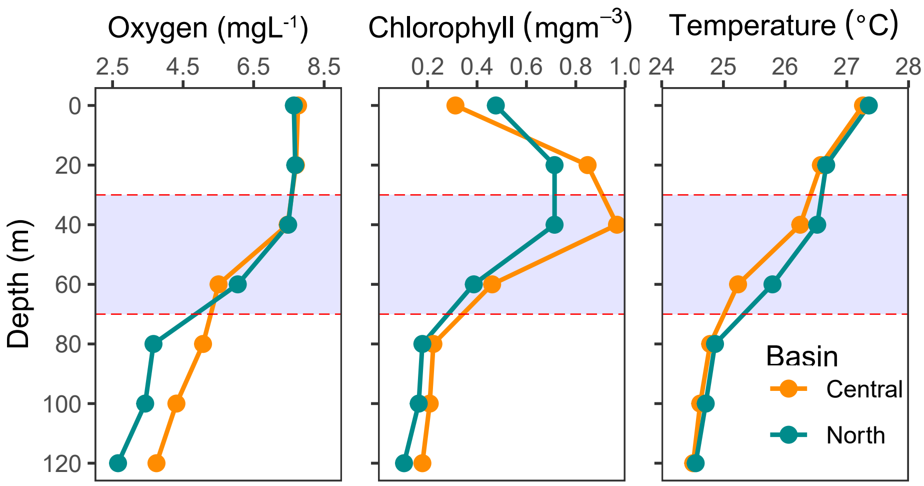

Figure 10: Mean vertical profiles of dissolved oxygen, chlorophyll and temperature sampled from the north and central basins of Lake Tanganyika

Comparison between the two basins (north and central) in terms of key nutrients that drive primary productivity of the lake is shown in Figure 11. The northern basin had relatively higher nitrate and soluble reactive phosphorus (SRP) concentrations compared to the central basin, except for the surface concentrations of SRP which were higher in the central basin compared to the northern basin. Contrary to the nitrate and SRP, the concentration of total nitrogen (TN) were highest in the central region of the lake. Meanwhile, total phosphorus did not show clear differences between the north and central basins. Phosphorus is a growth-limiting factor in lakes because it is often present in low concentrations (Horne and Goldman 1994). It has a strong vertical gradient across the thermocline with concentration increasing with increasing depth (Edmond et al. 1993).

Therefore, the upper waters of Lake Tanganyika are generally depleted of phosphorus because it is used phytoplankton, and its concentration varies with seasons. Phosphate in the upper productive layers increases during the dry season and vice versa during the wet season. During the wet season, the wind speeds are weak, weather conditions are calm, warm and the lake's thermal stratification is at its peak. Therefore, vertical mixing and nutrient generation from deeper waters is expected to be low (Mziray et al. 2018). This phenomenon may explain for a low SRP concentration observed in the upper layer relative to the bottom layer.

Nitrate is the most oxidized form of nitrogen. Vertical mixing, fixation and inputs from rainfall and runoff are the possible sources of nitrate in Lake Tanganyika (Edmond et al. 1993). Inflows and runoff from the rivers may have contributed to relatively high levels of NO_3 observed in the north compared to the central basin. However, uptake of SRP and NO3 by phytoplankton may explain for a relatively low concentrations of these nutrients in the central basin compared to the north basin. While Chl-a concentration was relatively high between 20 - 120 m in the central basin, the opposite was observed in SRP and NO_3 in the same basin (Figure 10).

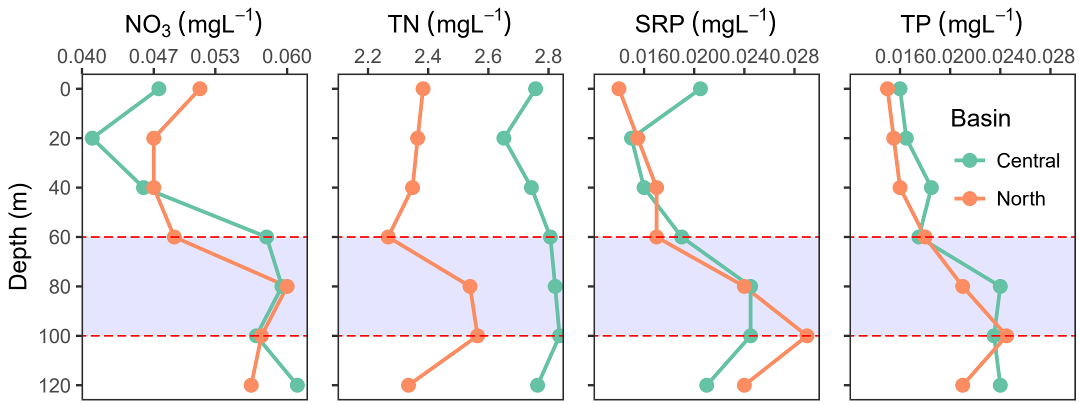

Figure 11: Mean vertical profiles of NO3, TN, SRP, and TP (mg/L) from the north and central basins of Lake Tanganyika, Tanzania

Chlorophyll a (Chl-a) concentration was relatively high in the central basin as compared to the northern basin. In the central basin, the Chl-a peak was observed between 20 and 40 m while in the north basin the peak was only measured at 20 m (Figure 10). The central basin had a thicker productive layer which occurred deeper (40 m) off the surface waters relative to the northern basin (Figure 10). During the wet season, the surface water temperatures are high and nutrient concentrations are low, which may not be optimal for algal growth. In such conditions, algae may trade-off bright light, warm temperature, and poor nutrients in surface waters for optimal temperature and nutrients in the deeper waters (Sigee 2005), provided that the water is clear enough to allow light penetration for photosynthesis (Mziray et al. 2018). Water in the central basin was, however, clearer compared to the north basin which may have contributed to a peak of Chl-a at 40 m in the central basin and only at 20 m in the north basin.

Moreover, Mziray et al. (2018) reported the occurrence of a deep chlorophyll maximum (DCM) during the wet season as the euphotic depth extended deeper in the water column. Their findings suggested further that, the expected reductions in primary production in the upper productive layer of the lake due to surface warming and strengthening of the lake thermal stratification occurring during the wet season may be partly compensated by increased primary production in the deeper layers if there is enough light and nutrients to support production. Secondary production, in this case, is more likely to occur in the central basin, thus supporting the findings of fish catches and densities reported by this survey (see Section 3.1 and 3.2). Acoustic signals were also in line with this observation. High fluorescence values in the central basin corresponded to high concentrations of Chl-a in the same basin, supporting our finding that the central basin was more productive relative to the northern and southern basins.

3.2.4. Influence of environmental variables on the fish densities

The pattern of fish density in Lake Tanganyika varies both in horizontally and vertically (depth) in response to the variability in the limnological variables. The hydrographic variables used clearly influence fish density in non-linear patterns (Figure 12). For instance, temperature (Figure 12b), fluorescence(Figure 12a), conductivity (Figure 12c), and turbidity (Figure 12d) and depth(-Figure 12e) all show a non-linear pattern with fish density. The tapering off temperature (Figure 12b) at 27 °C indicate an optimal temperature and thus has a positive influence on fish density. Increasing turbidity with decreasing transparency has a negative influence on fish density (Figure 12d). The optimal depth for high fish density in Lake Tanganyika was elucidated to be between 40 and 60 meters deep for all basins, while an increase in fish densities with depth was only observed for the central and southern basins (Figure 12e).

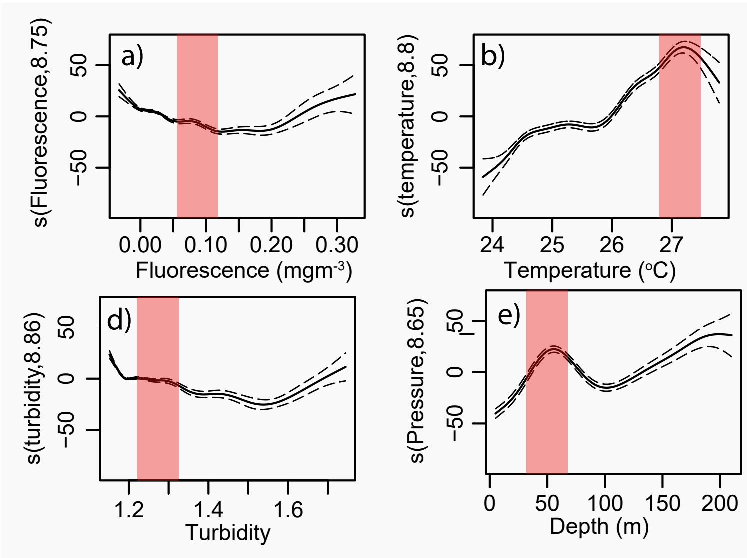

Figure 12: The Influence of hydrographical environmental variables in the vertical distribution of fish density in Lake Tanganyika. The red filled column indicates an optimal range of the variables with relatively high fish densities

4. CHALLENGES, RECOMMENDATIONS AND WAY FORWARD

4.1. CHALLENGES

Several challenges were encountered when fulfilling the objectives of the survey and deserve a mention and suggestions of how to deal with them in the future.

i. During the survey, water samples could not be measured beyond the Kigoma-Katavi border village because the team encountered severe rough weather around Ikola, which resulted in losing some of the sampling equipment. This hindered greatly the limnological sampling campaign. The boat used for limnological sampling was unable to handle extreme weather, and so, better equipment will be needed to effectively conduct the next survey. In this incident, some of our prized limnological sampling and measuring equipment were lost, which will need new investment in buying new ones.
ii. During the survey there were extremely few catches of fish from our fishing boats, which hindered us from collecting enough and robust samples size to support calculating species composition enough to help apportion the total fish biomass into different species.
iii. The improvised metal system that was used to mount the acoustic system bent twice against water current, this cost us time for repair.
iv. Lack of an hydroacoustic equipment and the analysis software cost us time and money for hiring from Kenya and delayed both the execution of the survey and the analysis and writing of this report

4.2. RECOMMENDATIONS

i. The current estimated biomass of 144,690 tonnes is slightly lower by about 8% from the 157,493 tonnes reported by the survey of February 1998. While the findings of the current survey should be considered preliminary, we recommend a precautionary approach of harvesting not more than 70% of the standing biomass which may be beneficial to the stock. That is, harvesting should not exceed 101,283 tonnes annually.
ii. This survey is an attempt to understand the stocks of the pelagic fish species in the lake from almost 30 years after the last survey in 1995-1998. During thing time, fishing effort has nearly tripled (LTA-Secretariat, 2012), and environmental changes have worsened. It is needed, therefore, to have regular stock assessment surveys in Lake Tanganyika in different seasons as a basis for determining fishing policy.
iii. The lake is shared by four countries Burundi, Democratic Republic of Congo, Tanzania, and Zambia. It is important to aim for a Lake-wide enforcement of fisheries regulations, and efforts being taken by the Lake Tanganyika Authority should be embraced and supported by all member states.

iv. There is a need to ensure, when planning another survey, various fishing methods like pelagic trawl, and gillnets are used to increase the probability of collecting updated biometric data from the three species. In this survey we used ring nets only for fishing and it was difficult to catch fish especially during the day and from such a deep depth.

4.3. WAY FORWARD

i. In order to maximize the possibility of correctly estimating the biomass of the various pelagic species in Lake Tanganyika, we will conduct an experiment to determine acoustic target strength in Kigoma. This will help in future estimations both at a country and regional levels.

ii. The government of Tanzania has set aside funding to conduct the second phase of the survey to ensure that both dry and wet seasons are covered, which will improve the quality of biomass estimates. While we had intended to conduct this during the dry season, we will conduct this during the wet season, probably around the same time. This has multiple benefits, one of which is that we will be able to use information to apportion the species and observe interannual variations.

REFERENCES

APHA (1998) Standard Methods for the Examination of Water and Wastewater Washington, DC American Public Health Association.

Beard, T.D., JR., Hewett, S.W., Yang, Q., King, R.M. and Gilbert, S.J. (1997) Prediction of Angler Catch Rates Based on Walleye Population Density. North American Journal of Fisheries Management, 17:621-627. https://doi.org/10.1577/1548-8675(1997)017<0621:POACRB>2.3.CO;2

Coulter, G.W. (1991) Lake Tanganyika and its life. British Museum (Natural History) and Oxford University Press, London

Coulter GW, Spigel RH (1991) Hydrodynamics. pp. 49-75. In: Coulter GW (ed) Lake Tanganyika and its life. British Museum (Natural History) and Oxford University Press, Oxford, UK

Demer D.A., Berger L., Bernasconi M., Bethke E., Boswell K., Chu D., Domokos R. et al. (2015) Calibration of acoustic instruments. ICES Cooperative Research Report No. 326, 133pp. DOI: http://dx.doi.org/10.25607/OBP-185

Edmond, J. M., Stallard R. F., Craig H., Craig V., Weiss R. F., Coulter G. W. (1993) Nutrient chemistry of the water column of Lake Tanganyika. Limnology and Oceanography 38: 725-738.

Horne, A. J., Goldman C. R. (1994) Limnology. McGraw-Hill New York.

Jolly GM, Hampton I (1990) A Stratified Random Transect Design for Acoustic Surveys of Fish Stocks. Canadian Journal of Fisheries and Aquatic Sciences 47: 1282-1291.

Kasangaki, A., Chapman L. J., Balirwa J. (2008) Land use and the ecology of benthic macroinvertebrate assemblages of high-altitude rainforest streams in Uganda. Freshwater Biology 53: 681-697.

Kilham P., Kilham S.S. (1990) OPINION Endless summer: internal loading processes dominate nutrient cycling in tropical lakes. Freshwater biology 23: 379-389.

Kimirei, I.A. (2005) Variability in Pelagic Catches and the Physico-Chemical Parameters in Kigoma Area, Lake Tanganyika, Tanzania. University of Dar es Salaam.

Kimirei, IA., Mgaya YD. (2007) Influence of environmental factors on seasonal changes in clupeid catches in the Kigoma area of Lake Tanganyika. African Journal of Aquatic Science 32: 291–298.

Kimirei IA, Mgaya YD, Chande AI (2008) Changes in species composition and abundance of commercially important pelagic fish species in Kigoma area, Lake Tanganyika, Tanzania. Aquatic Ecosystem Health & Management 11:29-35

Lloyd, D. S., Koenings, J. P., & Laperriere, J. D. (1987) Effects of turbidity in fresh waters of Alaska. North American Journal of Fisheries Management, 7:18-33.

LTA-Secretariat, (2012) Lake Tanganyika Regional Fisheries Frame Survey 2011, Bujumbura, Burundi, 30 pp

Malawi, N. S. O. o. (1998) Census. http://www.nso.malawi.net/

MFP, NBS(TZ), NBS (ZnZ) (2022) Sensa ya Watu na Makazi ya Mwaka 2022: Matokeo ya Mwanzo. Dodoma, Tanzania. 119 p. https://www.nbs.go.tz/nbs/takwimu/Census2022/matokeomwanzo-oktoba2022.pdf (accessed 10th January 2023)

Mannini P., Aro E., Katonda I., Kassaka B., Mambona C., Milindi G., Paffen P., Verburg P. (1996) Pelagic fish stocks of Lake Tanganyika: biology and exploitation. FAO/FINNIDA Research for the Management of the Fisheries of Lake Tanganyika. GCP/RAF/271/FIN—TD/53 (En): 60p.

Mölsä H, Sarvala J, Huttula T, Salonen K, Lindqvist OV (2005) Management of an African Great Lake Wshery: challenges to research and community. In: Hietanen O (ed) University partnerships for international development. Finland Futures Research Centre (FFRC) Publication 6/2005, Helsinki, pp 115–142

Mziray, P., Kimirei, I., Staehr, P., V. Lugomela, C., Perry, W., Trolle, D., M. O'Reilly, C., F. Mgana, H. (2018) Seasonal patterns of thermal stratification and primary production in the northern parts of Lake Tanganyika. Journal of Great Lakes Research 44: 1209–1220.

Naithani J, Deleersnijder E, Plisnier P-D (2002) Origin of intraseasonal variability in Lake Tanganyika. Geophysical Research Letters 29:1-4

Naithani J, Deleersnijder E, Plisnier PD (2003) Analysis of Wind-Induced Thermocline Oscillations of Lake Tanganyika. Environmental Fluid Mechanics 3:23-39

O'Reilly CM, Sharma S, Gray DK, Hampton SE, Read JS, Rowley RJ, Schneider P, Lenters JD, McIntyre PB, Kraemer BM, Weyhenmeyer GA, Straile D, Dong B, Adrian R, Allan MG, Anneville O, Arvola L, Austin J, Bailey JL, Baron JS, Brookes JD, de Eyto E, Dokulil MT, Hamilton DP, Havens K, Hetherington AL, Higgins SN, Hook S, Izmest'eva LR, Joehnk KD, Kangur K, Kasprzak P, Kumagai M, Kuusisto E, Leshkevich G, Livingstone DM, MacIntyre S, May L, Melack JM, Mueller-Navarra DC, Naumenko M, Noges P, Noges T, North RP, Plisnier P-D, Rigosi A, Rimmer A, Rogora M, Rudstam LG, Rusak JA, Salmaso N, Samal NR, Schindler DE, Schladow SG, Schmid M, Schmidt SR, Silow E, Soylu ME, Teubner K, Verburg P, Voutilainen A, Watkinson A, Williamson CE, Zhang G (2015) Rapid and highly variable warming of lake surface waters around the globe. Geophysical Research Letters 42:10,773-710,781

Plisnier, P.-D., Mgana, H., Kimirei, I.A., Chande, A.I., Makasa, L., Chimanga, J., Zulu, F., Cocquyt, C., Horion, S., Bergamino, N., Naithani, J., Deleersnijder, E., Andre, L., Descy, J.-P., Cornet, Y. (2009) Limnological variability and pelagic fish abundance (Stolothrissa tanganicae and Lates stappersii) in Lake Tanganyika. Hydrobiologia 625:117-134

Plisnier, PD., Chitamwebwa D., Mwape L., Tshibangu K., Langenberg V., Coenen E. (1999) Limnological annual cycle inferred from physical-chemical fluctuations at three stations of Lake Tanganyika. Hydrobiologia 407: 45-58

Sigee, D. C. (2005) Freshwater microbiology: biodiversity and dynamic interactions of microorganisms in the aquatic environment. John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.

TAFIRI (2020) The Use of Freemaya Gillnet for Migebuka Fishery in Lake Tanganyika. Report. TAFIRI, Dar es Salaam. 23 p.

Walther G-R, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389-395

Wood S (2017). Generalized Additive Models: An Introduction with R, 2nd Edition. Chapman and Hall/CRC.

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