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Need for harmonized long-term multi-lake monitoring of African Great Lakes

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ABSTRACT

To ensure the long-term sustainable use of African Great Lakes (AGL), and to better understand the functioning of these ecosystems, authorities, managers and scientists need regularly collected scientific data and information of key environmental indicators over multi-years to make informed decisions. Monitoring is regularly conducted at some sites across AGL; while at others sites, it is rare or conducted irregularly in response to sporadic funding or short-term projects/studies. Managers and scientists working on the AGL thus often lack critical long-term data to evaluate and gauge ongoing changes. Hence, we propose a multi-lake approach to harmonize data collection modalities for better understanding of regional and global environmental impacts on AGL. Climate variability has had strong impacts on all AGL in the recent past. Although these lakes have specific characteristics, their limnological cycles show many similarities. Because different anthropogenic pressures take place at the different AGL, harmonized multi-lake monitoring will provide comparable data to address the main drivers of concern (climate versus regional anthropogenic impact). To realize harmonized long-term multi-lake monitoring, the approach will need: (1) support of a wide community of researchers and managers; (2) political goodwill towards a common goal for such monitoring; and (3) sufficient capacity (e.g., institutional, financial, human and logistic resources) for its implementation. This paper presents an assessment of the state of monitoring the AGL and possible approaches to realize a long-term, multi-lake harmonized monitoring strategy. Key parameters are proposed. The support of national and regional authorities is necessary as each AGL crosses international boundaries.

Introduction

The seven main African Great Lakes (AGL) consist of Lakes Albert, Edward, Kivu, Malawi/Niassa/Nyasa, Tanganyika, Turkana, and Victoria. Their basins spread across 11 countries (Burundi, D.R. Congo, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, South-Sudan, Tanzania, Uganda and Zambia). All provide invaluable ecosystems services (e.g.: >1.5 million ton of fish/year; Lymer and Welcomme, 2012) for the rapidly growing population of > 90 million people in the region (Sterner et al., 2020). Because these AGL have existed for millions of years (Cohen et al., 1993; Tiercelin and Lezzar, 2002), they shelter an exceptional, highly

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endemic biodiversity across a large range of groups of taxa including the so-called "species-flocks" (Martens et al, 1994; Sturmbauer, 2008). This biodiversity represents a global heritage. The AGL contain >2000 fish species, including over 1800 species of cichlids, ~95% of which are endemic (Salzburger et al., 2014). Further, the AGL represent ~29% of the world's surface freshwater (Ogutu-Ohwayo et al., 2020; Shiklomanov, 1993). The lakes also modulate regional climate and are important sources of moisture contributing to precipitation regulation and regional hydrology (Balagizi et al., 2018a; Docquier et al., 2016; Thiery et al., 2015).

In the recent decades, both recurrent and emerging environmental and anthropogenic threats have been identified in the AGL (Table 1). The relative importance of each of those threats is lake-specific and more information is provided in the present issue of the JGLR. Each of the seven AGL are large and share boundaries with two or more countries. Managers have a common set of concerns related to the drivers and pressures, threatening the states of the lakes' ecosystems (Atkins et al., 2011). Therefore, the use of standardized and regularly collected metrics of key interest would provide stakeholders with a greatly improved understanding of ecosystem health.

The need for, and utility of, long-term data collection has often been described and is well known within lake research (Bahlai et al., 2021; Hampton et al., 2019; Iwaniec et al., 2021; Rastetter et al., 2021). With the exception of mainly fishery surveys on Lakes Victoria and Malawi/Nyasa/Niassa (Irvine et al., 2019), monitoring programs within the AGL have often been achieved through short-term research projects such that there are large temporal gaps between intervals with data collection, inconsistent use of indicators, and differences in methodological approaches. Lack of monitoring, evaluation and research personnel, and sometimes infrastructures, within fisheries departments and research institutions further complicate the monitoring challenge.

The resolution of the 2017 AGL Conference of Entebbe (>300 participants) recognized the need for timely information, robust data, and continuous monitoring to guide policy for conservation and management of the AGL aquatic and other resources (AGL, 2017; Doran et al., 2018). To address the variety of drivers and threats, and disentangle natural and anthropogenic factors, a consistent multi-lake monitoring framework is needed (Mudakikwa et al., 2021; Ogutu-Ohwayo and Balirwa, 2006; Plisnier et al., 2018).

A few key parameters could form a common basis for data sharing among the partners that compose a network of AGL institutions. Such a network would include institutions from each AGL country that have a mandate (or could acquire one) from their government in one or several of the environmental and anthropogenic topics related to the proposed continuous multi-lake monitoring (water, fisheries and aquaculture, climate, biodiversity, land-use, socio-economic conditions of riparian populations using the lake's ecosystem services). A list of the various institutions, organizations and other potential stakeholders is presented later in this manuscript. A subset of those institutions participating in the multi-lake monitoring network will need to be identified for efficacity, but others could be called upon in case of need. Primary stakeholders who have been identified will require authorization from their national authorities to participate in the multi-lake monitoring.

The proposed monitoring network would greatly improve timely ecological understanding and provide managers with the information needed to better address and mitigate the drivers and threats, as well as to enable them to predict future changes including trade-offs, costs and benefits. Strategically, collaboration with regional and international institutions will be necessary to strengthen the continuous long-term monitoring. Such a network would boost the state of knowledge of AGL and the sustainable long-term ecosystem services that constitute a common goal shared by all stakeholders. This necessity has already been bolstered in the African Centre for Aquatic Research and Education (ACARE)'s advisory groups based on each of the AGL (Obiero et al., 2020; Robarts and Zohary, 2018). The benefits of multi-lake monitoring advances beyond obtaining data that can be used to assess the sustainability of ecosystems. This is also needed to determine the impacts of policies and socio-economic changes that impact lakes (for instance urbanization, livelihoods etc.). This is also important for the non-academic community including local policymakers and civil society.

This paper is structured so that the first part underlines the importance of indicators based on regularly collected data and the present state of monitoring at various AGL covering climate variability and change and the anthropogenic impacts. The advantages of multi-lake monitoring are then presented, including main

Table 1
Environmental and anthropogenic threats at the AGL.

THREATS	References
Climate variability and change	O'Reilly et al., 2003; Verburg et al., 2003; Katsev et al., 2014; Kraemer et al., 2021; Naithani et al.,2011; Ogutu-Ohwayo et al, 2016;Rugema et al., 2019; Souverijns et al., 2016; Vanderkelen et al., 2018a,b; Van der Knaap, 2019
Hazardous thunderstorm	Thiery et al., 2016,2017; Virts and Goodman,2020.
Shoreline flooding	Bakibinga-Ibembe et al., 2011
Massive algal blooms	Mchau et al., 2019; Witte et al., 2012; Cocquyt et al., 2021
Fish kills	Ochumba 1987, 1990
Parasite infestation	Gabagambi and Skorping, 2018, Gabagambi et al., 2020
Limnic gas eruption risk	Balagizi et al., 2018b; Schmid et al., 2005; Bärenbold et al., 2020.
Heavy exploitation	Haambiya et al., 2015; Kolding, 1995; Van der Knaap, 2013; Nyamweya et al., 2020; Obiero et al., 2015
Excessive sedimentation from intensive agriculture/deforestation	Bootsma and Hecky, 2003; West, 2001; Bakibinga-Ibembe et al., 2011
Eutrophication	Deirmendjian et al., 2021; Hecky et al., 2010; Lung'ayia et al., 2001
Oxygen depletion	Hecky et al., 1994; Jane et al., 2021; Njiru et al., 2012
Loss of fish biodiversity	Sayer et al., 2018; Mgaya and Mahongo, 2017
Invasive fish species	Obiero et al.,2020; Ogello et al., 2013; Ogutu-Ohwayo et al., 1997; van Zwieten et al., 2016
Invasive water weeds	Mgaya and Mahongo, 2017; Ofulla et al., 2010
Habitat loss due to shoreline development	Owino and Ryan, 2007
Pollution (mining, chemicals, plastics etc.)	Kanangire et al., 2018; Odada and Olago, 2006; Scheren et al., 2001
Cage fish farming	Kashindye et al., 2015; Mwamburi et al., 2020
Hydrocarbon extraction	Heather-Clark and de Jong, 2007; NEMA, 2012; Verheyen et al., 2016
Public health issues	Medard et al., 2002; Muro et al., 2005; Muyodi et al., 2009; Bompangue et al., 2011
Internal and inter-state conflicts	Yongo et al., 2010; Glaser et al., 2019

principles and the needs for certain equipment. Practical ways for setting up a network are then proposed in addition to the selection of possible monitoring sites. We then list key parameters for priority topics (water, fisheries, meteorology, remote-sensing, biodiversity, land-use and socio-economy/human environment). The targeted frequency of observation is proposed and specific situations are addressed when capacities are not yet sufficiently available, or, inversely, particularly well-developed allowing a possible increased monitoring intensity. Important aspects of the network database are then presented, including possible standardization of data collection, use and interest of sharing data to better support research, policy, management and AGL sustainability. This is followed by a list of institutions and organizations of the countries where the AGL are located and amongst which partners of long-term, multi-lake monitoring need to be actively involved. A possible establishment of an international consortium to support the monitoring is then proposed, including a reference to a similar existing consortium, the "Charles Darwin Foundation", in another global hotspot of biodiversity. We conclude, by stressing the need for such a collaborative and harmonized continuous long-term monitoring effort, a strategy supported by many researchers in the region and globally.

Monitoring indicators for lake managers

Lakes are continuously affected by both internal pressures and external drivers thus their management requires regularly collected scientific data to evaluate trends and spatial patterns in response to environmental changes. Such data are required to better understand these complex ecosystems of which, without such information, management decisions can only be based on best guesses or quasi-scientific approaches that are unlikely to address threats in an optimal manner. Further, the lack of data from regular monitoring makes it difficult to determine the efficacy of management to address the threats.

Though there exist some short-term, high-quality data collection efforts on the AGL, coverage is spotty and time gaps between projects are often long (Fig. 1). The disruption of data acquisition may also be linked to other reasons such as civil strife or the departure of key personnel charged with data collection. Scientists that we know working on the AGL and beyond also agree that long-term data are essential for scientific investigation and better understanding. For example, long-term data series can help identify environmental drivers for the occurrence of cyanobacterial blooms and composition in the context of climatic and anthropogenic pressure (Le Moal et al., 2021).

AGL respond to climate variability and in turn influence the climate of the surrounding terrestrial environment. The lakes respond to atmospheric and oceanic variability on annual and interannual time scales as well as, over much longer periods (Barker, 2006; Bergonzini et al., 2004; Birkett et al., 1999; Burnett et al., 2011; Cohen et al., 2006; Gownaris et al., 2018; MacIntyre, 2013; Mercier et al., 2002; Mudakikwa et al., 2021; Nicholson, 2017; Olaka et al., 2010; Plisnier, 1997, 1998; Smith and Semazzi, 2014; Thiery et al., 2015, 2016). Long-term environmental data, including the meteorological and biogeochemical data from the surrounding environs as well as within lake data, are essential also to support the development and evaluate models of lake hydrology, hydrodynamics, and ecosystems, which are critical for sustainable management (e.g. mixing regimes: Delandmeter et al., 2018; Kranenburg et al., 2020; Thiery et al., 2014a, 2014b); disentangling the impact of bottom-up drivers versus top-down drivers in fisheries (Kolding et al., 2008); dynamics of invasive species (van Zwieten et al., 2015). Validated models also lead to better forecasting of long-term changes related to human activities or climate, including changes in fisheries and lake levels. Such models are also useful for guiding management decisions by predicting the ecosystem response to various management scenarios. Harmonized continuous multi-lake monitoring is a necessity in order to achieve such objectives.

Current state of monitoring in the AGL

A preliminary survey by ACARE, in partnership with the International Institute for Sustainable Development (IISD), conducted between February and March 2021 (Electronic Supplementary

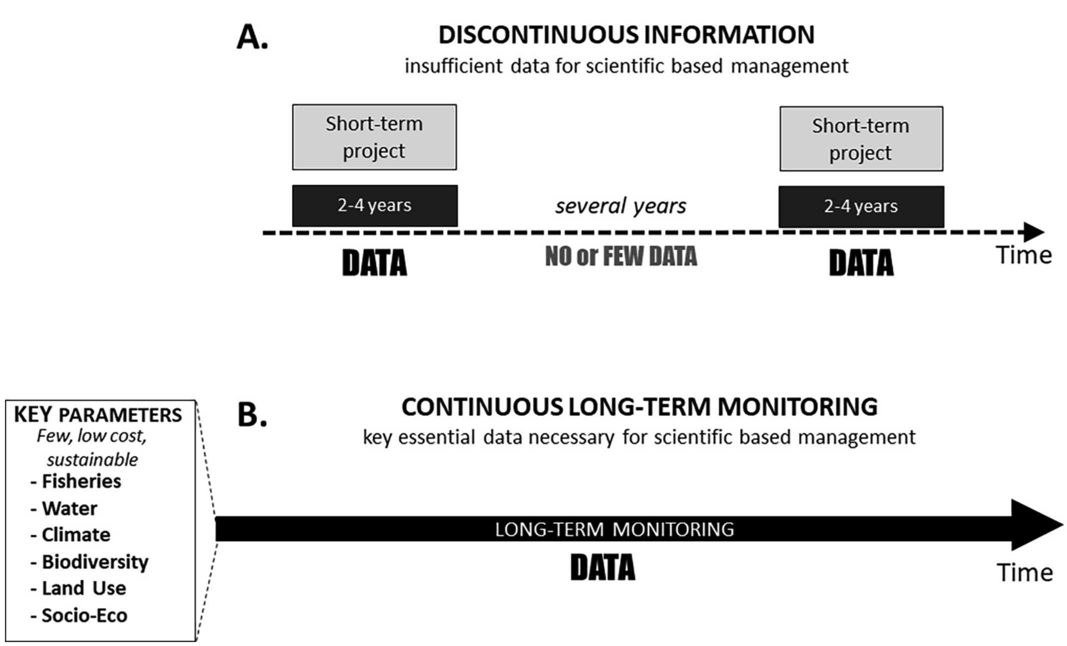

Fig. 1. Schematic presentation of (A) discontinuous information based on irregular data collection during short-term projects/studies and (B) continuous long-term monitoring including key parameters needed for science-based management. This long-term monitoring is independent from possible short-term projects that may take place as previously and may reinforce the long-term monitoring (adapted from Plisnier et al., 2018).

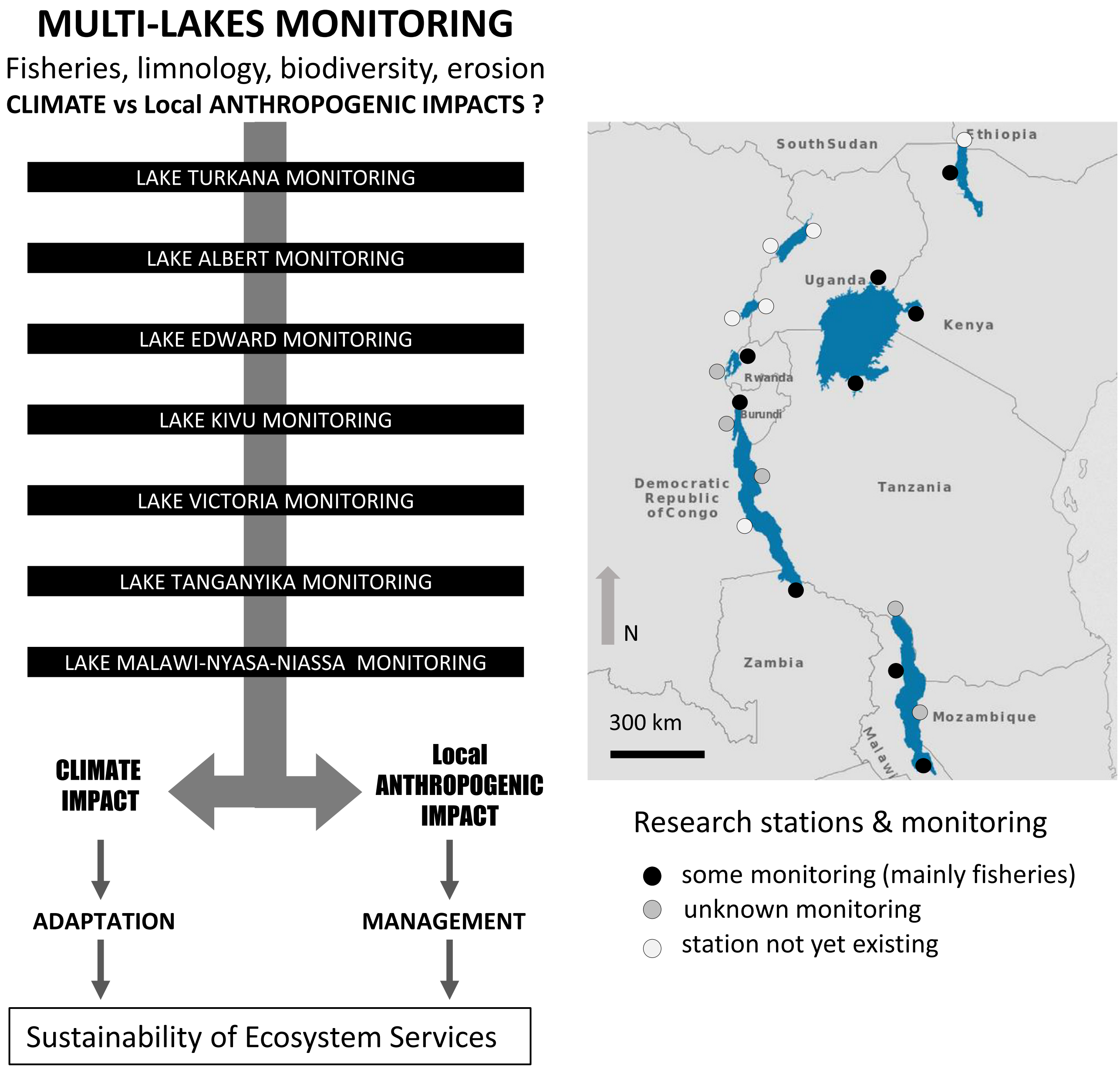

Fig. 2. Developing a multi-lake monitoring program provides a way to better evaluate climatic and anthropogenic impacts on ecosystem services. Research stations with some long-term monitoring are indicated while some sites do not have yet a research station enabling a monitoring.

Material (ESM) Appendix S1) involved a variety of aquatic experts from institutions, organizations and universities active in the AGL region. Responses on current monitoring were received from 64 African Great Lakes experts.

The results indicated that some lakes have no field stations (Lake Edward and Lake Albert) or regular monitoring sites while others implement routine monitoring activities for a sub-set of indicators (such as for fisheries), or a wider set of indicators during short-term projects or studies. Available information does not allow detailed statistics of the situations, but a map (Fig. 2) gives an indication of the present state of the situation concerning research stations and long-term monitoring activities. When monitoring takes place, it mainly focuses on fisheries and rarely limnological measurements on a continuous basis.

On Lake Victoria, a harmonized multi-national fisheries monitoring program has been established through the Lake Victoria Fisheries Organization (LVFO) and various Standard Operating Procedures (SOPs) have been set up (LVFO, 2016). LVFO monitors various aspects including fisheries, limnology and, socio-economic indicators though with some gaps. Furthermore, the Lake Kivu Monitoring Programme collaborates with various institutions/universities in Rwanda and D.R. Congo to conduct a multidisciplinary regular monitoring program of Lake Kivu. Similarly, in Malawi, continuous fisheries monitoring is taking place. Recently installed automated lake buoys provide a platform for monitoring weather parameters and underwater currents measurements. Other monitoring activities are taking place at other lakes, but there is no central clearinghouse documenting these efforts.

As indicated by the results of the ACARE and IISD survey, many activities depend on sporadic funding and/or foreign donor support, which results in irregular and ineffective monitoring. This highlights that lack of adequate funding is one of the main obsta-

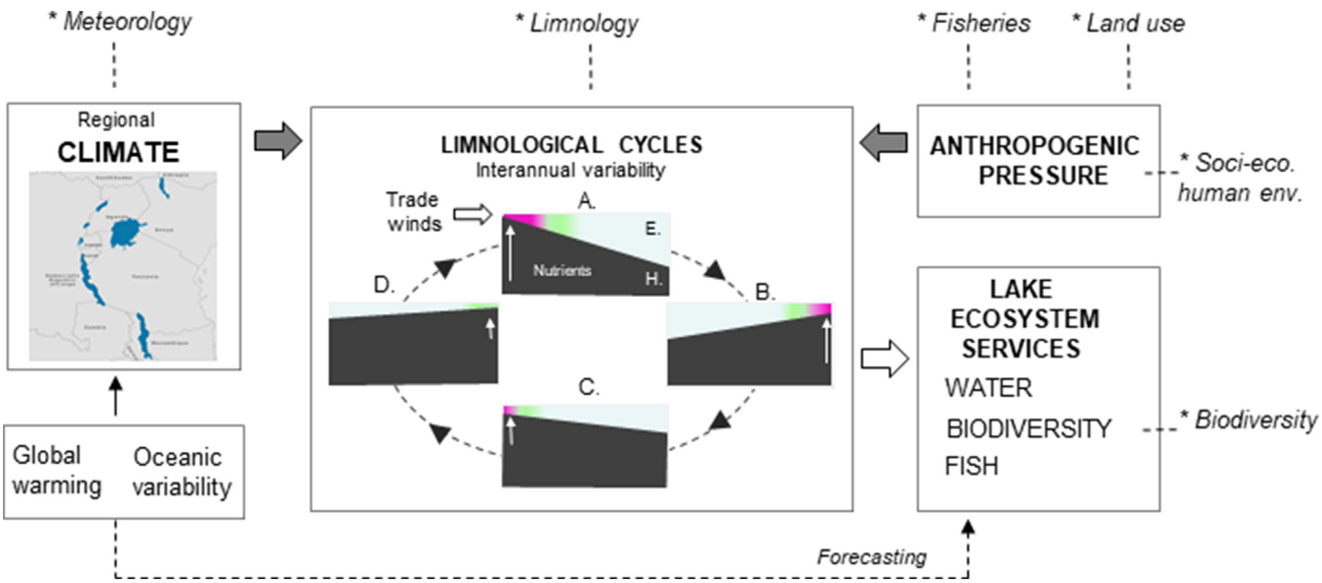

Fig. 3. The six multi-lake monitoring themes (*) address main aspects of ecosystem functioning of the AGL from climate impacts on the limnological cycles to ecosystems services impacted by direct anthropogenic pressures. Upwelling and internal waves are important drivers which supply nutrient-rich water from the hypolimnion (H) into the epilimnion (E.). A. Trade winds cause upwelling upwind and a resulting nutrient flux that may enable an increase in primary production and algal biomass. B.C.D: On cessation of the trade winds, the thermocline oscillates suppling nutrients at different ends of the lake. Higher nutrient supply and growth (magenta); lower supply and growth (green to blue). Differences in hydrodynamics between lakes are expected according to their depth, stratification, and the magnitude and duration of the trade winds. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cles for long-term monitoring. Several institutions indicated that they have the capacity to conduct monitoring activities if funding is available.

Although various historical observations have been made since the end of the 19th century (e.g., Beadle, 1932; Beauchamp, 1939; EAFRO, 1951; Lowe-McConnell, 1997; Moore, 1899; Talling, 1956; Worthington, 1930; etc.), in general in the AGL, there is little baseline data available to assess environmental and anthropogenic stressors. In addition to the setting up of continuous monitoring of key parameters, the collection and rescue of historical data is essential and their accessibility to researchers is very much needed.

Monitoring themes

In recognition of these urgent needs for sustained data collection on the AGL, we propose a long-term, networked and harmonized approach. In regard to the various environmental and anthropogenic threats on AGL (Bootsma and Hecky, 2003; Hecky et al., 1994, 2010; Kolding, 1995; Kolding et al., 2008; Lung'ayia et al., 2001; Mgaya and Mahongo, 2017; Njiru et al., 2012; Odada and Olago, 2006; Ogutu-Ohwayo et al., 1997), the proposed multi-lakes monitoring is designed to support an ecosystem approach to management. Six main themes are relevant to the harmonized multi-lake monitoring strategy: climate, limnology, fisheries, land-use, biodiversity and socio-economy/human environment (Fig. 3 and Table 2):

Climate has a strong impact on the stratification and productivity of AGL (Barker, 2006; Cohen et al., 2006; Kraemer et al., 2021; Olaka et al., 2010). Therefore, it is essential that meteorological data are continuously collected at each lake. Seasonal changes and particularly trade winds induce an annual limnological cycle on the AGL including upwelling, internal waves in stratified lakes and nutrient mixing (Coulter, 1988; Eccles, 1962; MacIntyre, 2013; Naithani et al., 2002; Patterson et al., 2000; Plisnier et al., 1999; Talling, 1966). An understanding of the regional impact of climate on the AGL in a multi-lake approach, as proposed here, will allow better understanding of how this has an impact on fluctuating fisheries production (Kolding and van Zwieten, 2012) and ecological conditions linked to particular events such as fish kills and

Table 2
The six themes of the proposed multi-lake long-term monitoring of AGL

Themes	Description
Climate	The main meteorological parameters (as detailed below) are included in the monitoring. This component is an essential input to all themes. Meteorological data from some dedicated networks are missing or difficult to access and often costly or not available.
Limnology	The water quality topic includes physical–chemical characteristics, hydrodynamics, planktonic abundance and pollution. Water key parameters related to the lake's ecology mainly are targeted. Polluted water will be sampled and analysed by specialized laboratories not part of the present monitoring proposal.
Fisheries	Concerning the fisheries topic, it focalizes particularly on catches and efforts although other topics such as fish stock, biology and ecology of main fish species are also important if there are enough capacities to conduct a continuous monitoring.
Land use	Land use addresses the impact of deforestation and agriculture practices on erosion with impact on sedimentation and eutrophication.
Biodiversity	The monitoring of biodiversity is meant to document distribution and abundance as well as assess population trends and impacts of factors that impact biodiversity, with specific attention to the risks of invasive species and possible loss of endemic species.
Socio-economy/human environment	The socio-economic monitoring includes collection of information on fishers, fish products and aquaculture as indicators of anthropogenic pressure and surveys linked to the human environment related to AGL.

algal blooms (Ochumba and Kibaara, 1989). Human pressure also plays a role with important fisheries and land-use impacts on increased sedimentation, particularly affecting the coastal environment and its biodiversity (Bootsma and Hecky, 2003; Hecky et al., 1994; Kolding, 1995; Kolding et al., 2008; Mgaya and Mahongo, 2017; Njiru et al., 2012). The human environment, including various activities such as aquaculture, is also part of the proposed monitoring themes. The acquired data should facilitate a better understanding of AGL ecological cycles and guide responses to the multiple threats to the AGL. Two methodological aspects are also important and would provide common services to all partners. Remote sensing can provide repeatable and standardized assessment of lake wide parameters, land-use in the lake basins, as well as lake-specific and regional meteorology, e.g. rainfall intensity and cloud cover. Critical to the continued success of multi-lake monitoring will be open-source database setup and management

Modeling (fisheries, ecosystems, hydrodynamics, lake level changes, etc.) could be undertaken in the longer-term based on the critical indicators that will be selected. In a first step, modeling may address the impact of local climate on the AGL (Lam et al., 2003; Musinguzi et al., 2017; Naithani et al., 2012). In a second step, modeling and teleconnections may link local conditions with global indicators (Indian Ocean dipole, ENSO, etc.) that could provide a significant prediction value for the lakes (Behera et al., 2005; McGlue et al., 2020; Saji et al., 1999). The multi-lake monitoring themes thus open wide perspectives for modeling and forecasting key topics related to AGL ecosystem services, among which are fisheries and water level changes.

Advantages of a harmonized multi-lakes monitoring framework

Added value results from monitoring the AGL using a harmonized, consistent, multi-lakes approach: acquired experience gained from one lake may inform a better understanding of other lakes and comparative studies, as freshwater systems have fundamental similarities. Many threats (as listed above) are common to the lakes that are shared by different countries and communities. Common field, analytical, and data management methods would allow information to be more broadly shared and compared. For example, balancing the sustainability of fish stocks with fisheries catch data would be easier with agreed upon approaches and metrics. Some examples follow below.

The various limnological cycles show strong regional similarities and climate patterns linked particularly to trade winds. For example, a southern upwelling is observed at the south of Lake Tanganyika and Lake Malawi/Nyasa/Niassa, while the thermoclines of both lakes are tilted toward the north (Coulter, 1963, 1991; Eccles, 1962, 1974). A secondary upwelling has been detected at the northern end of both lakes: around September/October (derived from physical-chemical measurements for the period 1993–1995) at Lake Tanganyika (Plisnier et al, 1999; Plisnier and Coenen, 2001); and in October (remote sensing observations in 1993) at Lake Malawi/Nyasa/Niassa (Patterson and Kachinjika, 1995). North to south downwelling of the thermocline at the onset of the trade winds occurs in Lake Victoria as well, and it is not yet clear whether the arrival of cooler water near the bottom to the north at the end of the trade winds is due to relaxation of the tilted thermocline or due to flow of cooler, denser water from the south where evaporation is greater (MacIntyre et al., 2014). These flows are critical for oxygenation of the lower water column and sustained habitat for fish. Strong and sustained internal waves (seiches), sometimes with large amplitude, have been observed at Lakes Tanganyika, Malawi/Nyasa/Niassa and other AGL (Beauchamp, 1953; Eccles, 1974; MacIntyre, 2013; Spigel and Coulter, 1996). Simultaneous monitoring would strongly reinforce the links between atmospheric-hydrodynamical processes and ecological responses of AGL including eutrophication, phytoplankton blooms, changes in anoxia and fish kills and would provide a strong basis for important applications including forecasting the abundance of the main fish stocks and lake levels change with concomitant changes in nutrient loading and depth of mixing. The lakes also share in common population growth and growth in demands on land use and natural resources.

Similar types of anthropogenic pressure have been observed at the different lakes (overfishing, deforestation, increased sedimentation, pollution, etc.) (Irvine et al., 2019). Because the average population density linked to anthropogenic pressure is different among lakes (43 persons/km^2 at Lake Tanganyika (Xu et al., 2020) compared with 495 persons/km^2 in the Lake Kivu area (Imasiku and Ntagwirumugara, 2020), the multi-lakes monitoring approach offers an opportunity to compare the common threats arising from population that AGL face and to better identify causal factors (Fig. 3). This comparison would help managers to select the most appropriate adaptation or management measures favorable to the sustainable use of AGL ecosystems services (Kolding and van Zwieten, 2012). Although hydrodynamic cycles in relation to climate show similarities, the lakes display also differences in relation to their latitude and depth impacting their thermal stratification and oxygenation (Katsev et al., 2017; Spigel and Coulter, 1996). Those differences will be instructive in the framework of the multi-lake comparison.

The Laurentian Great Lakes, like the individual African Great Lakes are a large aquatic ecosystems shared by more than one country. As a result of historical agreements, including the Boundary Waters Treaty of 1909 and the Great Lakes Water Quality Agreement (which has undergone several updates since its original inception in 1972), monitoring efforts on the Laurentian Great Lakes are coordinated to some extent between Canada and the U. S. and their various state, provincial, tribal and municipal agencies (McKindles et al., 2020). Lessons may be learned from these efforts about what works (and what does not work) with regard to coordinated management and monitoring including physical processes, light penetration, water chemistry, fish and plankton biology, atmospheric deposition, invasive species, coasts and wetlands. About 50 to 125 buoys (depending on the season) are deployed across the Laurentian Great Lakes (glbuoys.glos.us). They have a variety of sensors and are owned by companies, universities, and government agencies. Much of their data is publicly available online. There are also programs coordinated by NOAA and Environment Canada for remote sensing of the lakes, including prediction of toxic algal blooms (Binding et al., 2020). At the individual lake scale, monitoring and management of fisheries is coordinated through Lake Committees composed of state, provincial, tribal and federal members, which in turn are organized by the Great Lakes Fishery Commission. Results of some of these monitoring programs are provided in regular "State of the Great Lakes" reports that are coordinated by federal agencies within both countries, and these results form part of the basis on which the U.S.-Canada International Joint Commission makes management recommendations to the federal governments (Lemarquand, 1993).

Multi-lake monitoring: main principles and equipment

Long-term monitoring needs to focus on a few key parameters or indicators only to ensure its maintenance and sustainability ($\gg$40 years) at all stations. The proposed parameters below are based on their importance, ease of implementation and, in particular, "low cost" and robustness. The goal is the acquisition of consistent time series data without gaps in a harmonized way at the seven lakes to allow status and trend evaluations, responses to perturbations, and inter-lake comparisons. Monitoring additional parameters is possible in relation to the long-term availability of qualified staff in charge of instruments calibration and quality data acquisition. The objective is to ensure a sustainable continuous and accessible high-quality data collection. This objective requires that only a few key parameters be monitored (unlike an intense monitoring that can take place during short-term project). An additional consideration is data quality, which requires trained staff, high quality instruments, effective data management, and a quality control quality assurance (QA/QC) protocol that includes regular auditing. Short-term monitoring is often more intense, and many parameters are measured more frequently. This is not detailed here although it remains essential for specific studies. It is recommended that short-term projects implementing a monitoring program take place simultaneously on more than one lake as much as possible in order to increase the possible comparison between lakes.

The proposed multi-lakes monitoring specifies continuous measurements and a network approach. It requires comparable parameters and methods of monitoring (fisheries, limnology, biodiversity etc.) while considering as much as possible the currently applied methodologies at the different lakes where continuous monitoring is carried out. Standardization of methods is important and it should be pursued as much as possible.

The monitoring sites are linked to the presence of research stations (infrastructure and staff) nearby the lakes (Irvine et al., 2016). Remote sensing will extend the spatial scale of investigation for the whole region as detailed below.

It is essential that research stations that are part of the multi-lake monitoring program are located on the shoreline or as close as possible to the lake (at least one station per country and per lake). In the absence of such stations, the countries are encouraged to install them, with possible support from government allocations or donors, in regards to the importance of the lake for the national economy and all exceptional characteristics detailed above. Additional to the staff, each research station needs electricity, water supply and long-term national support related to the mandate of the institution in charge.

Critical equipment and facilities required for a basic monitoring program are presented in Table 3. In some of the existing stations, it is probable that part of the necessary equipment which, for most of it, is basic, is presently available. An inventory will have to be made of monitoring equipment present in the institutions and additional or spare equipment could be provided by the multi-lake monitoring program depending on the available financial support. For the long-term, a cost sharing (country financing and multi-lake monitoring program) is needed to maintain or replace the targeted equipment. Boats, laboratories, vehicles, etc. are expected to exist at the partner institutions, but a budget for maintenance related to the multi-lake monitoring is very necessary. Computers and internet connections are critical in addition to quick access to duplicate instruments, spare parts, and consumables such as bottles, containers, ethanol, formalin, fuel, etc. which is related to a "no gaps" objective in time series collection of indicator data. Maintenance of equipment is also crucial.

Moorings are an option for the continuous collection of water parameters (particularly temperature) throughout the water column and possibly automated buoys with additional sensors for other important water quality variables and meteorological recording. An ideal location at the northern and southern ends of the larger lakes would allow the real-time collection of data to track the seasonal upwelling events critical to nutrient cycles and fisheries and to link these events to changing meteorological conditions. The safe installation and proper maintenance (biofouling, calibration) of automatic buoys instruments are, however, necessary for their long-term use and cost effectiveness.

Monitoring network facilitation

ACARE with its partner IISD may facilitate communication and connect the different partners who will carry out the long-term monitoring, in partnerships with local and international freshwater and fisheries experts. The objective is to harmonize methods among lakes, implement or strengthen the present, long-term monitoring and help to develop it where there is little or none presently. More information is presented at www.agl-acare.org and www.africangreatlakesinform.org/.

A network of freshwater experts on the AGL, with each clustered on a lake as an advisory group, has been established by ACARE (www.agl-acare.org/advisory-groups) with regular monthly and annual meetings. Its role is to exchange information about each lake and to strengthen science, research, and education on the AGL. Such a network increases collaboration opportunities for research and services that managers can call upon if they wish (e.g. sampling and analytical protocols, taxonomic identification, training, quality check, data sharing prerequisites, etc.). This network consists of individual researchers and managers.

Monitoring sites

A few sites (two to five) at each lake are targeted for field monitoring (including at least one site per country). Many of those sites

Table 3
Facilities and critical equipment required for a basic multi-lake monitoring program; Opt. means "optional", DO = Dissolved oxygen.

Facilities and equipment	Country institution	Multi-lake program
Research station on lake shore (+electricity, water)	x	
Staff	x	
Boats/vehicles	x	
Functionning (related to the multi-lake program)	x	x
Computer - printer - internet connection	x	x
Hand held probe - temperature		x
- conductivity, pH, DO		Opt.
CTD (conductivity, temperature and depth probe)		Opt.
Mooring and thermistors/possibly other sensors		Opt.
Underwater light sensor (automatic)		x
Underwater light sensor manual		x
Thermistors for coastal temperature measurement		x
Sampling bottle and messenger		x
Secchi disk		x
Level gage		x
Weighing balances		x
Fish measuring board		x
Equipment for biodiversity monitoring (gears etc.)		x
Automatic weather station		x

(about 13) correspond to existing research stations with relevant staff while other research stations (about 7) remain to be installed. Some nearby universities could be tasked to conduct regular monitoring activities. Other relevant regional authorities like Water Boards may have stations in the basin that could monitor land-use/erosion and tributaries. Water intakes may also be used for routine monitoring such as done by the REGIDESO in Burundi for Lake Tanganyika and the Province of Ontario for the Laurentian Great Lakes (https://data.ontario.ca/dataset/drinking-water-surveillance-program). This generally includes many additional parameters than the targeted key parameters presented here. Remote sensing could extend the monitoring to a wider area of the lakes and their water basins.

The monitoring sites (also including sites for autonomous sensor platforms) are ideally situated at the northern and southern ends of the lakes. This strategy enables capturing the influence of the changing direction of the trade winds (SE and NE) and the resultant upwelling of the thermocline on various lakes. At the deep lakes, the seasonal change of trade winds and the release of tilting of the thermocline activates internal waves (Coulter, 1963; Eccles, 1974; MacIntyre et al., 2002; Spigel and Coulter, 1996). These oscillations of water layers affect the supply of deep, nutrient-rich waters via upwelling to the euphotic surface zone, enabling increased growth of plankton and supply of food to sustain the fisheries in these lakes. Since most lakes have a North-South orientation, a high frequency monitoring of thermal structure at the northern and southern ends is advisable. This approach was applied at Lake Tanganyika with moorings and autonomous sensors in southern and northern positions (Huttula et al., 2006; Huttula and Sarvala, 2012). Internal waves influenced the limnology of the upper layers and the catches of pelagic fishes (Chitamwebwa, 1999; Langenberg et al., 2003; Naithani et al., 2003; Plisnier et al, 1999, 2009). Although these results have illustrated the critical role of the trade winds and resultant internal waves in deep elongated stratified lakes, between year variability in phytoplankton and zooplankton abundance due to El Niño-Southern Oscillation (ENSO) induced variability in duration and magnitude of the trade winds in Lakes Victoria and Kivu (Cózar et al., 2012; Sarmento et al., 2012). Thus, it is critical to investigate the impact of trade winds on lakes' hydrodynamics as a key driver of ecological variability (Delandmeter et al., 2018; Docquier et al., 2016; Naithani et al., 2012) and establish the links between ENSO cycles, with the intensity and frequency of their cycles varying with climate warming (Nakamura et al., 2009; Wolff et al., 2011), primary productivity and diversity and abundance of fish. It has been shown that ENSO is significantly correlated to the abundance cycles of pelagic fish at Lake Tanganyika (Plisnier, 1997, 1998). For large lakes, a monitoring research station in their central area is also advised to acquire information lakewide.

Important information for the monitoring of fisheries includes recording fish catches corresponding to a defined fishing effort (example: catches by a standard type lift net unit fishing during one night). Such a catch assessment survey (CAS) may be implemented at different geographical scales with various frequencies. A monthly CAS is proposed nearby the research stations. An example of a simple long-term monitoring of a fish community is from Lake Kariba, where a site on the lake nearby the research station in Zimbabwe has been sampled (bi)weekly with a fleet of gillnets almost without interruption since 1960 (Kolding et al., 2003).

For the monitoring of biodiversity, the long-term monitoring considers only a few key taxa at sites that are situated fairly near research stations (maximum of a few hours travel). More investigations need specialists during short-term projects as indicated below and in ESM Appendix S1. For land-use, the calibration sites should also be situated in close-by regions near the field stations of the network, in order to be reachable without much effort. Those sites need to represent as much as possible the various characteristics of the region including erosion sites and at least one tributary to monitor changes of sediments loads. The socio-economic surveys would also be carried out in the nearby areas of the research stations mainly unless special surveys would require a wider spatial investigation.

Multi-lakes monitoring parameters

The harmonized, long-term, multi-lake monitoring that is proposed includes only a limited number of key indicators or parameters mainly related to the added value of the multi-lake approach. Those are summarized in Table 4; ESM Appendix S2 provides detailed explanation for the monitoring of parameters that are indicated in Table 4

At some sites, many of those parameters are already measured. For such sites, the present list provides a proposed frequency of sampling and methodology which will enable harmonization.

Adaptable monitoring at some sites

The description above constitutes "standard monitoring" with a level of intensity that is likely to be achievable at most sites. However, the preliminary survey identified two other cases:

(1) Sites with no lake monitoring stations: It is proposed that at these sites, a reduced monitoring program could be implemented with a lower frequency of measurements until a monitoring station (infrastructure, staff) is installed within a specific timeframe. Such less-intensive monitoring could be implemented by partner institutions ideally situated in the region. For example, at Lakes Albert and Edward (D.R. Congo and Uganda) and at Lake Turkana in Ethiopia there are no stations with permanent staff presently. In these cases, institutions/universities situated in the region (<300 km for example) could monitor some parameters at a lower frequency than the rest of the network. The list of parameters for a reduced monitoring program needs to be discussed with partners to fit local possibilities, needs.

(2) Sites with enhanced capacity (staff, laboratory etc.): It is proposed that at sites with capacity above the network average, a more intense monitoring (with more parameters) could be implemented. Members of the Lake Victoria Basin Commission at Lake Victoria indicated such a possibility during the recent ACARE and IISD survey. Some lake-specific monitoring parameters could be added (e.g., CO_2 and CH_4 at Lake Kivu) if they could sustainably be monitored.

Data management

The most common water quality evaluation methods are i) in-situ data analysis based on data generated from direct measurements in the water systems and laboratory analysis, ii) water quality modelling, and iii) remote sensing/satellite imagery (World Water Quality Alliance, 2021). Overall, there is a reliance on in-situ data collected via either grab samples for laboratory analysis or in-situ water quality measurements (such as data loggers). Grab samples have a limited temporal detail in data, while data loggers often have a lack of spatial detail due to the cost of the equipment. This is exacerbated by valid concerns around data sharing by data owners (United Nations, 2021). As a result, there is a need to promote data sharing between institutions and countries at transboundary lakes. New monitoring data will need processing (quality checking, flagging, integration into a usable and unique database providing various tools for data retrieval) and a secure

Table 4
Main parameters for long-term multi-lake monitoring related to limnology and water quality, fisheries, meteorology, biodiversity, land use/erosion and socio-economy and frequency at different locations (x = mandatory, (x) = optional, S = station, C = coast, P = pelagic, L = lake, B = basin, SD = Secchi disk, Chl a = chlorophyll-*a*, RS = remote sensing, AWS = automatic weather station, CAS = catch assessment survey, T = near surface temperature, prec. = precipitations, WS = winds speed, WD = wind direction, Atm. P = atmospheric pressure, ISR = incoming shortwave radiation, ILR = incoming long wave radiation, RH = relative humidity, cloud. = cloudiness, agric = agriculture). Additional descriptive information is presented in ESM Appendix S2.

	PARAMETERS	SITES	FREQUENCY								
			30 min	Daily	Weekly	15 days	Monthly	6 months	1/2 years	3/4 years	5 years
Water	Temperature	S-C		x							
		S-P				(x)	x				
	Conductivity	S-C		x							
		S-P				(x)	x				
	SD transparency	S-C		(x)	x						
		S-P				(x)	x				
	Underwater light measurement	S-P				(x)	x				
	Lake level	S-C		x							
	Chl a	S-C				(x)	(x)				
		S-P				(x)	(x)				
	Chl a, cyanobacteria, temperature (RS)	L		x							
Fisheries	Catch assessment survey CAS	S/L			(x)	(x)	x	(x)			
	Sizes of fish	S			(x)	(x)	x				
	Frame survey	L							(x)	x	(x)
	Biomass/stock assessments	L								(x)	(x)
Meteorology	T, prec, WS, WD, Atm. P., ISR , ILW, RH (AWS)	S	x								
	WS, WD, prec., sol. R., cloud. (RS)	L + B		x							
Biodiversity	Changes from baseline (fish)	S							x	(x)	
	Changes from baseline (plants)	S									x
Land use / erosion	Surface types (agric/forest/…)	S							x	(x)	
	Exposed soil by slope categories	S							x	(x)	
	Erosion hazard risk assessment	S							x	(x)	
	Population distribution	S								x	
	Land use maps (RS)	B								x	
Socio-economy	Employment statistics	S						x			
	Fish prices at the market	S					x				
	Aquaculture statistics	S					x				
	Specific surveys	S						(x)	x		

long-term storage. Also, it would be appropriate to gather historical monitoring data as a baseline for comparisons and evaluation of changes taking place at the AGL.

To enhance data sharing and information access, ACARE and University of Nairobi's open-source African Great Lakes Information Platform (www.africangreatlakesinform.org) could be a common database for all partners. It will allow each partner to upload and retrieve information. Importantly, uploaded information needs to be checked for quality before being fully integrated into the database. The management of such a central database needs to be discussed and agreed upon by all partners. The Great Lakes Observing System (https://glbuoys.glos.us), the Great Lakes Data Stream (https://greatlakesdatastream.ca) and the open database on Swiss lakes (www.datalakes-eawag.ch) could provide a suitable and achievable model. An upgrade/ initiation of localized databases at research stations in the different partner states would be carried out in the framework of training or harmonization sessions.

The exchange of collected information among partners is a key point for enabling a better understanding of interannual variability of many lakes through comparative data. For lake levels, comparable data at some lakes (Stager et al., 2007) indicates that large-scale climate fluctuations impact the AGL region. Sharing data is easier when partners appreciate the benefit that it brings not only to the network but also to individual researchers. Accessible shared data needs the development of a common data-management system, with agreed upon data types and formats that allow for better collaboration between organizations/institutions/countries (Poikane et al., 2015; United Nations, 2021). An agreed protocol will allow each partner to decide what data can be shared including publication priority regulations to ensure that appropriate credits are given for the hard work of scientists who have collected and processed the data. Long-term data collation enables additional information from subsequent projects to be placed in an appropriate spatial as well as temporal context, while building the overall database.

Guidelines would also be set up for data accessibility to a wider community as this is expected to multiply the interest of the monitoring in addition to the optimal use of the information and an increased support from various organizations. An example is the GEMS/Water Data Policy (gemstat.org) which allows data providers to select from three different levels of data sharing. This standard protocol ensures data providers retain data ownership and recognition. Sharing of data could multiply the database size by seven (at the lake level) and by as much as the number of monitoring sites (~20). Comparing time-series data increases the scientific benefits of collected data by giving them a wider perspective for interpretation, leading each participant, each institution and indeed each country to a win–win collaboration. Undoubtedly, this is expected to boost science and benefit managers in their efforts toward the long-term sustainable management of the lakes.

Institutional framework of the AGL

A preliminary survey (ESM Appendix S3), in the framework of the ACARE and ISSD freshwater experts network, has allowed the gathering of information on institutions in each AGL country in relation to fisheries, water quality, biodiversity, land use/erosion, climate and socio-economy (Table 5 a,b,c). It investigated if those institutions were active for the lakes, for their basins or both.

Table 5
(a): National institutions/organizations related to lakes in Kenya, Uganda and Tanzania (V = Lake Victoria, Tu = Lake Turkana, A = Lake Albert, E = Lake Edward, Ta = Lake Tanganyika, MN = Lake Malawi/Nyasa/Niassa; M = mandated, LTM = long-term monitoring currently, TBD = to be determined, NBP = No monitoring but possible; L = lake, B = basin).

Lakes	Mandate	Monitoring	INSTITUTIONS/Organizations	Water	Fisheries	Biodiversity	Land use	Socio-eco	Climate
			KENYA						
V,Tu	M	LTM	Kenya Marine and Fisheries Research Institute (KMFRI) www.kmfri.co.ke	L + B	L + B	L + B		L + B	L + B
V,Tu	M	LTM	Kenya Fisheries Service www.kenyafisheriesservice.go.ke		L				L + B
V,Tu	M		Kenya Coast Guard kcgs.go.ke		L				L + B
V,Tu	M		Kenya Wildlife Service (KWS) www.kws.go.ke	L	L	L + B		L + B	
V,Tu	M		Local County Councils	L	L				
V,Tu	M		National Environment Management Authority (NEMA) www.nema.go.ke	L + B		L + B		L + B	
V,Tu	M		National Land Commission www.landcommission.go.ke				B		
V,Tu	M		State Dept for Fisheries, Aquaculture & The Blue Economy kilimo.go.ke		L				L + B
V,Tu	M		Water Resources Management Authority (WARMA) wra.go.ke	L + B					L + B
V	M		Lake Basin Development Authority (LBDA) lbda.go.ke						
Tu	M		Kerio Valley Development Authority (KVDA) kvda.go.ke	L + B	L		B	B	
V,Tu			Universities (e.g. Maseno, Eldoret, Nairobi etc.)	L + B	L + B	L + B		L + B	L + B
V,Tu			Osienala, Friends of lake Victoria osienala.net		L + B			L + B	L
Tu			Friends of Lake Turkana www.friendsoflaketurkana.org	L + B	L + B	L + B	L + B	L + B	
Tu			Turkana Basin Institute (TBI) www.turkanabasin.org/	L + B	L + B	L + B	B	L + B	L + B
Tu			Turkana University College (TUC) www.tuc.ac.ke	L + B	L + B	L + B	L + B	L + B	L + B
V,Tu			Inter-University Council of East Africa (IUCEA) iucea.org	L + B	L + B	L + B	L + B	L + B	L + B
V,Tu			Institute for Climate Change and Adaptation (ICCA) www.icca.uonbi.ac.ke	L + B	L + B	L + B	L + B		L + B
			UGANDA						
V,E,A	M	LTM	National Fisheries Ressources Research Institute www.firi.go.ug	L + B	L + B	L + B		L + B	
V,E,A	M	LTM	Min. of Water & Environ. (Dir. Water Res. Manag.) www.mwe.go.ug	L + B		L + B		L + B	
V,E,A	M	LTM	Min. of Agr. Animal Industr. & Fish. (Dir. Fish. Res.) www.agriculture.go.ug	L + B	L + B	L + B		L + B	
V,E,A	M		Min. of Agr. Animal Industr. & Fish(Dir. Crop Res.) www.agriculture.go.ug				B		
V,E,A	M	LTM	Uganda National Meteorological Authority www.unma.go.ug						L + B
V,E,A	M		National Water and Sewerage Corporation www.nwsc.co.ug	L + B					
V,E,A			Fisheries Training Institute		L + B				
V,E,A			Water Resource Institute, Entebbe	L + B					
V,E,A			Makerere University www.mak.ac.ug/	L + B	L + B	L + B	L + B	L + B	L + B
V,E,A			Mbarara University Science &Technology www.must.ac.ug	L + B	L + B	L + B	L + B	L + B	L + B
V,E,A			Busitema University busitema.ac.ug/	L + B	L + B	L + B	L + B	L + B	L + B
V,E,A			Gulu University	L + B	L + B	L + B	L + B	L + B	L + B
V,E,A			Various fisheries organization (*)		L + B				
			TANZANIA						
V,Ta,MN	M	LTM	Tanzania Fisheries Research Institute (TAFIRI) www.tafiri.go.tz	L + B	L + B	L + B		L + B	
Ta	M	TBD	Lake Tanganyika Basin Water Board (LTBWB) www.lvbwb.go.tz	L + B					
MN	M	TBD	Lake Nyasa Basin Water Board (LNBWB) lakenyasabasin.blogspot.com	L + B					
V,Ta,MN	M		Fisheries Development Division www.mifugouvuvi.go.tz		L + B	L + B		L + B	
V,Ta,MN	M		Aquaculture Division www.mifugouvuvi.go.tz		L + B			L + B	
V,Ta,MN	M		Ministry of Agriculture www.kilimo.go.tz				B	B	
V,Ta,MN	M		Ministry of Natural Resources/forestry www.maliasili.go.tz			B	B	B	
V,Ta,MN	M		Ministry of Natural Resources/wildlife www.maliasili.go.tz		L + B	L + B		L + B	
V,Ta	M		Beach Management Units (BMUs) Community organisation		L + B				
V,Ta,MN	M		Ministry of Water www.maji.go.tz	L + B	L + B			L + B	
V,Ta,MN	M		Ministry of Land www.lands.go.tz				B	B	
V,Ta,MN	M		Ministry of Environment	L + B	L + B		L + B		
V,Ta,MN	M	LTM	Tanzania Meteorological Authority www.meteo.go.tz						L + B
V,Ta,MN	M		National Environnent Manag. Council (NEMC) www.nemc.or.tz	L + B	L + B		L + B		
V,Ta,MN	M		Local government Authorities (LGAs)		L + B	L + B			
V,Ta,MN			Universities	L + B	L + B	L + B	L + B	L + B	L + B

(*) Fisheries Protection Force, Association of Fishers and Lake Users, Uganda National Women Fisher Organisation, Bugiri UN Women Group, Katosi women Group, Katosi Development Trust, Uganda Fish conservation Association, Uganda Fish Processors and Exporters Association, Walimi Fishers Organisation, Federation of Fishers Association.

Table 5
(b) National institutions/organizations related to main environmental topics in Rwanda, Burundi, D.R. Congo and Zambia (V = Lake Victoria, Tu = Lake Turkana, A = Lake Albert, E = Lake Edward, K = Lake Kivu, Ta = Lake Tanganyika, MN = Lake Malawi-Nyasa-Niassa; M = mandated, LTM = Long term monitoring, TBD = To be determined, NBP = No monitoring presently but possible; L = Lake, B = basin).

Lakes	Mandate	Monitoring	INSTITUTIONS/Organizations	Water	Fisheries	Biodiversity	Land use	Socio-eco	Climate
			RWANDA						
K	M	LTM	Rwanda Environment Management Authority www.rema.gov.rw	L + B	L + B	L + B	L + B	L + B	
K	M	LTM	Rwanda Agriculture & Animal Resources Development Board www.rab.gov.rw		L + B	L + B		L + B	
K	M		Rwanda Water and Resource Board www.rwb.rw	L + B				L + B	
K	M		Ministry of Agriculture and Animal Resources www.minagri.gov.rw		L + B	L + B	L + B	L + B	
K	M	LTM	Rwanda Meteo Agency www.meteorwanda.gov.rw						L + B
K		NBP	University of Rwanda ur.ac.rw	L + B	L + B	L + B	L + B	L + B	
K			Institut d'Enseignement Supérieur (INES) Ruhengeri ines.ac.rw	L + B			L + B	L + B	
			BURUNDI						
Ta	M	LTM	Direction de la Promotion des Filières halieutiques	L + B	L + B			L + B	
Ta	M	LTM	REGIDESO www.regideso.bi	L + B					
Ta	M		Office burundais pour la Protection de l'Environnement (OBPE) www.obpe.bi	L + B	L + B	L + B	L + B	L + B	
Ta	M		Office burundais de l'urbanisme, de l'habitat et de la construction (OBUHA)				B		
Ta	M		Institut Géographique du Burundi (IGEBU)	L + B					L + B
Ta	M		Programme National de Lutte Anti-Erosive (PNLAE)				B		
Ta	M		Autorité de régulation des secteurs eau potable et énergie www.areen.bi	L + B					
Ta	M		Direction Générale de l'Aménagement du Territoire				B	B	
Ta	M		Dir. Générale Envir., Res. en Eau & Assainissement	L + B			B		
Ta		NBP	Université du Burundi www.ub.edu.bi	L + B	L + B	L + B	L + B	L + B	L + B
Ta			International Rice Research Institute (IRRI) www.irri.org/where-we-work/countries/burundi				L + B	L + B	
			D.R. CONGO						
Ta	M	NBP	Centre de Recherche en Hydrobiologie (CRH)-Uvira	L + B	L + B	L	B	L + B	L
K	M	LTM	Observatoire Volcanologique de Goma	L + B					B
K	M		Centre de Recherche en Sc. Naturelles africanbirds.fieldmuseum.org	L + B			L + B		
Ta,K,E,A	M		Ministère de l'Agriculture/ Direction Nationale des Pêches www.agriculture.gouv.cg	L + B	L + B				
Ta,K,E,A	M		Ministère de l'Environnement/ Direction des Ressources en Eau medd.gouv.cd	L + B					
Ta,K,E,A	M		Ministère de l'Agriculture pêche et élevage/Bureau de pédologie				B		
Ta,K	M		REGIDESO www.regidesordc.com	L + B					
Ta,K,E,A	M		METTELSAT						L + B
Ta,K,E,A	M		Institut Congolais pour la Conservation de la Nature (ICCN) www.iccnrdc.org			L + B			
K	M	NBP	Institut Supérieur Pédagogique de Bukavu www.uerhaispbkv.org	L + B	L + B	L + B	L + B	L + B	L + B
K	M	NBP	Université Officielle de Bukavu (UOB) www.univofbukavu.org	L + B	L + B	L + B	L + B	L + B	L + B
K		NBP	Université Catholique de Bukavu Bukavu ucbukavu.ac.cd	L + B	L + B	L + B	L + B	L + B	L + B
K		NBP	Centre de Recherche en Biodiversité, Ecologie, Evolution et Conservation	L + B		L + B			
E		NBP	Université Officielle de Ruwenzori www.uor-rdc.net	L + B	L + B	L + B	L + B	L + B	L + B
E		NBP	Institut Supérieur du Bassin du Nil - Beni (ISBN)	L + B	L + B	L + B	L + B	L + B	L + B
A		NBP	Université Shalom de Bunia www.unishabunia.org/	L + B	L + B	L + B	L + B	L + B	L + B
			ZAMBIA						
Ta	M	LTM	Department of Fisheries (DOF)/ Ministry of Fisheries and Livestock www.mfl.gov.zm	L	L + B	L + B		L + B	L
Ta	M	LTM	Dept of Water affairs (DWA)/Ministry of Water Development Sanitation and Environmental Protection www.mwdsep.gov.zm	L + B	L + B	L + B	L + B	L + B	L + B
Ta	M		Zambia Environmental Management Agency (ZEMA) www.zema.org.zm	L + B	L + B	L + B	L + B		L + B
Ta	M		Dept of Public Health /Ministry of Health www.moh.gov.zm					L + B	
Ta	M		Zambia Meteorological Department (ZMD) www.zmd.gov.zm						L + B
Ta	M		Land Husbandry/ Ministry of Agriculture www.agriculture.gov.zm				L + B	L + B	L + B
Ta	M		Forestry Dept/Ministry of Lands and Natural Resources www.mlnr.gov.zm			L + B	L + B	L + B	L + B
Ta	M		Department of National Parks and Wildlife/ Ministry of Tourism and Arts www.mota.gov.zm		L + B	L + B			
Ta			University of Zambia (UNZA) www.unza.zm		L	L			
Ta			Copperbelt University (CBU) www.cbu.ac.zm		L	L			

Table 5
(c): National institutions/organizations related to lakes in Ethiopia, Malawi and Mozambique, Uganda and Tanzania (Tu = Lake Turkana, MN = Lake Malawi/Nyasa/Niassa; M = mandated, LTM = long-term monitoring currently, TBD = to be determined, NBP = No monitoring but possible; L = lake, B = basin).

Lakes	Mandate	Monitoring	INSTITUTIONS /Organizations	Water	Fisheries	Biodiversity	Land use	Socio-eco	Climate
			ETHIOPIA						
Tu	M		Ministry of Agriculture www.moa.gov.et		L + B		L + B	L + B	L + B
Tu	M		Ministry of Water, Irrigation and Electricity www.mowie.gov.et	L + B			L + B	L + B	L + B
Tu	M		Ethiopian Biodiversity Institute www.ebi.gov.et			L + B			
Tu	M		Ethiopian Environ., Forest & Climate Change Commission www.efccc.gov.et www.efccc.gov.et/	L + B	L + B	L + B	L + B		L + B
Tu	M		Ethiopian Energy Authority eea.gov.et	L + B			L + B	L + B	
Tu	M		Ethiopian Electric Power www.eep.com.et/en/	L + B			L + B	L + B	
Tu	M		Ethiopian National Meteorology Agency www.ethiomet.gov.et						L + B
Tu	M		The Central Statistics Agency of Ethiopia www.statsethiopia.gov		L + B		L + B	L + B	
Tu		NBP	Addis Ababa University www.aau.edu.et	L + B	L + B	L + B	L + B	L + B	L + B
Tu		NBP	Jimma University ju.edu.et	L + B	L + B	L + B	L + B	L + B	L + B
Tu			Jinka University www.jku.edu.et	L + B	L + B	L + B	L + B	L + B	L + B
Tu			Ethiopian Institute of Agriculture Research (EIAR) www.eiar.gov.et	L + B	L + B	L + B	L + B	L + B	L + B
			MALAWI						
MN	M	LTM	Department of Fisheries		L	L			
MN	M	LTM	Department of Water Resources agriculture.gov.mw	L					
MN	M		Ministry of Natural Resources, Energy, and Environment				L + B		
MN	M		National Statistical Office www.nsomalawi.mw					L + B	
MN	M		Department of Climate Change and Meteorological Services (DCCMS) www.metmalawi.gov.mw						L + B
MN	M		LFMA Local Fisheries Management Authority		L				
MN			Lilongwe University of Agriculture and Natural Resources (LUANAR) www.bunda.luanar.mw	L + B	L + B	L + B	L + B	L + B	L + B
MN			Mzuzu University (MZUNI) www.mzuni.ac.mw	L + B	L + B	L + B	L + B	L + B	L + B
MN			University of Malawi - Chancellor College www.unima.mw	L + B	L + B	L + B	L + B	L + B	L + B
MN			University of Malawi - The Polytechnic www.mubas.ac.mw				B		
MN	M	LTM	Ministry of Health www.msh.org › partner › malawi-ministry-of-he…					L + B	
MN	M	LTM	Marine Department - Ministry of transport and Public Works					L + B	
MN			Malawi College of Fisheries (MCF) www.facebook.com › … › B		L				
MN			Malawi Fisheries Research Institution (MAFRI)		L				
			MOZAMBIQUE						
MN	M	LTM	Fisheries Research Institute (IIP)		L + B	L + B			
MN	M		National Directorate for Fisheries Policies (DIPOL)	L	L	L			
MN	M		National Directorate for Fisheries Operations (DNOP)		L				
MN	M	LTM	National Fisheries Administration (ADNAP)		L				
MN	M	LTM	National Institute of Fisheries and Aquaculture Development (IDEPA)		L			L + B	
MN	M	NBP	National Directorate of Environment			L + B	L + B		L + B
MN	M		National Directorate of Land				B		
MN	M		National Administration for Conservation Areas			L + B			
MN	M		ARA Zambeze - Water resources administration	L + B					
MN	M	LTM	Provincial Directorate of Agriculture and Fisheries, Niassa		L			L + B	
MN		NBP	Universidade Eduardo Mondlane www.uem.mz	L + B	L + B	L + B	L + B	L + B	L + B
MN		NBP	Universidade Lurio	L + B	L + B	L + B	L + B	L + B	L + B
MN		NBP	Universidade Rovuma	L + B	L + B	L + B	L + B	L + B	L + B
MN		NBP	CBO - Community Based Organizations		L				

Table 6
Regional institutions related to AGL (L = lake, B = basin, M = mandated, V = Lake Victoria, Tu = Lake Turkana, A = Lake Albert, E = Lake Edward, K = Lake Kivu, Ta = Lake Tanganyika, MN = Lake Malawi/Nyasa/Niassa).

Countries	Mandated	Lakes	REGIONAL INSTITUTIONS	Water	Fisheries	Biodiversity	Land use	Socio-eco	Climate
Burundi	M								
Kenya	M	V,A,E, K	Lake Victoria Fisheries Organization (LVFO) - EAC	L	L + B	L + B		L + B	L + B
Rwanda	M	Tu,Ta, MN	www.lvfo.org	L + B	L + B	L + B	B	L + B	L + B
Tanzania	M		Lake Victoria Basin Commission (LVBC) - EAC						
Uganda	M		www.lvbcom.org						
Burundi	M								
D.R. Congo	M	Ta		L + B	L + B	L + B		L + B	
Tanzania	M		Lake Tanganyika Authority (LTA)						
Zambia	M		lta-alt.org						
Burundi	M								
D.R. Congo	M	K	Autorité de Bassin du lac Kivu et de la Ruzizi (ABAKIR)	L + B	B	L + B	L + B	L + B	B
Rwanda	M		www.anbo-raob.org						

For the long-term monitoring (≫ 40 years), implementing institutions need the official mandate from their governments (Table 5). Other institutions that are interested in AGL but not mandated (such as universities for example) are often involved during short-term monitoring made possible by the funding of short-terms projects often covering a few years at most. Many members of these non-mandated institutions have indicated their willingness to be involved in long-term monitoring (e.g. various universities in D.R. Congo seem to be the only institutions situated near some lakes with the required human capacities to presently implement a monitoring).

Several regional institutions identified in the AGL region are presented in Table 6. These institutions would be ideal to help with the implementation of the multi-lake monitoring in their partners countries. Harmonized fishery monitoring between Kenya, Tanzania and Uganda is currently taking place on Lake Victoria in the framework of the Lake Victoria Fisheries Organization (LVFO), an institution of the East African Community (EAC). The LVFO convention was amended in 2016 to expand the scope to cover all EAC Partner States and is mandated to cover all waterbodies. To add on, the Republic of Burundi has joined the membership while The Republic of Rwanda and South Sudan are still in the process of fulfilling the requirement of depositing the instrument of accession with the Director General of FAO. This organization is a depository of all Regional Fisheries Management bodies legal instruments in the world as provided in the UN charter of the FAO, CAP 102. LVFO as one of the Regional Fisheries Management bodies, its Convention is deposited there. Therefore, any changes to the convention and membership must be requested through the Director General of FAO. For any country to join LVFO, it must submit instrument of accession to FAO. This means that five countries (riparian of the seven Great Lakes) are part of the same political union where an institution has already started to implement a harmonized monitoring activity. Consideration should be given to establishing an AGL Secretariat in such a multi-national institution or within the African Union Development Agency (AUDA) representing all participating countries. Unless country's members decide otherwise, it would be up to each country to follow the advice of the Secretariat to implement recommended actions. This will be supported by the improved scientific information that the multi-lake monitoring program will provide.

For Lake Tanganyika basin, the Lake Tanganyika Authority launched a preliminary initiative related to a long-term monitoring (Plisnier and Marijnissen, 2010). At Lake Kivu, there exists the monitoring program (Lake Kivu Monitoring Program, LKMP) created by the Rwandan Government, supported by a strong collaboration with Congolese institutions (Institut Supérieur Pédagogique at Bukavu and Goma Volcano Observatory), a framework under which ongoing collaborative capacity building projects are being developed and implemented.

Identifying the key institutions is important since it would not be possible to involve all the AGL-related institutions in the harmonized long-term monitoring. In addition to the institutions in Table 6, we must recognize the existence and expertise of the Regional Centre for Mapping of Resources for Development (RCMRD), as an inter-governmental organization established in 1975. It currently has contracting Member States in the Eastern and Southern Africa Regions. RCMRD provides Spatial Decision Support Systems, GIS Application in the Management of Natural Resources, Flood Prediction & Modeling and has been very instrumental in supporting LVFO to develop satellite and mapping based services. LVFO and RCMRD have a current MOU and have implemented several activities including water quality monitoring and forest cover mapping.

The proposed harmonized long-term monitoring of the AGL is closely linked to the blue economy principles whose development is supported by the African Union Inter-African Bureau for Animal Resources (AU-IBAR), a technical office of the Department of Rural Economy and Agriculture of the African Union Commission. Blue Economy constitutes the Goal 6 of the Agenda 2063 and Goal 14 of the UN Agenda 2030 (AU-IBAR, 2019a). The establishment of monitoring and information systems for inland waters is one of the main objectives of the blue economy strategy (AU-IBAR, 2019b, AUC-NEPAD, 2014). National and regional policies and strategies are expected to provide for information sharing between national agencies and between countries (AU-IBAR, 2015).

Setting up the multi-lakes monitoring framework

Setting up of a long-term multi-lake monitoring program is a process involving many partners (individuals, lake users, institutions, funders, managers). Proposed implementation steps are summarized in Fig. 4 and detailed below.

(1) Information on each institution related to the management of the AGL is needed. Long-term monitoring is generally implemented by institutions that are mandated by their governments. Institutions in Table 5 (national institutions) and Table 6 (regional institutions) include mandated and non-mandated institutions (by their national authorities). Institutions that could usefully be involved in the long-term monitoring could seek a mandate from their governments. This is generally linked to financial support, authority in some fields (regulations) and responsibility for wide dissemination of reports.
(2) Detailed information on current monitoring activities is then needed (methods, frequency, sites, etc.) in order to base the proposed monitoring methods as much as possible on existing methods and possibly on intercalibration (Poikane et al., 2015).
(3) If an institution agrees to join the network of the multi-lakes monitoring programme, then the cooperation could be formalized by signing an agreement to participate in the network. This agreement would specify what information may be shared, as well as the contributions of the parties. Specific data sharing policies exist in various countries and data sharing should be evaluated by the authorities as to the benefits it provides. A general agreement could previously be agreed upon at a high level such as the African Union Development Agency (AUDA) or other multi-national institutions.

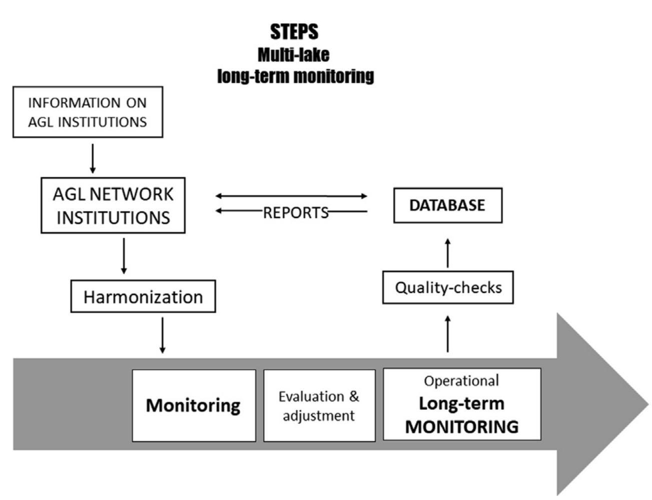

Fig. 4. Steps toward a long-term monitoring network of the African Great Lakes (AGL).

(4) Harmonization sessions will then be organized on site with the staff who would be designated in each institution for the monitoring to discuss, e.g. field manuals, instruments, methodologies, reporting, database, quality control. In addition, in the case of moored thermistor array or buoys, it would be important to also meet and communicate with fisher organizations, the riparian community authorities and the security forces about the objectives of collecting data with those instruments, so that the buoys could be deployed and safely maintained.

The database (see below) needs to be operational before the multi-lake monitoring activities are initiated. The remote sensing component should also reach an advanced stage of implementation before the beginning of the operational phase of the monitoring. To ease implementation, the multi-lake monitoring could address fisheries, water and meteorological aspects in the first phase of the networking. Biodiversity, land-use, and socio-economic aspects could be added during a second phase.

An international consortium

Although the need for monitoring is widely recognized, local governments often do not have sufficient funds to support and international funding is rarely available for long-term projects. As Lovett et al. (2007), we urge government agencies and other funding institutions to make greater commitments to increasing the amount and long-term stability of funding for environmental monitoring programs. The benefit for AGL management and research is huge in regards to costs.

What would be the expected costs? If the installation of seven research stations that are presently missing (Fig. 2) are funded separately, the main costs to launch the monitoring during a period of 5 years would concern:

(1) Initial equipment and harmonization sessions
(2) Functioning costs related to monitoring (staff allowance, boat's fuel and oil, maintenance etc.)
(3) Remote sensing component: initial procedures, training and operating team
(4) Database: setting up and operating team
(5) Quality checks
(6) Reporting

In proportion to the regional and global importance of the AGL, multi-lake monitoring data require an innovative approach for funding. One possibility is the development of a trust with sufficient funds so that the earnings from the trust are used to provide long-term support (self-sustaining). Another (possibly complementary) approach is that a great number of participants (and/or a few main donors) join a consortium (with regular subscriptions) to support the cost of the monitoring. Given the socio-economic and environmental importance of the AGL ecosystems globally, there is no doubt that various institutions will consider being actively involved in participating in order to safeguard the sustainable use of these major resources. This consortium (possibly called "Friends of AGL") could involve a great number of stakeholders (international agencies such as FAO and World fish, UNEP, UNDP, WMO, research agencies, multilateral and bilateral cooperation agencies, universities, NGOs, foundations, public funding etc.) interested in the AGL ecosystems, their long-term sustainability, research, biodiversity, preservation of natural sites etc. Such support by this consortium would be continuous and could override the problem of short-term projects funding that are by essence restricted to a few years of data collection only. Funding by enterprises that do have commercial interest in the AGL and only whose activities are compatible with the sustainable use of AGL could be possible. This should be made through an intermediary charitable organization.

Such a consortium exists for another world biological hotspot: the Galapagos Islands. The "Charles Darwin Foundation" has developed inter-institutional agreements with many governmental institutes, national and international universities, and private organization. It promotes the causes of joint research projects, facilitation of research amongst many other topics related to this other exceptional environment. (www.darwinfoundation.org/en/other-institutions). This consortium could be an excellent example of what is proposed here for the AGL multi-lake continuous monitoring.

Conclusions

The main African Great Lakes (AGL) and their basins provide invaluable resources and ecosystem services to populations of 11 countries: Burundi, D.R. Congo, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, South Sudan, Tanzania, Uganda, and Zambia. Various anthropogenic and environmental pressures and drivers threaten the AGL in the fields of water quality, fisheries, climate change, biodiversity, land use and socio-economics related to anthropic pressure particularly. Managers and researchers need a set of ongoing indicators to evaluate trends in environmental changes to better understand those complex ecosystems. Presently, long-term, continuous data sets are few and existing data often remain inaccessible to researchers. This situation is not conducive to a scientific approach to management as managers often lack the necessary information needed for sustainable environmental and fisheries management.

The present manuscript proposes a few key parameters to be monitored and that could form a common basis to inform managers and decision makers for the sustainable management of the AGL. The objective is also the acquisition of consistent time series of data in a harmonized way for the seven lakes. Multi-lake monitoring presents multiple advantages to improve the understanding of the AGL's ecological functioning which is essential to address the various threats that are all related in one way or another to the lake ecosystems and the impacts of climate and/or regional anthropogenic pressures and drivers.

To reach the AGL multi-lake continuous monitoring objective, two to five stations per lake (depending on lake size) would be necessary (total: ~20 stations). The information would be collected locally near those stations but a common remote sensing service for the entire AGL monitoring network would spatially increase the information collected. A harmonized procedure with partners is also possible providing that a coordination takes place.

In the AGL, the mixing of water and the associated availability of nutrients in the upper zone where light can support photosynthesis is essential to understand their productivity. In addition to the field monitoring, a network of automatic buoys with sensors (mainly thermistors, possibly including meteorological measurements) could collect important data to allow the increased understanding of the lakes' hydrodynamics in relation to climate variability and change. It is expected that this could be followed by modeling and forecasting important topics such as fisheries production, eutrophication, fish kills, planktonic blooms and lake level changes.

Steps toward such a long-term monitoring network for the African Great Lakes have been proposed (here above) and discussed during various ACARE and IISD meetings. The main national institutions will be asked to participate in the monitoring network. Their national authorities are aware of the importance of the AGL and could authorize their participation. Regional organizations could be helpful to set up and possibly coordinate the proposed multi-lake monitoring that concern so many countries sharing the same lake problems.

Each partner of the multi-lake monitoring network acknowledges that it is essential to collect and exchange data. Therefore, increased information, available to each country and network partners, is expected to boost the knowledge of the AGL and provide managers of each country with the necessary and best information on which to better base their management decisions in the various fields related to the sustainable use of ecosystem services provided by the AGL.

AGL challenges are huge and need a variety of specialists in a range of disciplines (taxonomy, hydrodynamics, remote sensing, climate science, fisheries ecology, social sciences etc.). Key for this is the collaboration with the national, regional and international community that will strengthen the network. It is anticipated that a support will be accessed by an international consortium (international agencies, universities, NGOs) interested in the AGL ecosystems. Such a consortium could be built with the help of ACARE that has already developed a network of freshwater experts on the African Great Lakes who meet regularly monthly and annually to exchange information and data.

Lakes are effective sentinels for climate change because they are sensitive to climate, respond rapidly to change, and integrate information about changes in the catchment (Adrian et al., 2009). Their value for paleo-climate reconstruction is well established (Cohen, 2018; Johnson and Odada, 1996; Johnson et al., 2002). Lake levels may be considered as an index of the global hydrological cycle (Street-Perrott and Harrison, 1984). Given the importance of AGL, among the largest lakes in the world, they thus present a considerable interest as indicator of past and present ecological changes on earth.

The authors of this paper, many with decades of experience in the region, have unanimously agreed on the vital importance of long-term data series, and have detailed essential aspects (principles, parameters, steps) to develop the multi-lake harmonization of long-term monitoring of the AGL as needed to support their sustainable use in providing essential resources and services for >90 million inhabitants in the region. The objectives of the harmonized long-term monitoring of the AGL are in line with the sustainable development goals of the United Nations (sdgs.un.org/goals) and the African Union's blue economy (AU-IBAR, 2019a,b).

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jglr.2022.01.016.

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