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Current Status and Strategic Way forward for Long-term management of Lake Kivu (East Africa)

Muvundja Fabrice Amisi[1, 2, *], Masilya Pascal Mulungula[1], Kisekelwa Tchalondawa Kisse[1], Balagizi Charles Muhigirwa[3], Pasche Natacha[4], Hyangya Béni Lwikitcha[1], Mudakikwa Ruhanamirindi Eric [5], Akonkwa Balagizi Désiré[6], Nahayo Déo[7], Ajode Z. Migeni[8], Stephanie Smith[8], Alfred Wüest [4,9], Ted Lawrence [8,10]

[1]Unité d'Enseignement et de Recherche en Hydrobiologie Appliquée (UERHA), Institut Supérieur Pédagogique de Bukavu (ISP/Bukavu), BP. 854, Bukavu, D. R. Congo

[2]Centre des Recherches en Environnement et Géo-Ressources (CREGéR), Catholic University of Bukavu (UCB), BP. 285 Bukavu, D. R. Congo

[3]Geochemistry and Environmental Department, Goma Volcano Observatory, 142, Avenue du Rond-Point Quartier des Volcans, Goma, D. R. Congo

[4]Swiss Federal Institute of Technology Lausanne (EPFL), Limnology Center, GR A2 435, Station 2, 1015 Lausanne, Switzerland

[5]Lake Kivu Monitoring (LKM), Rwanda Environmental Management Authority (REMA), Gasabo District, P.O. Box 7436 Kigali, Rwanda

[6] Faculté des Sciences et Sciences Appliquées, Département de Biologie, Université Officielle de Bukavu, BP 570 Bukavu, R. D. Congo

[7]Institut d'Enseignement Supérieur de Ruhengeri (INES-Ruhengeri), Faculté des Sciences Fondamentales Appliquées, Département de Génie Civil, Musanze - Po. Box 155 Ruhengeri, Rwanda

[8]African Center for Aquatic Research and Education, Ann Arbor, 2200 Commonwealth Blvd., Ste. 100, Ann Arbor, MI 48105, USA

[9]Eawag (Swiss Federal Institute of Aquatic Science and Technology), Surface Waters – Research and Management, CH-6047 Kastanienbaum, Switzerland

[10]International Institute for Sustainable Development, 325-111 Lombard Ave, Winnipeg, MB R3B 0T4, Canada

*Corresponding author: Fabrice Muvundja (amisimuv@yahoo.fr)

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Abstract

Lake Kivu is one of the Great Lakes lying in the Albertine Rift Area. It provides livelihoods to 5.7 million people living in the two riparian countries of the Democratic Republic of the Congo and the Republic of Rwanda. Lake Kivu is currently experiencing numerous stressors, including fish habitat destruction, pollution, invasive species, weak governance and law enforcement as well as conflict between riparian countries. One of the biggest challenges on Lake Kivu is the limitations of coordinated and consistent research on the lake. Scientific attention to large lakes is often not seen as a high enough priority by the riparian countries, despite that the lake sustains millions of people's livelihoods, and contributes to the GDP of both countries. Although we have a fair understanding of the basic geology, physics, chemistry, and biology of the lake, there is a need for a stronger long-term monitoring and research frameworks to gain more comprehensive understanding of the changes resulting from human uses and global warming. These would be needed to develop good policies and management decisions for sustainable and long-term health and use of the lake's resources. This manuscript presents an opinion of experts on what is known about the current lake's current status and its resources as well as about what should be done. It highlights key threats, issues and gaps that needs to be urgently addressed, and provides specific and strategic ways forward for long-term monitoring and management, essential to achieving a healthy Lake Kivu, able to sustain its dependents.

Keywords: Lake Kivu, Sustainable Management, Research, Capacity building

1. Introduction

Lake Kivu is located on the western branch of the East African Rift Valley between two riparian countries, the Democratic Republic of the Congo (DRC) and Rwanda. It is of great socio-economic importance for 5.7 million people who depend on the fisheries and other natural resources. Lake Kivu contributes 30% of the riverine hydraulic inputs to Lake Tanganyika (Vandelannote et al., 1999; Hecky et al., 1991). Therefore, the health of Lake Tanganyika, a regionally important great lake, depends also on the health of Lake Kivu. As for most of large lakes on earth, growing population, urbanization and other stressors have negative impacts on the lake's resources and conservation of the lake (Bootsma and Hecky, 1993). However, in developing countries, poor natural resource management due to insufficient knowledge and weak law enforcement can inhibit a sustainable use of these resources. Lake Kivu is surrounded by fast growing cities for which it provides resources for several industries such as hydropower and methane energy, fisheries and aquaculture, transport and tourism. The lake lies in an environmentally risky region characterized by active volcanoes, earthquakes, tectonic plate movement and rifting as well as floods, landslides and soil erosion. This manuscript presents an opinion of what is known about the lake ecology and resources. It highlights the key threats and management challenges as well as gaps that needs to be urgently addressed provides specific and strategic ways forward essential to achieving a healthy Lake Kivu.

This manuscript was written by active collaborating freshwater scientists from the Democratic Republic of the Congo and Rwanda known as the Lake Kivu Advisory Group (LKAG). The LKAG is a consultative group comprised of freshwater and large lake stakeholders and experts knowledgeable about Lake Kivu and its issues. Members are involved in research, management, and development on the lake. LKAG also mobilizes international advisors who provide technical and administrative support. The LKAG has been holding monthly virtual meetings for its establishment and was represented in international conferences on large lakes of the world since 2018. This advisory group aims to:

- Standardize the research and monitoring protocols on the lake between different research institutions to make the results comparable for the lake.
- Identify lacking information and scientific knowledge gaps for research on the lake
- Build technical capacity and acquire state-of-the-art research infrastructure

- Advance the training of the people and the human resources in the field of interest while considering gender balance and social equity
- Act as a frame to promote collaborative research and education (i.e. project proposals, fundraising, etc.)
- Share data on a common platform and disseminate the findings
- Provide recommendations to inform policymakers to achieve positive impacts on policies and regulations in place regarding Lake Kivu basin management
- Facilitate transfer of knowledge and new technology to the riparian communities to assure research oriented towards the needs of the communities
- Understand, get inspiration, and value the traditional knowledge of the local communities.

The intent of the LKAG is to shift short-term, parochial, and disparate approaches to research on Lake Kivu towards harmonize efforts to build comprehensive and long-term data and information that can support the sustainable management of the lake.

2. Methods

This study is based on literature review (Table 1) and discussions among the members of the LKAG group focussing on the gaps and challenges on the lake scientific knowledge and management practices. For a full description of methods (of which members of each advisory group used to write their papers for this special edition of the Journal of Great Lakes Research), see [PAPER # 0, overview paper] in this issue. For this manuscript, the members of LKAG developed the priorities and ways forward using the following methods:

1) Semi-formal and formal discussions. Started in December 2019 to date through monthly virtual meetings facilitated by ACARE. At each meeting, discussions that highlighted important issues were noted and prioritized as monthly themes to provide inputs for this manuscript.

2) Ranking and prioritization of most critical issues affecting the African Great Lakes, including Lake Kivu, as well as how these could be addressed were extensively discussed during the ACARE stakeholder workshop held in Entebbe, Uganda, in 2019 (ACARE, 2019) . This information was synthesized, and the top priority issues identified are summarized in Table 2. The surveys resulted in issues and threats ranked in order of urgency, importance, and benefits to addressing the health of the lake. Surveys were administered through structured web-based questionnaires to different categories of stakeholders (respondents) that included scientists, researchers, managers, and academics, including the members of the LKAG. The respondents were given a link to the web-based survey tool for completion.

3) Literature review was used to support the discussions and surveys taken by the LKAG and other freshwater experts demonstrating that some issues regarding the lake had peer-reviewed support, need more attention, or other needs. In this review, we searched and examined the relevant existing literature (technical reports, journal articles, periodicals, statistical abstracts, and policy documents among others) on the previous and ongoing interventions on Lake Kivu. Searches were done in online repositories (Eawag, https://www.eawag.ch/en/department/surf/projects/lake-kivu/; Scopus, web of science and Google scholar) using relevant key words. The focus was mainly to identify inadequacies and gaps in previous work and the key challenges facing Lake Kivu. This would form a basis for setting priorities of future research and development actions on the lake.

3. Geophysical and demographical features of Lake Kivu catchment

a. Location, geomorphology, and geological history

Lake Kivu is located on the western branch of the East African Rift Valley, between the Republic of Rwanda and the Democratic Republic of the Congo (DRC). Situated near the equator (1.3-2.3°S, 28.4-29.2 °E) at an elevation of 1463 m, with a catchment area of 5097 km^2, Lake Kivu has a surface area of 2370 km^2, a volume of 549 km^3 and a maximum depth of 486 m (Beadle, 1981; Haberyan and Hecky, 1987; Ross et al. 2014). The lake consists of four basins (Wong and Von Herzen, 1974; Schmid and Wüest, 2012): the Southern basin (Ishungu: ~180 m and Bukavu- bay: 100 m), the Western basin (Kalehe: ~230 m max depth), the Northern or Main basin (Goma and Gisenyi: 485 m max depth) and the eastern basin (Kibuye: 400 m max depth). Kabuno Bay (150 m max depth) situated in the northwest part of the lake is connected to the Northern basin by a narrow channel and can be considered as a pseudo-satellite lake (Fig.1).

Located at the north of Lake Kivu are two active volcanoes in the Virunga Mountains: the Nyiragongo and Nyamulagira. Lava flows from these two volcanoes have repeatedly entered Kabuno Bay and the main basin of Lake Kivu particularly during the Nyamulagira 1938-40 and Nyiragongo 2002 eruptions (Balagizi et al., 2018). The presence of these two volcanoes near Goma city (DRC), Gisenyi city (Rwanda) and many another villages in the two countries represent major natural hazards including: lava flows, which can cause destruction of property, associated "mazuku" where atmospheric CO_2 values rise to up to 70 %, killing people, and associated elevation of fluoride-rich surface and ground waters commonly used for drinking water (Balagizi et al., 2018, 2017, 2015) which can cause a widespread disease called fluorosis. Furthermore, as open system volcanoes with long-lasting lava lakes, the gas plume from the volcanoes cause poor air quality and acid rain in its vicinity, both negatively affecting human health. There are indicators of volcanic activity on the lake floor in the northwestern part of the lake such as volcanic cones, tuff rings, and traces of past lava flows (Ross et al., 2014).

Lake Kivu is an ancient rift lake, existing since the mid-Pleistocene. The lake formed while the Virunga Mountains were rising (Degens et al., 1973). Lake Kivu experienced low water levels in the late Pleistocene, until lava flows from the Nyiragongo and Nyamulagira volcanoes blocked its former outflow to the Nile. By 9500 years before present, Lake Kivu had become a deep lake with an overflow via the Ruzizi River to Lake Tanganyika (Haberyan and Hecky, 1987; Ross et al., 2014), with its hydrological outflow reversed to the Congo basin from the Nile River. The lake became strongly stratified about 3100 years before present (Votava et al., 2016). The sediment records showed that hydrothermal activity of the subaquatic springs in particular and volcanism in general play an important role for the chemistry of the sediments and the lake waters (Ross et al., 2015a,b; Votava et al., 2016).

b. Human demographics

The catchment is home to 5.7 million people (CAID 2016; INS, 2014; NISR, 2012). There are four main cities on the lake, Goma (DRC) and Rubavu (former Gisenyi, Rwanda) in the north, and Bukavu (DRC) and Rusizi (former Cyangugu, Rwanda) in the south. A large fraction of the population depends on fishing for food and subsistence agriculture, and cash crops such as coffee and tea are critically important to the region. Land use is dominated by dryland cropland and pasture, with [un-arable] shrubland mainly in the north and south-west (Muvundja et al., 2009). Part of the original evergreen montane forest remains in Gishwati Mukura as well as in Nyungwe (Rwanda), Kahuzi-Biega and Virunga (DRC) National Parks.

In the DRC, Lake Kivu catchment is shared by several territories from North Kivu to South Kivu (Table 3). The overall riparian population in the DRC side is estimated at ~2.7 million people among which 1.8 million are concentrated in the lake-side towns of Goma and Bukavu. The mean human density is 403 inhab/km^2 in rural areas and 12,673 inhab/km^2 in towns. In rural areas the most important sources of livelihoods are mainly crop and livestock, fisheries, forestry, mining, transport, and trading activities. The poverty rate is around 65% around the lake and 71% in the DRC in general (DSCRP 2006). The population in South Kivu is recorded among the poorest in the country. In territories bordering Lake Kivu, including Idjwi Island in the middle of the lake, economic activities related to the lake increases the probability of being "non-poor", highlighting the dependency and importance of the Lake Kivu's resources (Amuli et al., 2015). The population growth in South Kivu and North Kivu is around 3.6% per annum with a fertility index of 7 children per mother (higher than the national mean of 6.2; EDS-RDC 2008; MICS-PALU 2019). In North-Kivu and South-Kivu, 47% and 33% of the population has, respectively, access to mass media; 65% and 37% of adult people have access to birth control measures (MICS-PALU 2019). The child mortality of children aged 0- 5 years is 10.2 % in North-Kivu and 18.6 % in South-Kivu for a national average of 14.2% (EDS-RDC 2008).

In Rwanda, the census of 2012 indicated a population of 10,515,973 inhabitants, of which 52% are female and 48% male (NISR, 2012). The riparian districts of Lake Kivu are Rubavu, Rutsiro, Karongi, Nyamasheke with 403,662; 324,654, 331,808; 381,804 and 400,858 inhabitants, respectively, in 2012 (Table32; NISR, 2012). Based on the population growth rate of 1.2%, the riparian population of Lake Kivu in Rwanda was 2,051,633 inhabitants in 2020. Most of the population of Rwanda live in private households with an average size of 4.3 persons. Households are a bit smaller in urban areas, with average 4.0 persons/household. The population density in 2012 was 420 inhab/km^2 for the districts around Lake Kivu (Table 3). The population of Rwanda is young, with one in two persons being under 19 years old. People aged 65 and above account for only 3% of the resident population. 42% of the population living in rural areas is under 15 compared with only 35% in urban areas. On the contrary, urban areas attract more young adults, presumably for studies or work: 34% of the urban population is aged between 20 and 34, compared with 24% of the population in rural areas.

4. Ecosystem features

a. Climate and hydrology

Lake Kivu basin experiences a bimodal climate characterized by a long rainy season from October to May (catchment average annual precipitation of 1470 mm yr^{-1}; Muvundja et al., 2014) interrupted by two dry seasons, one in January and another one from June to September. According to Kranenburg et al.(2020) the (long) dry season is dominated by strong winds (up to 4.5 m s^{-1}) while the rainy season is calm (< 2 m s^{-1}). The average annual air temperature is 19.6°C (Sarmento et al., 2006). Muvundja et al. (2014) reported the catchment soil water balance as composed of 1470 mm yr^{-1} for rainfall, 1100 mm yr^{-1} for evapotranspiration, 150 mm yr^{-1} for surface runoff and 220 mm yr^{-1} for base flow (Fig. 2).

Lake Kivu's major water budget input (~49%) is through precipitation (2.9-3.7 km^3 yr^{-1}; Fig. 3) and secondly (~32%) by more than 100 small rivers (1.6-2.4 km^3 yr^{-1}; Fig. 3) (Bergonzini, 1998; Muvundja et al., 2009, 2014; Schmid and Wüest, 2012). Several sub-aquatic springs enter in its deep waters, accounting for ~20% (1.0-1.5 km^3 yr^{-1}; Fig. 3) of the total inflows. Lake Kivu has two hydrologic outputs, the Ruzizi River—the only outflow of the lake (3.0-4.0 km^3 yr^{-1}; Fig. 3)—accounting for ~54%, and through evaporation (46%) 2.6-3.4 km^3 yr^{-1}; Fig. 3) (Muvundja et al., 2014). Nevertheless, given the data scarcity and lack of long-time series data, the uncertainty of the individual in- and out-flow components may be considerable.

Lake Kivu's concentration of salts— elsewhere often caused by the large differences between evaporation and precipitation, as is the case in Lakes Tanganyika and Malawi/Nyasa/Niassa—is mainly due to the inputs by subaquatic springs. The sub-aquatic springs are an important driver for Lake Kivu, as they are also responsible for the accumulation of gases in the deep water (below 260 m) and slow upwelling transport of nutrients and dissolved gases (Pasche et al., 2009; Sommer et al., 2019). Ross et al. (2015a, 2015b) showed that several cool groundwater springs with low salinity enter the lake in the north. One large spring was located close to the volcanic cone of Mount Goma at about 250 m depth. This water spreads horizontally and maintains a major chemocline between 255 and 262 m. About 10% of the total spring water is composed of hydrothermal groundwater springs, which are warm, saline and provide CO_2 to the deep water (Ross et al., 2015a).

b. *Physical characteristics*

Lake Kivu is meromictic with seasonal mixing reaching only 60-65 m depth (Schmid and Wüest, 2012). In addition to the permanent stratification below this depth, a shallower seasonal stratification builds up during the rainy season, leading to a narrow oxic zone that is reduced to only 30 m depth towards the end of the rainy season (Sarmento et al., 2006). Light penetration does not reach beyond 20 m. The stable and permanently stratified layers of Lake Kivu below 60 m reduces the oxic biozone and create extremely homogeneous horizontal zones. The water column is characterized by increasing temperature, salinity, nutrient, and gas concentrations with depth and by several sharp gradients resulting from subaquatic inflows. The major chemocline between 255 and 262 m depth separates the deep waters rich in nutrients and gases. The subaquatic inflows further induce a slow upwelling of 0.15 m yr^{-1} below 250 m and 0.9 m yr^{-1} above 250 m. This slow vertical transport moves nutrients and gases towards the surface, where they are entrained into the surface layer by seasonal mixing. The water residence times are about 800 years below the major chemocline and about 200 years in the range between the major chemocline and the surface layers (Schmid and Wüest, 2012). A large amount of nutrients and gases have thus accumulated below 70 m depth and especially below the major chemocline (i.e., below 260 m).

c. *Chemical characteristics*

The seasonal mixing in Lake Kivu is like other tropical lakes with shallower stratification during the wet season and deeper mixing during the dry season. The maximum depth of seasonal mixing varies depending on the weather conditions, but never exceeds the chemocline at ~65 m (Sarmento et al., 2006; Schmid and Wüest, 2012). Dissolved oxygen is saturated only in the mixed surface layer. The depth of the oxycline varies from 30 m in the wet season to a maximum of 65 m in the dry season. While nutrient concentrations are rather low during the wet season, the seasonal mixing entrains nutrients to the surface layer, which leads to a bloom in phytoplankton. The algae production depends on the depth reached by the seasonal mixing (Darchambeau et al., 2014).

Muvundja et al. (2009) and Pasche et al. (2010, 2009) reported that nutrient cycling in Lake Kivu was dominated by internal loading of N and P. However, a detailed assessment of the contribution to the nitrogen budget by N-fixing bacteria which might not be negligible, especially during the rainy season, is still lacking. Investigating the anaerobic nitrogen cycling, Roland et al. (2018) showed that denitrification, nitrate reduction to ammonium and anaerobic ammonium oxidation occurred in Lake Kivu.

Nutrient cycling in Lake Kivu is dominated by continuous internal recycling (Pasche et al., 2012). The major nutrient inputs to surface layers are caused by the upwelling from the nutrient-rich deep waters, while the main loss occurs through the sedimentation of particulate organic matter. The external inputs through rivers, rain and dry deposition supply only ~20% nitrogen and ~15% phosphorus (P) of the total inputs to the epilimnion (Muvundja et al., 2009; Pasche et al., 2012). Si has a contrasting cycle with higher external inputs and less efficient recycling by the biomass. Phytoplankton is limited by P availability and to a lesser extent by N availability, and Si is a non-limiting nutrient (Sarmento et al., 2006).

The literature on methane production in Lake Kivu has recently increased (Table 1). However, there remains no data on the amount of methane trapped within sediments over 500 m, suggesting that actual methane resource in Lake Kivu is underestimated. Lake Kivu contains exceptionally large amounts of carbon dioxide (CO_2, ~300 km^3 STP) and methane (CH_4, ~ 60 km^3 STP, Bärenbold et al., 2020). Schmid et al. (2005) proposed that CH_4 concentrations had increased by ~ 15 % from 1974 to 2004, with an increased risk of a gas eruption through the chemocline and across the air-water interface. However, a detailed analysis of the lake carbon budget (Pasche et al., 2011) concluded that CH_4 concentrations are probably increasing at a lower rate than previously assumed. Furthermore, an intercalibration campaign to measure gas concentrations with different methods in 2018 suggested relatively constant methane concentrations since the 1950s and within the uncertainties of the present and previous measurements (Bärenbold et al., 2020; Boehrer et al., 2019). The methane deposit is therefore close to steady state, meaning that CH_4 annual production and loss are similar. It also means that the risk of a gas eruption is currently not increasing at the previously estimated rate in Lake Kivu due to methane accumulation. Currently, the total gas pressure at any depth in the lake reaches up to about half of the hydrostatic pressure at the same depth (Schmid et al., 2005). However, the risk caused by volcanic activity is still threatening.

Different hypotheses were proposed to explain the origin of the dissolved gases (Pasche et al., 2011; Schoell et al., 1988). Most of CO_2 is magmatic and enters the lake with the hydrothermal groundwater. CH_4 originates from two sources. Pasche et al. (2011) showed that above 260 m, methanogenic bacteria produce CH_4 through the decomposition of organic matter, as it occurs in most lakes. Below 260 m, an additional source of the CH_4 originates either from reduction of geogenic CO_2 with most likely geogenic H_2 or from direct inflows of geogenic CH_4 through the hydrothermal springs. Direct analyses of the hydrothermal spring water might help to better understand this unusual source in the deep water.

d. Biological characteristics

i. microbial community

Of the lower trophic level components, the microbial loop remains the least studied. Different studies only show that 1) the archaeal planktonic assemblage is mainly composed by members of ammonia oxidizing archaeal lineages (AOA; belonging to Marine I.1a and Soil I.1b Crenarchaeota groups), 2) that below the redoxcline, the structure of this archaeal assemblage is clearly different and members of the Miscellaneous Crenarchaeotic Group and methanogenic lineages are prevalent (Lliros et al. 2015, 2012, 2010) and 3) that the microbial food web contributes significantly to consumer (zooplankton and fish) production (Masilya, 2011a). Despite the recent studies on the lake microbiology (Table 1), it remains clear that much is still to be learned about the microbial loop of Lake Kivu. Thus, more studies on microbial communities and species as well as their abundances and ecological roles should be done to increase our understanding of the limnology and biogeochemistry of the lake.

ii. Plankton community

Phytoplankton biomass in Lake Kivu was recorded every two weeks from 2002 to 2015 (Rugema et al.; 2019; Sarmento et al.; 2006, Sarmento et al.; 2012). Prior to 2012, Lake Kivu phytoplankton was dominated by cyanobacteria and by pennate diatoms. Seasonal shifts usually occurred, with cyanobacteria developing more in the rainy season, and the diatoms in the dry season. From 2012, the phytoplankton community (Rugema et al., 2019) changed considerably, with the contribution of green algae increasing from 3% to 33 and a decline of cryptophytes and cyanobacteria. Simultaneously, the mean chlorophyll-a concentration in the euphotic zone (< 20 m depth) increased from 2.2 µgL-1 prior to 2012 to 2.8 µgL-1 after 2012. The most common algal species in Lake Kivu are the pennate diatoms *Nitzschia bacata* and *Fragilaria danica* and the cyanobacteria *Planktonlyngbya limnetica* and *Synechococcus sp*. (Sarmento et al., 2008). A very high abundance of the centric diatom *Urosolenia sp*. and the cyanobacterium *Microcystis sp*. near the surface under stratification conditions has also been reported by Sarmento et al. (2008). In total, 42 taxa of pelagic algae were recorded: 14 Cyanophyceae, 3 Cryptophyceae, 3 Dinophyceae, 7 Bacillariophyceae, 1 Chryophyceae, 7 Chlorophyceae, 3 Trebouxiophyceae and 4 Charophyceae (Sarmento et al., 2008). Vertical stratification seemed to be the most important factor of diversification. These observations strengthen the statement that has always been made in the literature by many authors that Lake Kivu has a poor biodiversity (Froese and Pauly, 2008).

In Lake Kivu, heterotrophic bacteria (HB) and photosynthetic picoplankton (PPP) cell numbers were found to be always high in the mixolimnion (top 60 m layer) but PPP concentrations (10^5 cell. ml^{-1}) were higher than those of HB (Sarmento et al., 2006). Three populations of picocyanobacteria were identified by Sarmento et al. (2006) namely: *Synechococcus* and two other categories corresponding to the same taxon. The *Synechococcus* biomass in the euphotic zone (15-18 m) was estimated to 24.7 mg C. m^{-3} corresponding to 0.42 g C m^{-2} for this layer whereas the mean HB biomass in the same zone was 31.5 mg C m^{-3} corresponding to 1.42 g C m^{-2}, integrated for the whole mixolimnion (Sarmento et al., 2006). Zooplankton is composed of copepods, cladocerans and rotifers (Isumbisho et al., 2006). Present mesozooplankton is dominated by cyclopoid copepods (*Thermocyclops consimilis, Mesocyclops aequatorialis and Tropocyclops confinis*) (Isumbisho et al., 2006). The dependence of zooplankton on phytoplankton resource suggests that mesozooplankton dynamics in Lake Kivu is mainly bottom-up controlled (Isumbisho et al., 2006).

iii. Invertebrates

Knowledge on macroinvertebrates in Lake Kivu is still in its early phase as it is still limited to diversity and taxonomy. Despite their recognized importance in the functioning of aquatic ecosystems (Poikane et al. 2016; Doric et al., 2021), macroinvertebrates in Lake Kivu remain less studied and little is known about their contribution to the lake's foodweb. Apart from the reference data available, collected between 1952 and 1954 by Verbeke (1957) and Chrispeels (1959) during the Kivu-Edouard-Albert (KEA) expeditions, the most recent data are those reported by Richard et al. (2020) in the northern basin of Lake Kivu. It should be noted that all these data are spatio-temporally limited and reflect the absence of an exhaustive database.

The available data show that macroinvertebrate communities of Lake Kivu are composed of the following major groups: Coleoptera, Diptera, Ephemeroptera, Heteroptera, Odonata, Trichoptera, Nematoda, Oligochaeta, Decapoda, Gastropoda (Verbeke, 1957; Richard et al., 2020; Hyangya, submitted). In total, 43 taxa were identified in 2017 sampling campaigns (Richard et al., 2020) against 42 in 1952-1954 (Verbeke, 1957). The distribution at the lake scale is not yet well known, but environmental degradation in the littoral zone might have led to a declining trend of macroinvertebrate communities. Wronski et al. (2015) highlighted the potential use macroinvertebrates as biological indicators of water quality in the catchment of Lake Kivu. In the littoral zone of Lake Kivu, lower abundance of macroinvertebrates was reported in the localities where human activities are acutely pronounced (Hyangya, Pers. Comm.). No benthic macroinvertebrate was found below 40 m depth due to prevailing anoxic conditions (Richard et al., 2020).

iv. Fishes

The fish fauna of Lake Kivu (Fig. 4) comprises only 29 species (Snoeks et al., 2012). This was formerly 27 species comprising 15 *Haplochromis* endemic to the lake, two Clarias, three Oreochromis, one *Tilapia* (now *Coptodon*), one *Amphillius*, one *Raiamas* and four *Enteromius* (Snoeks et al., 1997; Masilya et al., 2020). Between 1958 and 1959, the Tanganyika sardine *Limnothrissa miodon* (Boulenger, 1906) was introduced to Lake Kivu (Collart, 1960) to boost the lake fishery production in the pelagic zone (Fig. 4). However, the second introduction, that of *Lamprichthys tanganicanus* (Boulenger, 1898), which occurred very recently, was obviously accidental, and is still at an early stage of development (Masilya et al., 2011a; Muderhwa and Matabaro, 2010). Of the 29 species, 28 dwell inshore (Snoeks et al., 2012) or in inflowing rivers (Fig. 4)(Kisekelwa et al., 2020) and only *L. miodon* (Fig. 4) is pelagic.

Assessment of the genetic variation of the fish species of Lake Kivu is still needed in order to understand the pattern of speciation i.e. what have been the role of environment and the genetic variation in fashioning the fish diversity in this lake. Nevertheless, the genetic data that were up to date generated have been useful to understand the pattern of evolution of the cichlids across the aquatic system of the East Coast province where the lake belongs according to Snoeks et al. (1997). Haplochromine species from Lake Kivu and other cichlids from the lakes of the East Coast Province including Lakes Albert, Edward, Georges, Kyoga and Victoria, are monophyletic (Verheyen et al., 2003; Elmer et al., 2009). The Haplochromine species from other waterbodies belong to the so-called Lake Victoria Region Superflock (LVRS) except for *H. gracilior* Boulenger, 1914, an endemic species to Lake Kivu, revealed to be a distinct lineage from the flock but occupies a pivotal position. This suggests that this species is the most recent sister species to the LVRS (Verheyen et al., 2003). This position indicates that the Lake Kivu species were crucial in the evolution of the cichlids of the East Coast Province. As such, the Lake Victoria cichlids constitute a derivative lineage of an ancient form from Lake Kivu.

Despite the low species richness within the genus *Haplochromis* in Lake Kivu, 15 species compared with the hundreds of species known from Lake Victoria, the Lake Kivu *Haplochromis* species contain much more interspecific genetic differentiation than the Lake Victoria cichlids (Elmer et al., 2009), indicating that the Lake Victoria cichlids are recent compared with that of Lake Kivu.

A large caveat is still existing about the genetic understanding of the fish fauna of Lake Kivu. At present for example, we are still lacking the part of story on the evolution of the Lake Kivu fish fauna using the non-cichlid species as well as the genetic differentiation of *Haplochromis* at the lake scale. An ongoing KAE project that is investigating the phylogeny and phylogeography of (non)-cichlid species of the fish fauna of Kivu is expected to complete the existing information about the evolution of fish fauna of Lake Kivu (Snoeks, Person. Comm.) . A Research Centre for Biodiversity, Ecology, Evolution and Conservation is being established in Bukavu in order to contribute to develop locally some basic infrastructure and human resources needed to fill the gaps of genetic data about the fish fauna across the entire lake (Kisekeklwa, pers. comm.).

The distribution of fish fauna at the lake scale is not well known. The distribution may be considered at two levels: the distribution of species over the littoral compared with the pelagic zone and the distribution at the lake scale. For the first level, most of the acquired global knowledge suggests that 27 out of 29 live in the littoral zone (Snoeks et al., 1997; Masilya, 2011a&b), while *Limnothrissa miodon* and *Lamprichthys tanganicanus* are considered pelagic, still spawn along the littoral zone (Kaningini, 1995). The fifteen *Haplochromis* species have colonized the littoral zone although some species such as *H. kamiranzovu* (Snoeks, Coenen & Thys van den Audenaerde, 1984) and *H. insidae* (Snoeks, 1994) are occasionally found in the pelagic zone (Munyandamutsa et al., 2020). Our knowledge remains scattered and limited regarding the distribution of these species at the lake level. Certain species such as *H. vittatus* (Boulenger, 1901), *H. astatodon* (Regan, 1921), *H. graueri* (Boulenger, 1914) are widespread throughout the lake while others such as *H. insidae*, *H. kamiranzovu* are scarce in the southern part of the lake, across the Bukavu basin. For a long time, it has been noticed that *Haplochromis crebidens* (Snoeks, de Vos, Coenen and Thys van den Audernaerde, 1990), *H. occultidens* (Snoeks, 1988), *H. olivaceus* (Snoeks, de Vos, Coenen & Thys van den Audernaerde, 1990), *H. paucidens* Regan (1921), *H. rubescens* (Snoeks, 1994), *H. scheffersi* (Snoeks, de Vos and Thys van den Audernaerde 1990) and *H. vittatus* are regarded as endangered species due to fishing for livelihoods (Holland et al., 2011).

Oreochromis and *Coptodon* are very rare in the littoral zone of Lake Kivu. *Cyprinidae Enteromius* resides in the lake tributary rivers and their mouths (Masilya et al., 2020; Kisekelwa et al., 2020). The *Danionidae Raiamas moorii* (Boulenger, 1900) is very rare in the lake itself (Masilya et al., 2020). Similarly, the large cyprinid *Labeobarbus altianalis* (Boulenger, 1900) is also very rare in the lake and is more frequent in the Ruzizi River (Mazambi, 2016). The Amphiliidae are also very rare in the lake.

V. Fisheries

The history of fishing on Lake Kivu can be divided into two main periods: pre-1973 and post-1973, the latter defined by the introduction and establishment of the non-native sardine *L. miodon. B*efore the establishment of the sardine, the fisheries targeted three types of fishes, *Haplochromis*, *Tilapia* species and the African catfish using angling (long-line, pole, and line) and beach seines (Kaningini et al., 1999). Fishing was conducted for human subsistence. The second period began when the *L. miodon* appeared in the catches in 1973 and were reported by fishermen from Lake Kivu around the cement factory of Katana and the brewery of Bukavu (Kaningini et al., 1999). After the discovery of *L. miodon*, the Lake Kivu fishery began depending mainly on this species, enhancing the development of a prosperous pelagic fishery that has been considered as a successful economic fish introduction model (Gozlan, 2008; Spliethoff et al., 1983).

Before the introduction of *L. miodon* in Lake Kivu, the fisheries were mostly based on traditional practices such as seine nets, traps, lines, and poisonous plants (Akonkwa et al., 2017; Kaningini, 1995). They were generally practiced along the littoral zone targeting mainly *Haplochromis spp.*, but also limitedly *Oreochromis* spp. and *Clarias* spp. Subsequently, after the establishment of *L. miodon* many other fishing techniques were introduced, such as the use of light-attracting trimarans and gillnets of different mesh. Trimaran fishing (the use of multi-hulled boats) was introduced throughout Lake Kivu in 1976 from Lake Tanganyika, and as catches increased the fishery was adapted to local conditions. The trimaran fishery was modified at the end of 1989 to adapt it to the reality of Lake Kivu: all catamaran units were transformed into more stable trimaran units (Kaningini et al., 1999). Moreover, gillnets called 'filets maillants' were introduced during the 1980s after experimental fishing by Kaningini (1995). Based on experience and on biological studies of *L. miodon*, including breeding and growth rates, recommendations to use 9- and 10-mm knotted gillnets (Kaningini, 1995) were made, as these gillnets harvest mature individuals at a more economically profitable rate, and a in a more sustainable manner than the trimaran. These gillnets were distributed on the DRC side in the early 1990s during a project funded by the European Union (EU) and the Forum" Universitaire pour la Coopération Internationale" (Kaningini et al., 1999). The gillnets are still mostly used across the western flank of the lake whereas trimaran, although expensive, is still used from the Rwandan waters of Lake Kivu for historical reasons.

In recent years several factors such as the lack of the government investment in the fishing sector, weak law enforcement, and poverty among fishing communities have led to the growing use of illegal fishing gears such as mosquito nets and gillnets with small mesh size (6 mm). The use of such destructive fishing gears is still increasing across the DRC side regardless of their prohibition. As such, the fishery sustainability remains highly compromised. Furthermore, the fishery of Lake Kivu is also constrained by unregulated trading of fishing gears at the DRC side. From the 2000s to present day, private businessmen have invested an overwhelming amount of money to commercialize the “filet maillant”. Thus, that gillnet has become expensive. Despite the full acceptance of the “filet maillant” in DRC, the government of Rwanda does not allow it on its side of the lake (Kaniningi, pers. Comm.). The different rules of gear use on the lake have led to several confrontations between DRC fishermen and the Rwandan marine Police on the lake.

Illegal fishing across the DRC side has consequences for the sustainability of fish catches. Catch per unit effort (CPUE) has decreased drastically from a CPUE equivalent to 100 kg/fishing net/month (Kaningini, 1995) during 1989, to a CPUE equivalent to 43 kg/ fishing net/month in 2019 (Masilya, Person. Comm.) The negative socio-economic impacts to fishermen, their families, and the general population have become evident. *L. miodon* is now sold at ~ 3$ US/kg compared with higher previous prices, resulting in negligible profits for many fishermen. A large variation of CPUEs is observed between seasons and years. The high catches are observed in October-November-December (Akonkwa et al., 2015; Kaningini, 1995; Richard et al., 2020) resulting from the growth of *L. miodon* larvae hatched during the long dry season (June-August) following the plankton seasonal increase trend (Isumbisho et al., 2006; Sarmento et al., 2006; Villanueva et al., 2008). As such, fish are abundantly available during this period and seem to be of good nutritional quality (Masilya, 2011a).

The interannual variation and the decline in CPUE are explained by the current movement of fishermen from one basin of Lake Kivu to another or from Lake Kivu to Lake Tanganyika or Lakes Edward and Albert. Such movement of fishermen has recently resulted into the introduction of a new fishing practice using gillnets with LED lights to Lake Kivu from Lake Tanganyika. The effects of this new technique regarding the fish stocks of Lake Kivu are yet to be documented, as what done for Lake Tanganyika (Mgana et al., 2019).

Despite the drastic declines in catch, recent studies on the pelagic fishery in Lake Kivu suggest it is sustainable. The exploitable stock of *L. miodon* in Lake Kivu was estimated at ~6,000 tons during the first hydroacoustic survey organized in Lake Kivu (Lamboeuf 1991, 1989) and remained stable about 20 years later (Guillard et al., 2012), including up to the most recent surveys (Tessier et al., 2020). However, the results of the hydroacoustic stock assessment appear to contrast with available CPUE data which, as pointed out by FAO (1992), better reflect the action of fishing on the fish stock. Therefore, long-term monitoring is needed to regularly assess the stock dynamics of fish resource statistics as well as for *Lamprichthys tanganicanus* in relation to their habitat environmental quality. A framework survey is also needed to control the number of fishermen working on Lake Kivu, the number and type of gears they use and the number of landing sites. The ongoing analysis of genetic diversity of the resource species (Kisekelwa, Pers. Comm.) may also assist understanding of the sustainability of the fishery and the extent the different species are spatially linked to environmental variables (Kisekelwa, Pers. Comm.).

The exploitation of methane gas in the northern part of the lake may affect the biodiversity of Lake Kivu if not properly handled. Indeed, it was agreed that the gas-free water should be reinjected at a depth beyond 200 m to limit the related ecological damage such a bloom of eutrophication (Wüest et al., 2012). This resolution would better preserve the pelagic zone and especially the biozone where phyto- and zooplankton occur but somehow ignores the fish fauna that may be directly affected by activities along the coastal zone. For example, the northern part abounds in an important assemblage of fish fauna on the rocky carpet like habitat. In any case, the guidelines for mitigating the effects of exploitation have not considered the distribution of macroinvertebrates and fish fauna, yet the fishing in Lake Kivu is of unprecedented economic importance on the scale of the lake's catchment and the number of endemic species is very relevant in terms of diversity and evolution.

Lake Kivu Food web

Lake Kivu has the simplest foodweb among all East African Great Lakes, with only 4 trophic levels made of living and dead organic matter (detritus and phytoplankton) at level 1, zooplankton, bacterioplankton benthic fauna and *Tilapia* species level 2 (Figs. 5A&B), zooplanktivorous and benthophage *haplochromis* (all fish species except *clarias* and *haplochromis vittatus*) at level 3 (Fig. 6) and fish predators (*clarias*, *haplochromis vittatus* and otters) at level 4 (Verbeke, 1959; Villanueva et al., 2008; Masilya et al., 2011a). The annual primary production of 273 gC. m^{-2}. yr^{-1} was reported by Sarmento et al. (2006). The food web structure and interactions among different trophic levels of Lake Kivu was has been studied by Villanueva et al (2008) using the ECOPATH modelling approach (Christensen and Pauly, 1993; Christensen et al., 2005) to construct a steady-state description of the ecosystem (Bukavu Bay). In addition, feeding ecology at different trophic pools was assessed by Masilya et al. (2011a) using stable C and N isotope as well as fatty acid biomarker tools. The results of these studies show clearly that matter and energy transfer, from low to higher trophic levels, is largely dependent on phytoplankton biomass or primary production (Fig. 5A), although the contribution of bacterioplankton (Figure 6) is not negligible. In fact, FA profiles revealed that bacteria did contribute significantly to zooplankton and fish biomass (Fig. 6), highlighting the contribution of the microbial food web to consumer production. However given the greatest importance of zooplankton in the diet of the pelagic fishes, *L. miodon* and *L. tanganicanus* (Figs. 6&7), it remains clear that zooplankton is the most driving agent of matter transfer from low to high trophic levels in the lake. However low transfer efficiencies (4.5 to 9.5%) were reported among trophic levels by

Villanueva et al. (2008) confirming that sedimentation plays an important role within particulate organic matter cycling. The majority of fish biomass is located at the trophic level 3. The use of fatty acids (FA) as chemotaxonomic biomarkers for the organic matter transfer from primary producers to fish consumers in the pelagic food web of Lake Kivu was performed by Masilya et al. (2011a) with the aim assessing the organic matter sources in the diets of zooplankton and fish juveniles. Analysis of zooplankton samples showed that rotifers and all copepod stages fed mostly upon cryptophytes, chrysophytes and diatoms. *Diaphanosoma brachyurum*, the main cladoceran, fed upon cryptophytes and cyanobacteria (Fig. 5A). FA profiles in fish juveniles indicated that organic matter originated mostly from diatoms and cryptophytes. Adult FA profiles were similar to those of juveniles; *L. miodon* presented a higher proportion of organic matter from unknown origin than *L. tanganicanus* (Fig. 5B).

5. Resource use and Risk factors

a. Methane extraction

The large reservoir of methane in the deep layers of Lake Kivu is unique among other lakes of the world. The continuous injection of CO_2 and methane via the salty subaquatic spring waters (Ross et al., 2015a, 2015b) and conversion of CO_2 to CH_4 via oxidation or methanogenesis, coupled with the lake's permanent stratification, has allowed the significant accumulation of methane and geogenic CO_2 in the hypolimnion.

Although the methane reservoir in Lake Kivu has appeared to remain near steady state for decades (Schmid et al., 2019; Bärenbold et al., 2020), its exploitation may reduce the risks of hazardous limnic eruption due either to over-saturation or subaquatic volcanic eruption (Balagizi et al., 2018; Ross et al., 2014; Schmid et al., 2021, 2005). The governments of Rwanda and DRC have launched several degassing projects with methane recuperation for electrical power production purposes. Two power plants are operating: one in Gisenyi/Rubavu (Kivu pilot plant, KP1: 4.5 MW) and one in Kibuye (Kivuwatt: 100 MW) costing hundreds of millions of USD (https://www.afdb.org/en/news-and-events/afdb-approves-usd-25-million-for-kivuwatt-project-in-rwanda-7709;https://www.reuters.com/article/us-rwanda-gas-idUSKCN1PU1WW). Another one is under construction in Rubavu (Shema Power Lake Kivu, SPLK: 56 MW). The principle of methane harvesting from deep waters of Lake Kivu was discussed in scenarios by Wüest et al. (2012) and summarized by Schmid et al. (2019). It consists of withdrawing water from the methane resource zone (below 260 m) to the surface and separating methane from other dissolved gases and salt. Methane is then washed and sent offshore for energy production while the methane free waters are re-injected to the deep waters. First, deep water (below the major chemocline at 260 m) is withdrawn via vertical pipes and separated in the separator into raw methane gas and the degassed deepwater (Fig. 8). The latter is re-injected at a depth slightly above the extracting depth. The raw gas is then washed in the washing tower, where most of CO_2 is dissolved back into the washing water (Fig. 8). The sweet gas enriched in methane is transported in a horizontal pipeline towards the generators on shores (Fg. 8).

b. Aquaculture

Although aquaculture is still at its infancy, it is obvious that it is a very prominent sub-sector for improving commercial fish activities on Lake Kivu. People have benefited from some investments in Rwanda and DRC to promote this sub-sector. Along the lake side in Rwanda aquaculture is practised as cage fish farming. The same activity has recently started at the DRC side. *Tilapia spp.* is the only one fish species which is farmed so far. However, the challenges for promoting fish culture in Lake Kivu, especially on the DRC side remains the lack of technical capacities and good level of investments (training and education, infrastructure such as hatcheries and feed mills, etc.). This sub-sector has to be regulated in order to avoid environmental side effects such as the introduction of invasive species and pollution. Actually fish cage culture in large lakes is new in the region and most of countries have not yet set up binding laws on it. Therefore new policies and regulations are needed to organize its management in a proper manner given the growing potential that it shows.

c. Domestic and industrial effluents

In town and cities around Lake Kivu, solid waste is a serious challenge regarding the protection of Lake Kivu's environment. Municipalities have a weak capacity to prevent solid waste pollution of waterbodies including Lake Kivu. Domestic and industrial effluents are not treated and all the waste ends in the lake. Furthermore, risks from pesticide residues generated by agricultural activities are currently rising. For example, Houbraken et al. (2017) reported an exceedance over the risk thresholds by Malathion pesticide in surface waters of Lake Kivu, although deeper waters were not contaminated. At the Ruzizi outflow, solid plastic waste is limiting efficient energy production due to its accumulation in the dam reservoirs. Dam operators have to close the hydropower turbines twice a week for two hours allowing the plastics to be evacuated with water in the bypass which is not a sustainable practice (Muvundja et al., in revision).

d. Climate change

East African great lakes are very sensitive to global changes such as climate change (Delvaux et al. 2015). The atmospheric circulation over the Indian Ocean plays an important role on teleconnections between theses lakes and the Indian Ocean. Many authors have reported that part of the interannual variability in precipitation over East Africa is related to sea surface temperature perturbations over the Equatorial Pacific (El Niño Southern Oscillation) and Indian Ocean (Indian Ocean Dipole) (Khaki et al., 2021, Delvaux et al., 2015; Anyah and Semazzi, 2009; Bergonzini et al., 2004; Nicholson, 1996). Lorke et al. (2002) reported an increase of 0.5°C in the lake surface waters due to global warming. Some contradicting studies exist on the prediction of precipitation trend around Lake Kivu. Some predict an increase of precipitation with climate change in the future (Muvundja et al., 2014) whereas others simply pretend for decrease (Delvaux et al., 2015). However, a model suggested by Muvundja et al. (2014) indicates that a decrease of rainfall to 900 mm yr^{-1} for several consecutive years might lead to lake closure at Ruzizi River.

e. Tourism and recreational industry

Lake Kivu's beautiful landscape has attracted a lot of touristic and recreational settlements such as hotels, restaurants and bars, swimming beach development and religious events. Although no data exist on the amplitude of the economic benefits of this industry, we assume that they are high and should continue raising.

6. Lake management challenges and monitoring needs

Physical and chemical pollution is a growing issue in Lake Kivu because of changes in human population densities and land-use within the catchment. The degradation of water quality, especially in the littoral zone (Hyangya et al., 2021), have been linked to the continuous increase in human population associated with the rapid urban development of the large cities built along the lake without any treatment of domestic sewage or industrial waste (Lina, 2016; Basima et al., 2006), such as Bukavu and Goma in DRC and Gisenyi, Kibuye and Nyamasheke-Rusizi in Rwanda (Kaningini et al., 1999). Systematic elimination of macrophytes along the lake shores and sand harvesting by the riparian population are also frequently observed, leading to increased siltation and water turbidity (Kaningini et al., 2009; Basima et al., 2006). However, these aspects have not yet been sufficiently studied to understand their implications for the Lake Kivu ecosystem. The same applies to the rapid and ongoing development of cage aquaculture, where impacts to the lake ecosystem remains unknown. The lake pollution, which is linked to the intense land use and the high population density, might be caused by:

- The general lack of wastewater treatment plants to remove the nutrients before being released into Lake Kivu. Most of the population uses latrines and septic tanks. Microbial contamination by coliforms was observed in the lake water and was attributed to animals and human domestic wastes (Masilya et al., pers. Comm.; Olapade, 2012). This indicates that the lake inshore water is not safe for human domestic use without any form of treatment.

- Soil erosion (Karamage et al., 2016) due to the deforestation and agricultural practices generates high turbidity in rivers (Bagalwa et al., 2015; Ntadumba et al., 2014; Muvundja et al. 2009) and in the lacustrine littoral zone (Hyangya et al. 2021). From their results, Hyangya et al. (2021) pleaded for an integrated lake watershed management system in order to maintain the ecological functions of the lake and support livelihoods from the lake.
- Industrial activities are rather limited but include two breweries, mining sites, tea-drying and coffee-cleaning factories (Wronski et al. 2015, Houbraken et al. 2017). Their waste might release organic or mineral pollution, and their waste management would need to be further assessed. Methane extracting plants might also generate local pollution, such as solid waste, fuel leaks, and paintings directly into the lake.

- The use of pesticides and fertilizer in agricultural crops, especially for tea and coffee, might leach into rivers. In the Rwandan side, a growing risk of pesticide contamination in lakes including Lake Kivu was reported by Houbraken et al. (2017). These authors realized a limited environmental awareness among farmers about this risk despite of a significantly high use of pesticides. Even if the low nutrient input from rivers into Lake Kivu might reflect a limited use of fertilizers in the catchment (Muvundja et al., 2009), all potential pollution sources have to be monitored. For example, given the dominance of internal recycling, continuous additional inputs of nutrients might create long-term eutrophication in the future
- Plastic waste and microplastics are another global concern. Even if plastic bags are banned in Rwanda, they are widely used in DRC and often end up in the lake. Visibly, tons of floating plastic bottles from various uses contaminate the lake's surface waters. Fishing practices might also release plastic waste directly in the lake.
- Aquaculture in Lake Kivu might potentially release nutrients and other chemicals directly into the lake as well as the introduction of alien/invasive species.
- Atmospheric deposition contaminated by pollutants from biomass burning and cooking on charcoal even from far away could affect the lake through rain and dry deposition and alter the lake nutrients and pollutant inputs (Pasche et al., 2012; Muvundja et al., 2009).
- The plume from the Nyiragongo Volcano emits large amounts of toxic gases (fluoride and SO_2) and particles (Balagizi et al., 2018) which can lead to the lake acidification. This natural pollution might explain the heavy metal concentration found in Lake Kivu surface water (Nsabimana et al., 2020)

Strategic Way forward for the Lake Management and Sustainable Long-term Use

There are considerable knowledge gaps on many issues on Lake Kivu and every year that continued monitoring is not conducted keeps scientists and decision-makers ill-informed about what changes are occurring and how to address them, if necessary. One of the most important thing to do is to strengthen and build capacity of the "Autorité du Bassin du Lac Kivu et de la Ruzizi" (Lake Kivu and Ruzizi Basin Authority, ABAKIR) for a transboundary Strategic Management Plan. Other recommendations are to address the following issues:

- Lack of sufficient knowledge, insufficient basic infrastructure and basic equipment, weak technical and operational capacity by local research and monitoring bodies
- Poor fisheries and environmental management by governments

- Pollution, habitat destruction and degradation
- Lack of environmental awareness by riparian population
- Lack of updates and reinforcement of national management regulations and policies
- Poverty among the riparian populations and fishermen communities and limited access to basic social services such as water, sanitation and hygiene education, and health systems
- Land and resource degradation in the catchment
- Poor technical and administrative capacity among lake management stakeholders (fishermen and aquaculture cooperatives, fisheries officers and local governments, fisheries research, and education sector, etc.) including weakness of gender inclusion.

To improve the situation, a number of actions have to be urgently put in place:

- Review and update of fisheries and aquaculture policies and regulations
- Elaboration of strategic development plans for local governments
- Harmonization of fisheries and aquaculture management regulation tools between Rwanda and DRC for Lake Kivu
- Invasive species prevention and control
- Fisheries and aquaculture value chain development
- Security and safety assurance on the lake.

The components of the lake water budget, especially the riverine and underground inputs and evaporation need to be fully understood using high resolution time series data. Lake Kivu biodiversity is continuously under threats both natural (volcanism and tectonism) and human induced (pollution, erosion and habitat destruction and fragmentation). Unfortunately, the dynamics of its biodiversity including macroinvertebrates, fish (cichlids), etc. are not well addressed, especially regarding their distribution and interspecific vs. intraspecific variations. Assessing the diversity of macroinvertebrates, that of fishes in the lake, the distribution pattern of all biota groups is important. Evaluating the specific status of different fish species community structures i.e., environmental-based approach, advanced molecular approach on the sardine *Limnothrissa miodon* and *Lamprichthys tanganicanus* (population-genetic) and eventually environmental DNA approach, is also needed. In addition, a comprehensive and complementary lake monitoring program both in Rwanda and DRC is crucial for the sustainable management of Lake Kivu. The most important components of the monitoring program should include basic limnological parameters (water temperature, pH, conductivity and salinity, dissolved oxygen, water hardness, water light penetration, nutrients, and chlorophyll *a*), critical chemical parameters such as CO_2,CH_4 H_2S, fluorides; biota such as main algal groups, zooplankton taxa and fish stocks. The monitoring program should also consider the meteorological drivers and hydrological inputs from the lake basin. In addition, a capacity building of Higher Education Institutions is needed to implement training programs at masters and PhD levels in the field of freshwater sciences to alleviate the lack of qualified human resources and local expertise allowing overcoming the issue of insufficient skills. The current needs are listed in Table 2.

In a long-term perspective, it is essential to establish a continuous monitoring program of the physico-chemical and microbiological quality of the water to create a reference database that can guide the decision-makers and administrators of the lake's coastal cities. In the same context, it is essential that the laws and decrees relating to the use of the catchment area and land use in the catchment are implemented by the decision-makers in charge of environmental management issues. Raising the awareness of the local population on domestic waste management, land use and reforestation is necessary to slow down and possibly reverse the trend of the lake's pollution indices as revealed by the few available studies.

For the effectiveness of such studies, it is necessary to increase the capacity of existing research teams in terms of laboratory infrastructure, research and education staff as well as management skills. This is possible by promoting continued interaction with researcher from other large lakes as well as regional initiatives. For the sake of complementarity, it is encouraging to initiate multidisciplinary research projects by teams working in similar themes. This would make it possible on the one hand to properly channel expenditure and on the other hand to cope with the lack of certain expertise in different current research teams.

7. Conclusion

Lake Kivu is an important lake to study, monitor and conserve for (1) being a transboundary lake feeding another important great lake, Lake Tanganyika of the Albertine Rift, the western branch of the East African Rift, (2) its fisheries, water, methane resources and hydroelectricity production at the outflow, (3) hosting an important transport industry between North-Kivu and South-Kivu (D R Congo) as well as between Western Rwandan Districts; and (4) touristic and recreational potential. This paper summarized the existing knowledge about all the aspects of the lake and recognized gaps as well as challenges and opportunities for a sustainable use of the lake important resources.

Although an important ecosystem, the lake currently suffers from many stressors and challenges including pollution and habitat destruction, illegal and overfishing fishing, alien invasive species introduction, lack of harmonized transnational fishing regulations, knowledge gaps and weak governance. Some of these stressors are known, but more importantly many are not. For addressing these issues in a concerted manner, the Lake Kivu Advisory Group (LKAG) was created, to serve as a think tank for a better use of the lake. The mission of this board is discussed in detail in this paper. The main tasks were identified and classified as for short-term, mid-term and long-term tasks based on the existing knowledge. The resources needed and prominent actors were also highlighted.

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Table
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Tables

Table 1. Lake Kivu literature overview

Subjects on Lake Kivu	References (see ref list)	Publication status
Geology, geomorphology, and sedimentology	Célerier 1931; Poussin 1934; Denaeyer 1963; Wong and Von Herzen 1974; Stoffers and Hecky 1978; Haberyan and Hecky 1987; Ilunga 1991; Lahmeyer and Osae 1998; Furman and Graham 1999; Pasche et al. 2010; Zhang et al. 2014, Ross et al. 2014, 2015a; Wood and Scholz 2017.	Published
Stratification and mixing	Damas 1937; Degens et al. 1973; Tietze 1978; Newman 1976; Halbwachs et al. 2002; Schmid and Wüest 2012.	Published
Fluxes, turbulent and double diffusion	Schmid et al. 2004, 2005& 2010; Pasche et al. 2009& 2010; Wüest et al. 2012; Sommer et al. 2013a&b; Hirslund 2012; Schmid et al. 2012; Carpenter et al. 2012a&b; Katsev et al. 2014; Ross et al. 2015a; Toffolon et al. 2015; Sommer et al. 2014 &2019.	Published
Warming and climate	Lorke et al. 2004; Borges et al. 2011; MacIntyre S. 2013; Katsev et al. 2014; Thiery et al. 2014a, 2014b; Kranenburg et al. 2020.	Published
Hydrology	Bergonzini 1998; Bergonzini et al. 2002; Munyaneza et al. 2009; Habiyaremye et al. 2011; Muvundja et al. 2009&2014.	Published
Gases and geochemistry	Degens and Kulbicki 1973; Tietze 1978, 1980; Jannasch 1975; Tietze et al. 1980; Botz et al. 1988; Schmid et al. 2004& 2005; Tassi et al. 2009; Borges et al. 2011; 2012& 2014; Roland et al. 2016& 2018.	Published
Nutrient and organic matter cycling	Kilham and Kilham 1990; Muvundja et al. 2009; Pasche et al. 2012 Kneubühler et al. 2007; Al-Mutlaq et al. 2008; Morana et al. 2014, 2015a& b; Borges et al. 2014b ;	Published
Methane cycle and extraction	Deuser et al. 1973; Tietze et al. 1980; Wüest et al. 2012; Pasche et al. 2011; Wüest et al. 2012 ; Zigah et al. 2015; Vaselli et al. 2015; Roland et al. 2016; Boehrer et al. 2019; Bärenbold et al. 2020.	Published
Microbiology	Lliros et al. 2010, 2012& 2015; Bhattarai et al. 2012; Stoyneva et al. 2012; Plascencia et al. 2013; Finger et 2014 ; Masilya et al. 2021.	Published

Phytoplankton	Kilham et al. 1986; Sarmento 2012 ; Sarmento et al. 2006, 2007, 2008 & 2009; Descy and Sarmento 2007 ; Sarmento et al. 2012 ; Stoyneva et al. 2012 ; Darchambeau et al. 2014 ; Rugema et al. 2019 ; Mudakikwa et al. 2021.	Published
Zooplankton	Kiss 1959 ; Dumont 1986; Kaningini et al. 2003 ; Isumbisho et al. 2004, 2006;, Darchambeau et al. 2012.	Published
Fishes and fisheries	Verbeke 1957&1959; Collart 1960; De Iongh et al. 1983; Spliethoff et al. 1983; Lamboeuf, 1989& 1991; Ulyel et al. 1990 ; Marshall 1991; Snoeks 1994; Snoeks et al. 1997, 2012; Kaningini 1995 ; Kaningini et al. 1999; Roest 1999 ; Masilya et al. 2011 & 2020; Isumbisho et al. 2004&2006; Masilya et al. 2008; Muderhwa and Matabaro et al. 2010; Masilya 2011a&b; Guillard et al. 2012& 2017; Riziki et al. 2015; Akonkwa et al. 2015a&b; Munyandamutsa et al. 2020&2021 ; Tessier et al. 2020.	Published
Ecology of the littoral zone	Mazambi et al. 2020; Villanueva et al. 2008 ; Hyangya et al. 2021.	Published
Lake Kivu foodweb modelling	Villanueva et al. 2008; Sarmento et al. 2012; Darchambeau et al. 2014.	Published
	Pasche 2012; Pasche et al. 2010; Ross et al. 2015b; Votava et al. 2016.Hecky and Degens 1973; Hecky 1978; Haberyan and Hecky 1987; Stoffers and Hecky 1987.	Published
Lake Kivu paleolimnology	Pasche 2012; Pasche et al. 2010; Ross et al. 2015b; Votava et al. 2016.	Published
Lake Kivu natural hazards	Balagizi et al. 2018 ; Delvaux et al. 2016; Doevenspeck 2007 ; Ross et al. 2014, 2015a&b ; Tassi and Rouwet 2014; Schmid et al. 2004& 2005.	Published

Table 2. Assessment of needs to address biodiversity decline and ecosystem monitoring of Lake Kivu

What needs to be done and how?	Resources required	Who does it?	When?	Time scale
Identification of key biodiversity areas (KBAs) - Baseline biological and ecological surveys	Human resources, well equipped research vessels, financial resources, vehicles, and field research equipment, satellite research stations	Local experts (*) that are motivated to team with international colleagues	1-2 years	Short-term
Comprehensive fisheries stock assessment - Fisheries dependent (Catch and Effort) and independent (experimental fishing, hydroacoustics) surveys	Technical capacity building related equipment use and data analysis	Local experts	Annually	Long-term
Survey of the socio-economic dynamics of fishermen communities	Financial resources, capacity building on large data analytics and modelling	Local experts	1-3 years	Short-term
Genetic characterization of fish species	Molecular laboratory facilities, finances to purchase consumables, infrastructure development (including equipment)	Local experts that are motivated to team with international colleagues.	1-5 years	Medium-term
Dedicated field survey studies for key species, and -conservation status assessments (IUCN red list)	Capacity building on taxonomy, training of local communities on surveillance for invasive species	A citizen science approach - members of the general public collaborating with professional scientists	1-3 years	Short-term
Monitoring of the invasion of the pelagic zone by *Lamprichthys tanganicanus*				
Evaluation of the effects of floating cage fish farming on the diversity of ichthyofauna and on the				

physicochemical and microbiological quality of the lake waters		Local experts	1-3 years	
	Financial resources			Short term
Establishment of a reference Aquatic ecosystem laboratory for the region		Local experts, fish farmers	1-3 years	
	Microbiological laboratory facilities,			Short term
	Financial resources, Capacity building on big data analytics and modelling		1-5 years	
	Well-equipped laboratory, training on QC/QA laboratory management	Local expert with the international expert		
				Medium-term

[(*)] Local experts here means Lake Kivu Advisory Group (LKAG) members and other local researchers interested.

Table 3. Lake Kivu basin population estimates

Country	Territory	Area (km²)	Population (hab)	Population density (hab/km²)	Year	Reference
DRC	Bukavu	66	870,954	13,200	2013	CAID (2016)(*)
	Idjwi	310	298,237	962	2016	CAID (2016)
	Kabare	1960	780,616	398	2016	CAID (2016)
	Kalehe	5057	815,326	161	2016	CAID (2016)
	Masisi	4734	723,350	153	2016	CAID (2016)
	Rutshuru	5289	1,606,357	304	2016	CAID (2016)
	Nyiragongo	333	145,748	438	2016	CAID (2016)
	Goma	76	925,072	12,220	2014	INS (2014)
	Sub-total	17,825	6,165,660	-		
		Mean rural population density		403		
		Total rural population	1,807,095			
Rwanda	**District**	**Area (km²)**	**Population (hab)**	**Population density (hab/km²)**	**Year**	**Reference**
	Karongi	993	331,808	334	2012	NISR (2014) (**)
	Rutsiro	1155	324,654	281	2012	NISR (2014)
	Rubavu	389	403,662	1,039	2012	NISR (2014)
	Nyabihu	531	294,740	555	2012	NISR (2014)
	Ngororero	680	333,713	491	2012	NISR (2014)
	Rusizi	959	400,858	418	2012	NISR (2014)
	Nyamasheke	1175	381,804	325	2012	NISR (2014)
	Total	5882	2,471,239	420		

Total General (all lake basin)	**4798**		**5,743,935**	**411(***)**

(*) CAID (Cellule d'Analyse des indicateurs de développement), Bureau of the Prime Minister, Kinshasa, DRC, available at https://www.caid.cd/index.php/donnees-par-province-administrative/province-de-sud-kivu/?donnees=fiche

(**) NISR (National Institute of Statistics of Rwanda, 2014).

(***)Population density in the whole drainage area excluding the lake and the towns of Goma and Bukavu.

Figure
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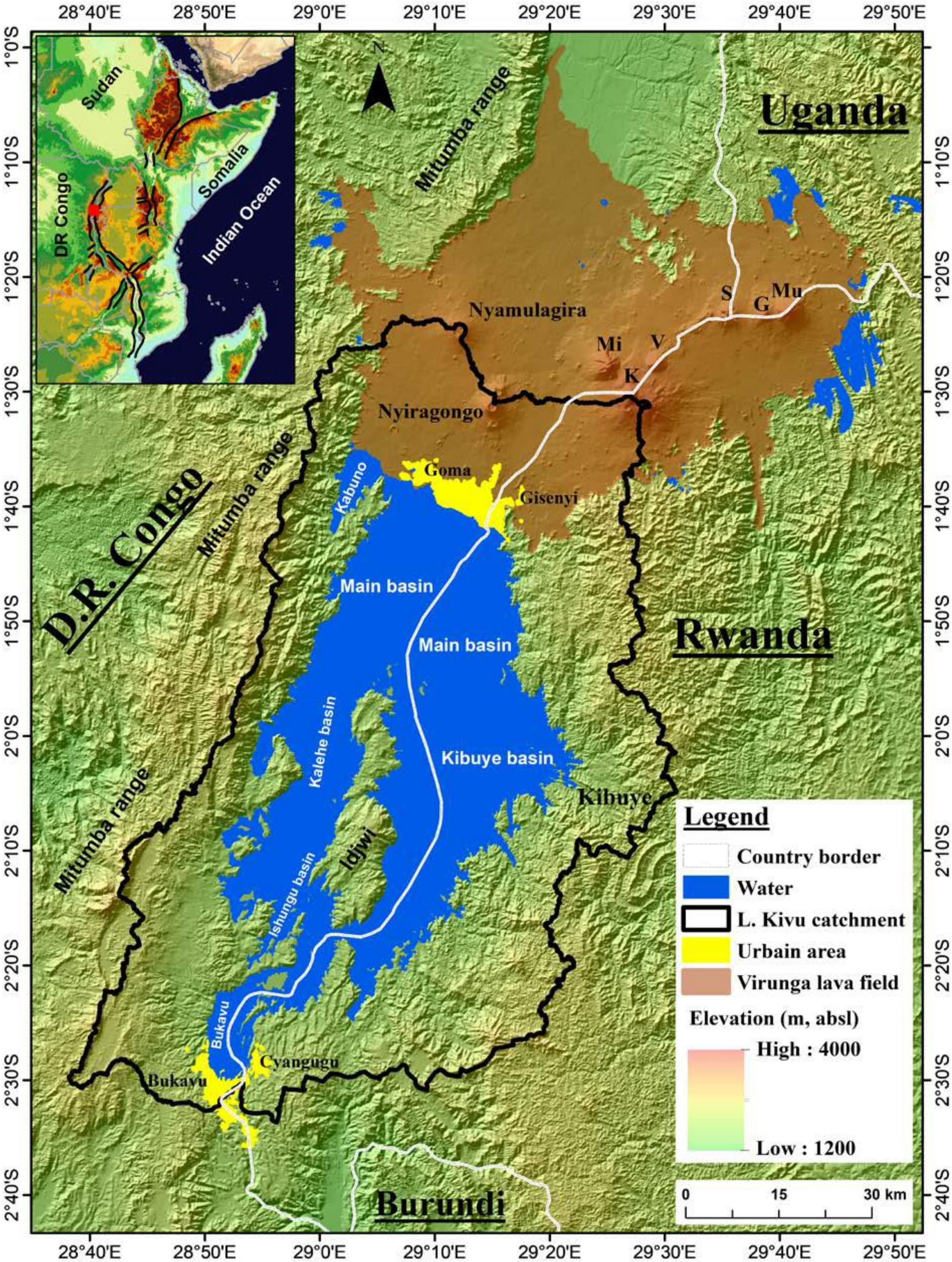

Figure 1. Map of the Lake Kivu basin with the field of Virunga volcanoes shown to the North. The local institutions that conduct research and monitor Lake Kivu are also given in. These are the Institut Supérieur Pédagogique de Bukavu (ISP), Goma Volcano Observatory (GVO), Centre de Recherche en Sciences Naturelles de Lwiro (CRSN/Lwiro) (located respectively to the south and north on the DRC side), and Lake Kivu Monitoring Program (LKMP at the north on Rwanda side). The triangles refer to the methane extraction power plants: Kivu Power 1 (KP1), (SPLK), and KivuWatt (KW). Research stations are located in each of the basins on both Rwanda and DRC sides. The map is also a Digital Elevation Model in which the eight major volcanoes of the Virunga are shown to the north, aligned along the border of the DRC, Rwanda and Uganda: Nyiragongo, Nyamulagira, Mikeno (Mi), Karisimbi (K), Visoke (V), Sabinyo (S), Gahinga (G), and Muhabura (Mu). The black lines in the inset map indicate the East African Rift System boundaries, of which the western branch covers parts of the Democratic Republic of the Congo, Uganda, Rwanda, Burundi, and Tanzania.

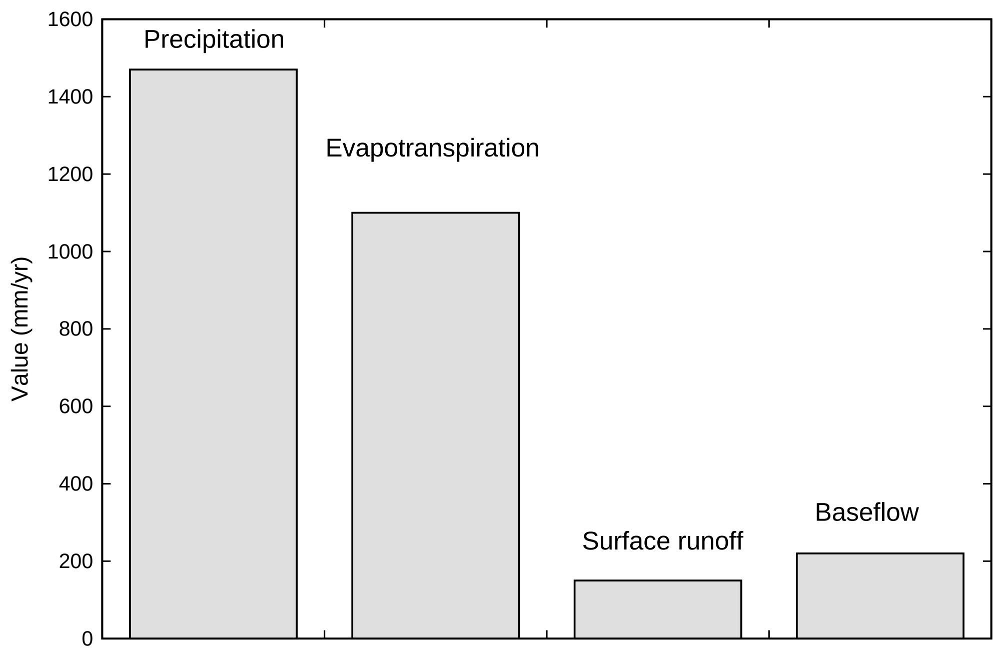

Figure 2. Soil water balance in Lake Kivu catchment

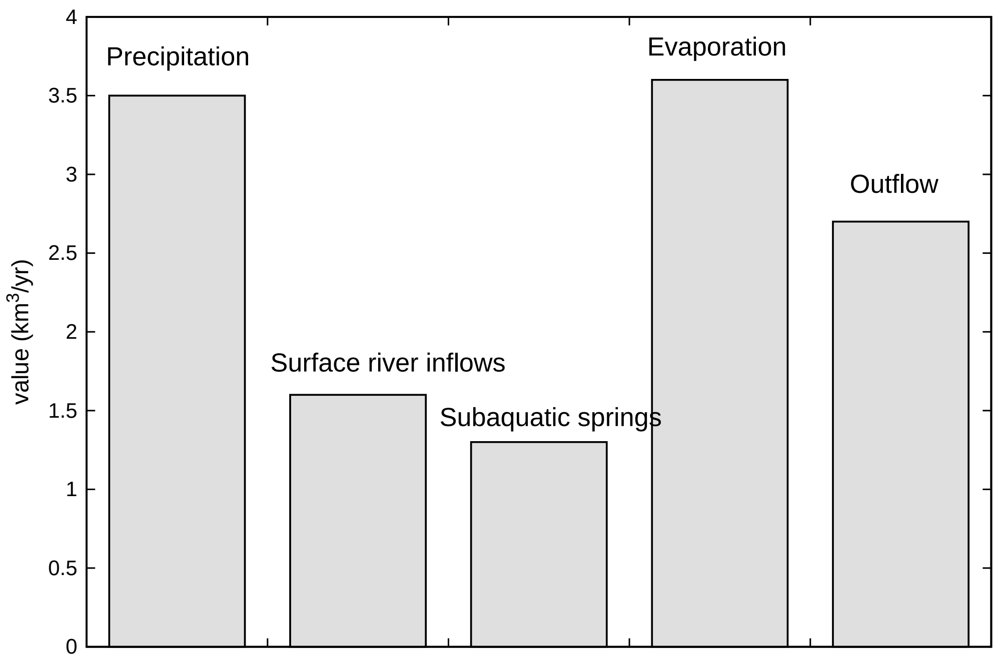

Figure 3. Lake Kivu water balance (Data from Muvundja et al., 2014)

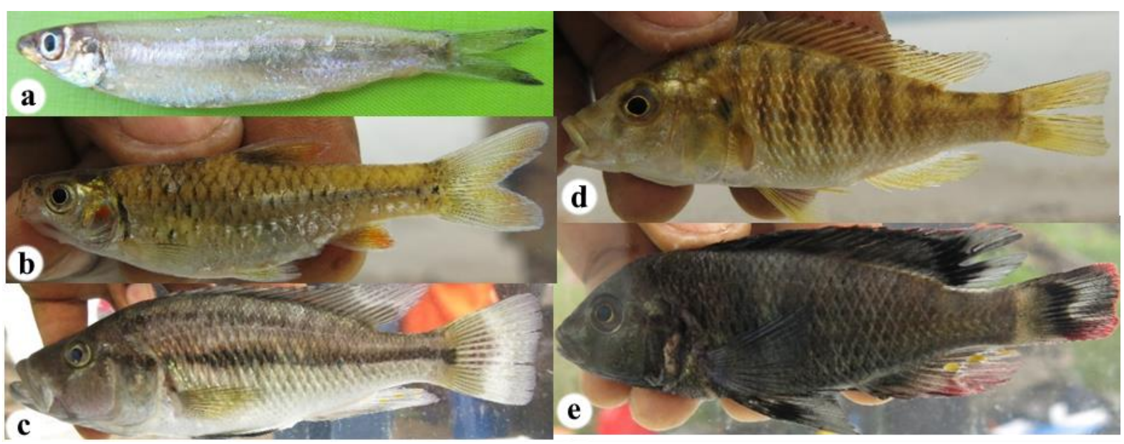

Figure 4. Illustration of some fish species from Lake Kivu: (a) *Limnothrissa miodon*, (b) *Enteromius kerstenii* (Peters, 1868), (c) *Haplochromis vittatus*, (d) *H. graueri* and (e) *H. olivaceus* (photo credits by Kisekelwa T.).

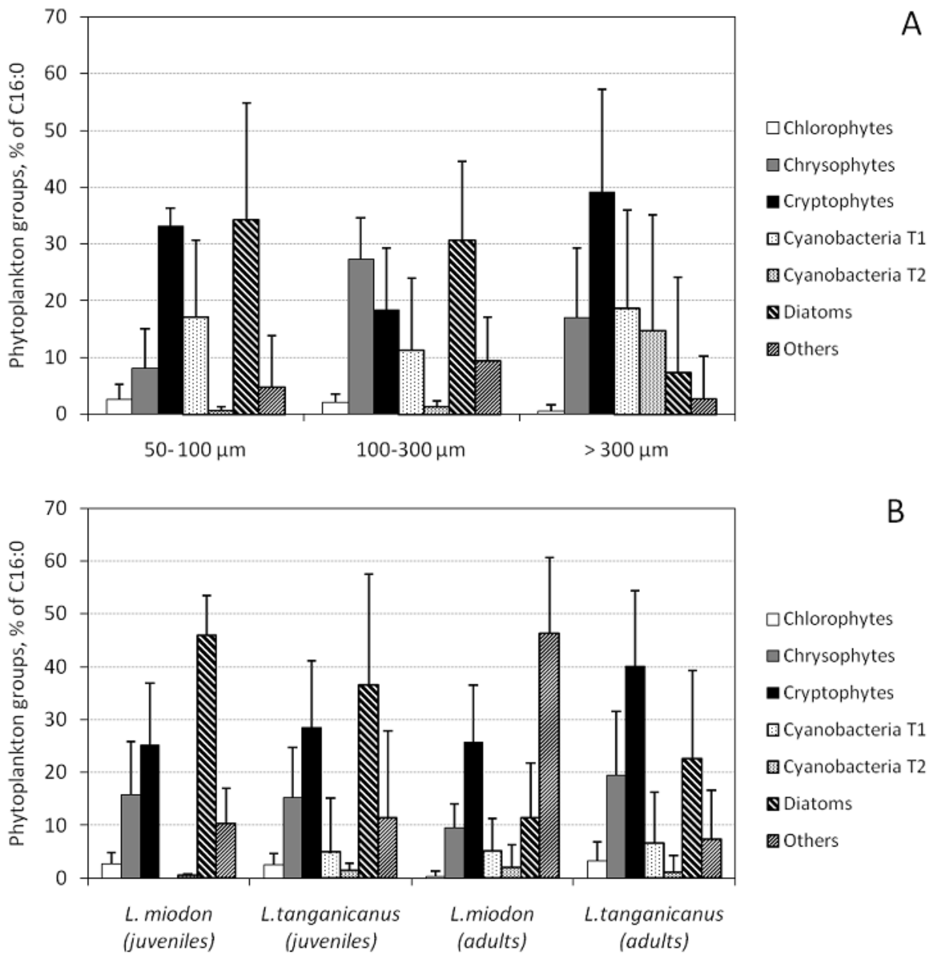

Fig. 5. Relative phytoplankton group abundance in diet of (A) zooplankton and (B) fishes using CHEMTAX and based upon PLFA content. Group abundance is expressed as % contribution to C16:0 (Data from Masilya, 2011a).

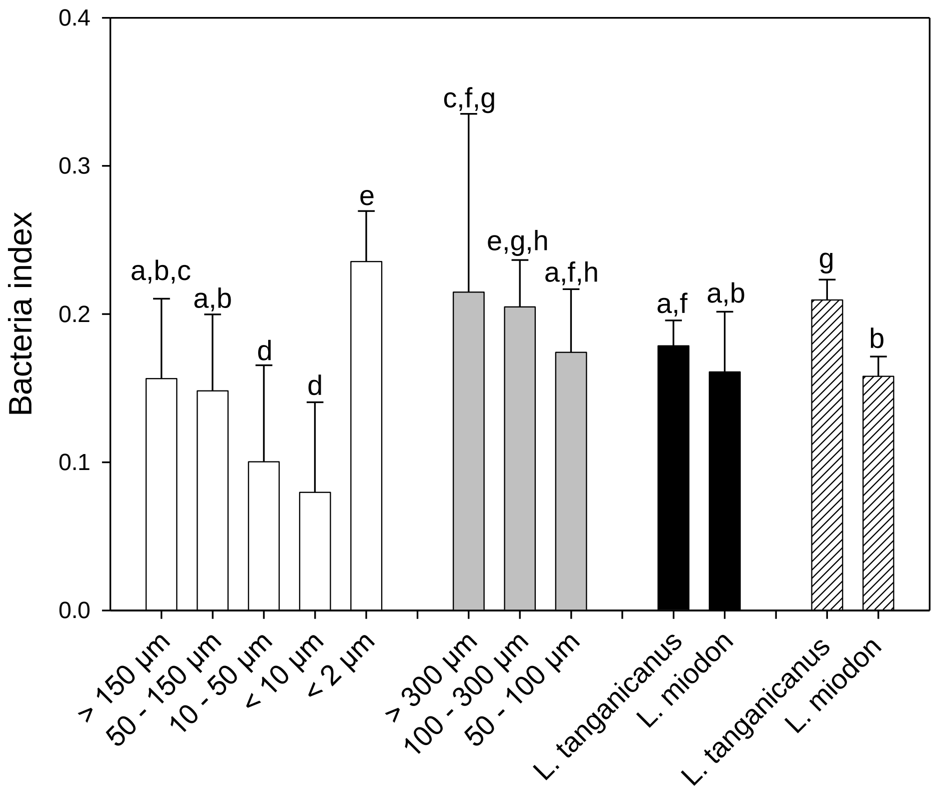

Figure 6. Fatty acid bacterial index (mean ± 95% confidence interval) following Dalsgaard et al. (2003) in seston (open histograms), zooplankton (grey histograms), fish juveniles (black histograms) and adults (shaded histograms) in Lake Kivu. Histograms with shared letters are not significantly different at the 0.05 level (Mann-Whitney U test with Benjamini-Hochberg correction) (Data from Masilya, 2011a).

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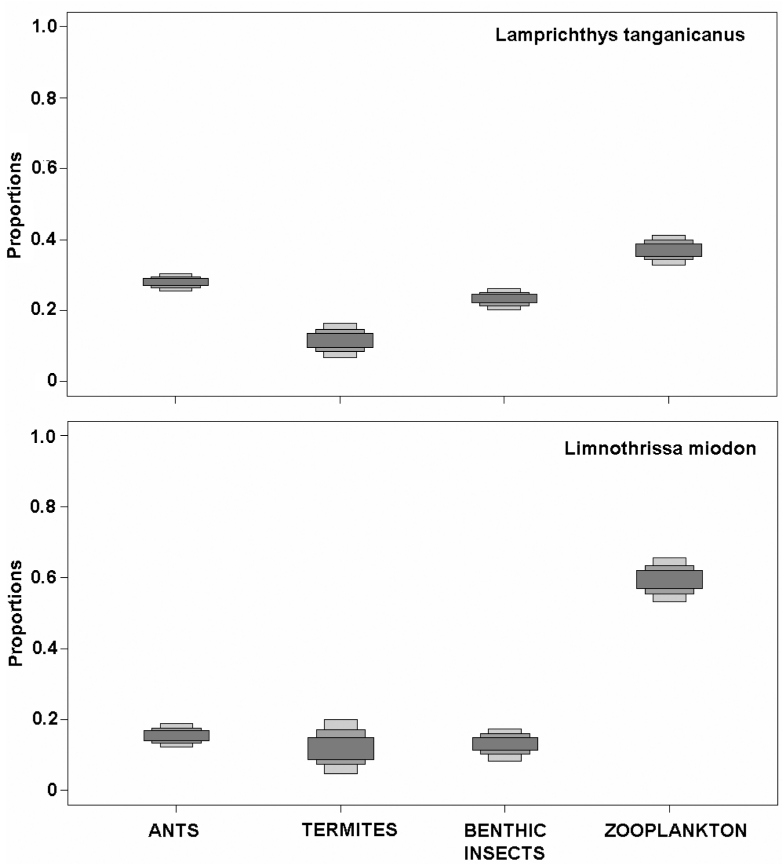

Figure 7. Proportions of zooplankton ≥ 300 µm, benthic insects, termites and ants assimilated by *Limnothrissa miodon* and *Lamprichthys tanganicanus* in Lake Kivu. Probability estimates are based on the SIAR mixing model and the shaded boxes represent the 50%, 75% and 90% credible intervals from dark to light grey (Data from Masilya, 2011a).

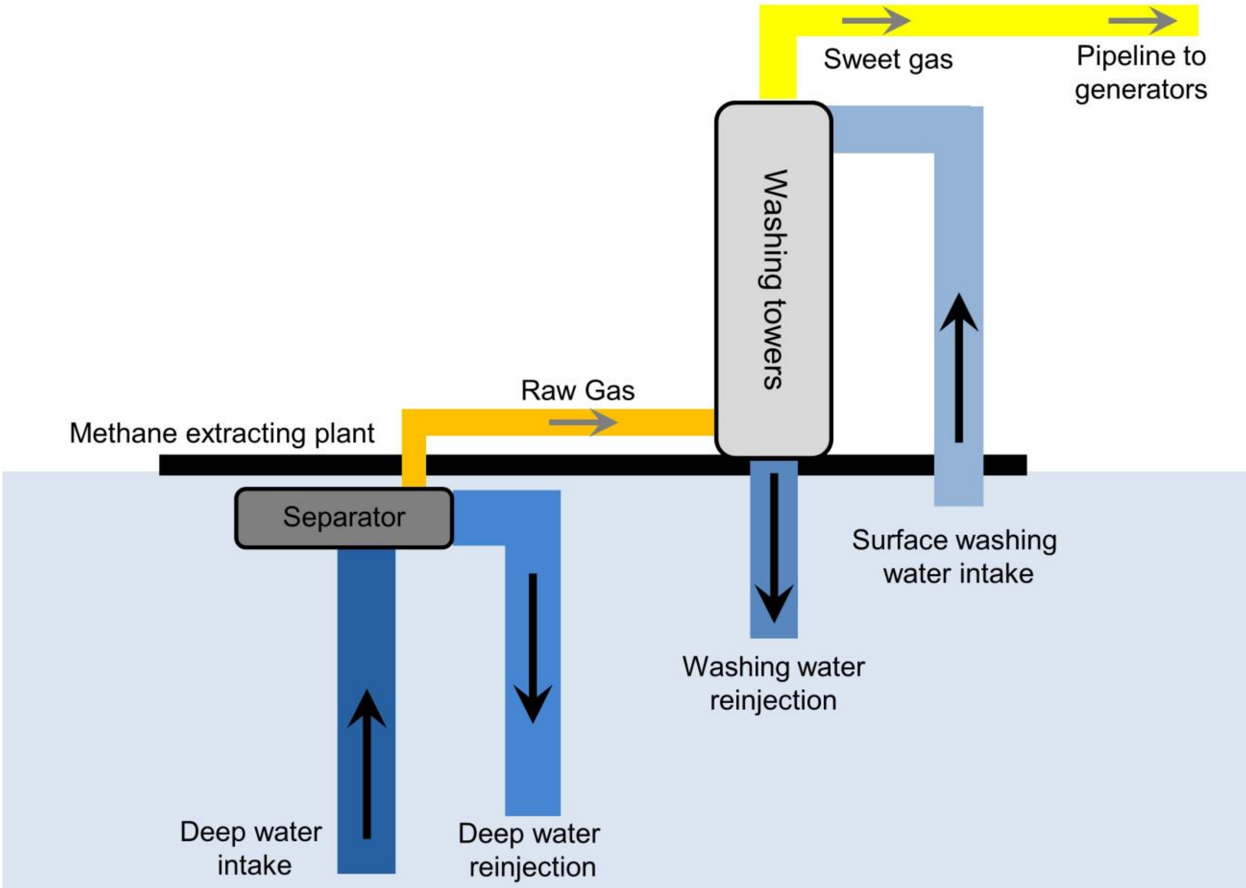

Figure 8. Schematic view of the methane extracting process in Lake Kivu. The black arrows represent the raw water flow and the grey arrows the gas flow.