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Commentary

Monitoring climate change and anthropogenic pressure at Lake Tanganyika

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ABSTRACT

The African Great Lakes are under threat from global and local environmental challenges including climatic change, water pollution and overfishing. To address those issues, managers need observations based on regularly monitored environmental indicators. However, environmental monitoring of the African Great Lakes is often lacking or not based on harmonised methods. The present manuscript is a case study based on Lake Tanganyika, impacted by climate change and anthropogenic pressure affecting water quality, fisheries and biodiversity changes. The implementation of environmental monitoring has often not been continuous or standardised among bordering countries. This prevents managers from taking data-based decisions and opens a risky field where speculation may overcome a rational approach. Long-term monitoring observations are essential to guide management measures to adapt to climate changes and decrease, whenever possible, unfavourable human impact on the Great Lake environment. A regionally standardised long-term monitoring programme is proposed. The sustainability of such monitoring requires that it remains inexpensive and focuses on a few essential parameters. Its strength would be its uninterrupted implementation. Setting up a long-term integrated monitoring programme is also a goal of the Lake Tanganyika Authorities (LTA) with mandated national authorities and stakeholders. A Lake Tanganyika Regional Integrated Monitoring Programme (LTRIEMP) needs to be widely encouraged and supported to ensure its sustainability. General principles from the Lake Tanganyika case study could be useful to develop a wider harmonised sustainable long-term regional monitoring network of the African Great Lakes in a multi-lakes collaborative approach.

Introduction

The Earth's major ecosystems include seven African Great Lakes namely Albert, Edward, Kivu, Malawi/Nyasa/Niassa, Tanganyika, Turkana and Victoria. Three of these lakes (Victoria, Tanganyika and Malawi) hold one quarter of the earth's total surface water supply. Their fisheries are productive and sustain more than 50 million people. These lakes harbour the world's richest lacustrine fish fauna (Coulter et al., 1986; Odada and Olago, 2006).

Natural and anthropogenic factors apply a strong pressure on African Great Lakes. In addition to climate change to which lakes are very sensitive (Hecky et al., 1994; Hecky et al., 2010; Olaka et al., 2010; Lehman, 1998) there is a high rate (between 3 and 4%) of human population growth in the region (Ogutu-Ohwayo and Balirwa, 2006). This anthropogenic pressure leads to high deforestation, habitat degradation, increasing sedimentation, pollution and eutrophication in shallower lakes, particularly Lake Victoria (Odada et al., 2003; Mugidde et al., 2003; Dobiesz et al., 2010). There are major risks of oil seepages for all the rift lakes in the near future. Deep lakes are particularly fragile to pollution because of their very long water retention times and low flushing rates (Abila et al., 2016). Overfishing is taking place in most of the African Great Lakes (Ogutu-Ohwayo et al., 1997; Kayanda et al., 2009). All these lakes face threats to the sustainability of their biodiversity from introduction of plants and fishes (Witte et al., 2013). Long-term harmonised environmental monitoring is lacking although solid data are needed by managers to take decisions (Odada and Olago, 2006). The present manuscript deals mainly with Lake Tanganyika as a case study to set up a long-term monitoring. Broader sets of principles for this lake could be useful for other lakes, leading toward a harmonised regional monitoring network of the African Great Lakes facing serious environmental threats.

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The Lake Tanganyika basin ecosystem and its biodiversity are threatened by the effects of global climate change and anthropogenic pressure on the environment. Managers and local authorities need regular information about various indicators to address those threats. However, national monitoring activities are either not, or seldom, implemented and not regionally integrated. For various reasons there have been extensive gaps and periods when no monitoring activities took place. This discontinuity of basic data is a major limitation to identifying trends of ecological changes and possible causes. There is thus a need to develop a Lake Tanganyika Regional Integrated Environmental Monitoring Programme (LTRIEMP) targeting a few essential parameters on a permanent basis.

The Lake Tanganyika Authority was installed in Bujumbura (Burundi) in 2008 with the mandate to oversee and coordinate regional activities aimed at sustainable management of Lake Tanganyika and its catchment basin, including fisheries conservation and management measures in compliance with the Convention on the Sustainable Management of Lake Tanganyika. A long-term regional monitoring is an objective that was indicated in the "Convention for the sustainable management of Lake Tanganyika" (2003) which aims to ensure the protection and conservation of the biological diversity and the sustainable use of the natural resources of Lake Tanganyika and its basin (LTA, 2003). This convention states that co-operation shall include exchanging information and the results of the harmonised monitoring of activities in the lake basin. A LTRIEMP would allow an assessment of environmental changes and provide managers with relevant data and decision-support tools (LTA, 2012).

The aim here is to: 1) provide an overview of the status and threats to Lake Tanganyika, 2) highlight past environmental monitoring and gaps, and 3) present proposals in relation to developing a potential LTRIEMP. There is currently urgent need to develop LTRIEMP to address five main areas: (1) climate change, (2) fisheries, (3) water quality, (4) land use and (5) biodiversity protection. It is hoped that the various stakeholders will unite their efforts and support the implementation of such long-term monitoring as a tool to address multiple threats to Lake Tanganyika and its population.

Lake Tanganyika

Lake Tanganyika is situated in the western branch of the East African Rift Valley between the latitudes of 3° 30′ and 8° 50′ S and the longitudes of 29°05′ and 31°15′ E (Fig. 1). The riparian countries are Burundi, Democratic Republic of Congo (DRC), Tanzania and Zambia. With an approximate surface area of 32,600 km^2, Lake Tanganyika is the longest (673 km) and second deepest (1470 m) freshwater lake in the world. This lake is of great global, regional and local importance. Its volume of 18,940 km^3 contains 17% of the Earth's surface free fresh water. The waters of Lake Tanganyika are oxygenated only in the upper layer (about 70 m deep at the north and 200 m at the south) and the lake is meromictic (Beauchamp, 1939; Coulter and Spigel, 1991). Annual wind and heat exchange cycles seasonal drive important hydrodynamics in Lake Tanganyika (Coulter and Spigel, 1991; Plisnier et al., 1999; Verburg et al., 2011).

Lake Tanganyika and its catchment basin are characterised by unique aquatic and terrestrial ecosystems with an extreme level of biodiversity, harbouring over 840 aquatic plant and 1318 aquatic animal species. The lake is valuable not only for the presence of unique, endemic species, but also as a microcosm in which to study the processes of evolution. The value of the lake to global biodiversity is beyond measure (LTBP, 2000).

The Lake Tanganyika fishery production is Africa's second largest after that of Lake Victoria. Its lake fishery influences about ten million people in the catchment and trade area in Eastern Africa (Mölsä, 2008). Representative visual aspects of Lake Tanganyika including fisheries, landscape and the inflowing Rusizi river are shown in Fig. 2.

Threats to Lake Tanganyika

The main threats to the environment of Lake Tanganyika include climate change and anthropogenic pressure with impacts on fisheries, water quality and loss of biodiversity.

Climate Change

Air temperature in the Lake Tanganyika region is showing a warming trend of 0.5–0.7 °C in average annual air temperatures from 1964 to 1990 (Plisnier, 1997, 2000). This is consistent with the global temperature increase. Upper water-column temperatures (150 m depth) show a significant warming trend of 0.1±0.01 °C per decade since 1913 (O'Reilly et al., 2003; Verburg et al., 2003; Tierney et al., 2010). Deep-water temperatures (below 600 m) increased from 23.10 °C in 1938 to 23.41 °C in 2003, a comparable increase to that found in other African Great Lakes. Wind velocities in the Lake Tanganyika watershed have declined by about 30% since the late 1970s (Plisnier, 1997, 2000; O'Reilly et al., 2003). The thermal stability of the lake water column during the non-windy season (defined as the work required to mix the water column to uniform density) increased by 97% from 84.4 kJ km^{-2} in 1913 to 166.3 kJ km^{-2} in 2003. These changes are probably linked to reduced mixing, and diminishing deep-water nutrient inputs to the surface waters, which could cause a decline in primary productivity rates that could affect fish production (O'Reilly et al., 2003).

Forecasts indicate an air temperature increase of between 1 °C and 3 °C over the period 2010–2050. This increase in air temperature could negatively impact fisheries yields, agricultural productivity and biodiversity. It could also encourage the development of invasive species following ecosystem degradation and possibly increase water-borne diseases such as cholera (Bompangue et al, 2011; Plisnier et al., 2013).

Lake Tanganyika is extremely sensitive to changes in climate, since temperature drives the stratification of the lake (including the thermocline, nutricline and oxycline depths). Changes in upwelling and internal waves caused by temperature variations affect the hydrodynamics and the mixing of nutrient-rich hypolimnion water and ultimately the primary and secondary productivity of the lake. This can subsequently have an effect on fisheries and aquatic biodiversity.

Climate over east and southern Africa is characterised by high inter-annual variations in precipitation, contributing to a frequent succession of extreme dry and wet periods (Kadomura, 2005; Mason et al., 1999). This is confirmed in the recent decades by the lakes levels and other indicators (Nicholson and Yin, 2001). In the northern Tanganyika basin, unusually wet periods were observed to alternate with unusually dry periods of about 10 years (République du Burundi, 2007) which could be related to the multidecadal variability of the Indian Ocean (Tierney et al., 2013). At Uvira (D.R.Congo), in recent decades, torrential rivers, tumbling from the highlands, have shown an increasingly irregular regime (Moeyersons et al., 2009). Contrasting changes in mean and extreme precipitation in the nearby Lake Victoria area are projected, with an increase in extreme precipitation and storms while mean precipitation decreases (Thiery et al., 2016). High rainfall years amplify the effects of increased runoff, erosion and nutrient inputs as in Lake Malawi (Hecky et al., 2003). Generally, it is expected that gully erosion will become more intense and widespread in the coming decades (Vanmaercke et al., 2016).

Fisheries

Fisheries in Lake Tanganyika are based on six pelagic fish species: two species of sardine (clupeids) fishes (*Stolothrissa tanganicae* and *Limnothrissa miodon*) and four species of *Lates spp* (*Lates stappersii*, *Lates angustifrons*, *Lates microlepis* and *Lates mariae*). Among those, the two sardine species and *Lates stappersii* are economically the most important.

The latest available annual yield of Lake Tanganyika was 165,000–200,000 tons (Mölsä et al., 1999). A 2011 lake-wide fisheries frame survey revealed increasing fishing pressure and declining catch

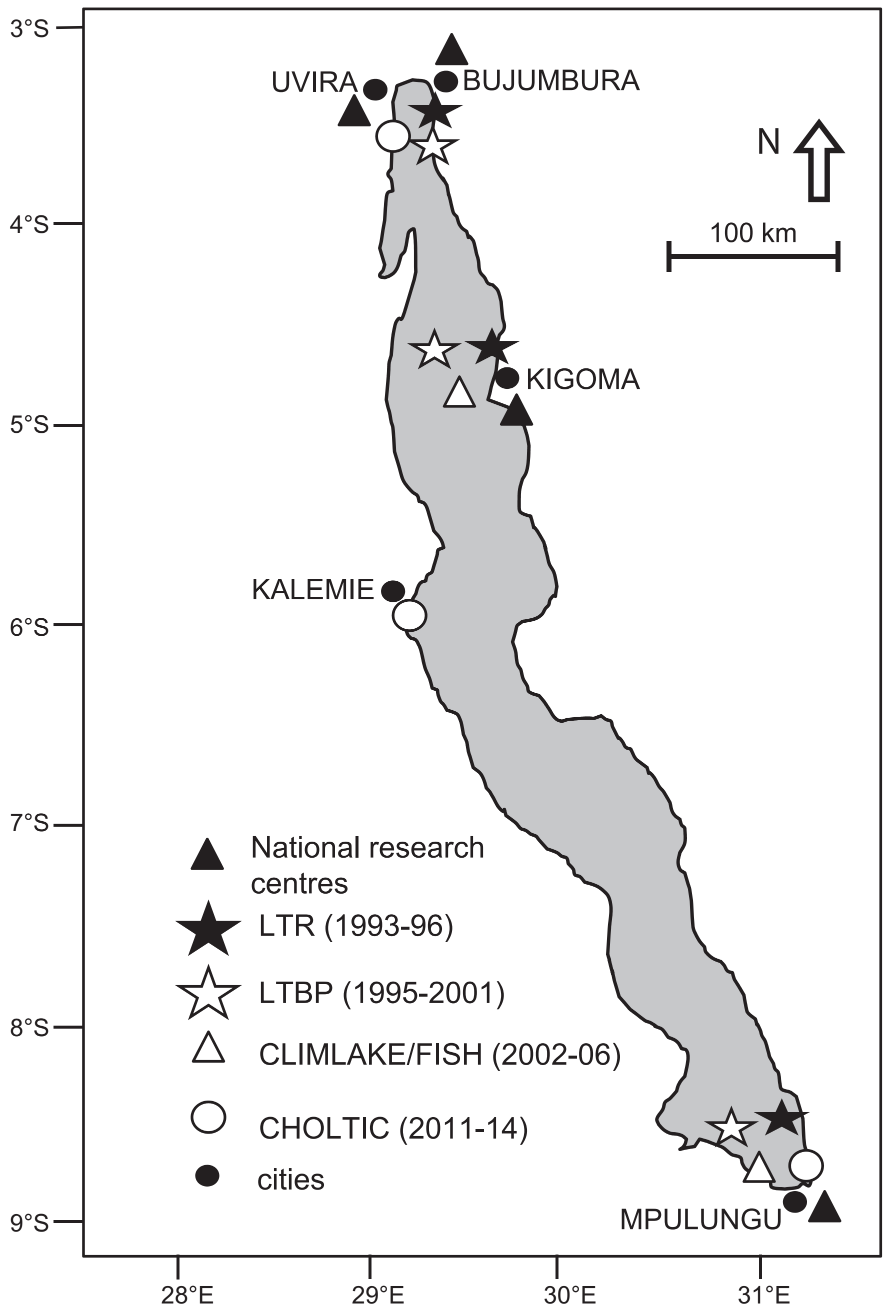

Fig. 1. Map of Lake Tanganyika with sites of past monitoring during short-term projects LTR (FAO/FINNIDA), LTBP (UNDP/GEF), CLIMLAKE-CLIMFISH (BELSPO), and sites of monitoring by mandated national institutions.

rates in Burundi but observed the lack of accurate fish production statistics in most countries (Van der Knaap et al., 2014). The adoption of formal monitoring, control and surveillance systems, community surveillance, improvement in licensing systems and a limitation in the number of fishermen and fishing units have been suggested (Van der Knaap et al., 2014).

Climate warming of the lake is also suspected to impact negatively on the primary production level with possible negative impact on fisheries (O'Reilly et al., 2003). This hypothesis is supported by the observed decline that seems to have started well before the onset of commercial pelagic fishing (Cohen et al., 2016).

Water quality

There is evidence in Lake Tanganyika of pollution by pesticides, heavy metals, sulphur dioxide, fuel, and oil (Patterson and Makin, 1998). As human population and urbanization are rapidly increasing, pollution risks are expected to increase. The city of Bujumbura (Burundi) on the lake shore is a major pollution threat. The city hosts a variety of industries and pollution sources. In addition, cities and towns such as Kigoma (Tanzania), Mpulungu (Zambia), Kalemie and Uvira (DRC) pose current and future pollution hazards. Waste from industries and domestic use are poorly treated or not treated at all. Various other pollution sources include agricultural runoff (fertilisers, pesticides), mining activities, waste from boats.

Another source of water pollution is sedimentation resulting from deforestation and inappropriate land use practices possibly exacerbated by stronger rainfall intensities. This causes land and lake shore degradation, excessive erosion and loss of lacustrine biodiversity and productivity (Cohen et al., 2005; Donohue and Irvine, 2004; Karamage et al., 2016).

A severe potential risk for the water quality and the whole lake ecosystem is the possible future petroleum extraction at Lake Tanganyika. The

Fig. 2. (A). Drying of sardines caught by liftnet fishermen during the night (Kigoma, Tanzania). (B) Mutobi and ring net fishermen at Mpulungu (Zambia). (C) Zambian coast of Lake Tanganyika. (D) Rusizi river after rainfall, showing sediments flowing into Lake Tanganyika. (Photos: P.-D. Plisnier).

lake is almost a closed system and would be highly sensitive to such pollution. Estimation of water residence time and flushing time are respectively 440 years and 7000 years (Coulter and Spigel, 1991; Bootsma and Hecky, 1993). Those characteristics make Lake Tanganyika the most fragile of all African Great lakes. Oil exploitation is a serious threat for the whole ecosystem of African Great Lakes (Abila et al., 2016; Baker, 1992). The present pollution levels and future risks emphasise the need to establish a long-term monitoring programme at Lake Tanganyika including water quality, erosion and sedimentation (West, 2001).

Land use

Population growth has led to major increases in land degradation in the Lake Tanganyika catchment basin. Expansion of unsustainable agricultural practices such as slash and burn, deforestation and grazing are principal causes. Other land management practices that lead to environmental degradation include inadequate urban and infrastructure planning, construction and maintenance. The combined impacts of these activities have three major impacts that affect the functioning and quality of ecosystem services in the Lake Tanganyika basin: loss of topsoil and fertility in the catchment, landslides and loss of biodiversity and reduce species diversity (LTA, 2012). Forest clearance on slopes, accompanying the introduction of widespread agriculture, appears to be the most likely cause of landscape instability. These unsustainable land-use activities, together with natural factors such as abundant tropical rainfall and steep topography, increase soil erosion rates in the highland of tropical areas (Karamage et al., 2016; Kalacska et al., 2017).

Biodiversity

Lake Tanganyika harbours an extraordinary diversity of species, many of which have adapted to a wide diversity of ecological niches. Different ecological food webs in Lake Tanganyika are intricately intertwined with each other, and each species plays its own specialized role. Without a wide range of species to maintain these intricate links, food webs in Lake Tanganyika would be at risk. Environmental changes and decreasing biodiversity may threaten biota while changes in nutrient flux may cause shifts in an entire ecosystem or the collapse of parts of it (Van Bocxlaer et al., 2012).

Protection, restoration and management of critical habitats are needed in addition to prevention of potentially invasive species introduction (LTA, 2012). A major strategic action to reach this objective is the establishment of long-term national and regional monitoring to assess the extent and habitats of biodiversity and the biological invasions into terrestrial and aquatic ecosystems. It also concerns food security and livelihood options and income generation as invasive species also concern fisheries and the aquarium trade.

Past monitoring and gaps

Lake Tanganyika has been the subject of over a century of scientific research, which has led to the collection of an extensive amount of limnological, biodiversity and applied fisheries data. Examples of various monitoring activities that have taken place are indicated in Table 1. These monitoring efforts were/are implemented near main accessible sites where research teams are located at Bujumbura, Uvira, Kigoma and Mpulungu (Fig. 1, Fig. 3). Some lake wide research cruises have taken place (LTR/LTBP/CLIMLAKE). Monitoring activities are also implemented by specialized national agencies (e.g. REGIDESO in Bujumbura, LTBWO in Kigoma) in addition to short-term projects in some countries. This information is not regionally centralized.

At present, the four countries around Lake Tanganyika have national research institutes and regulatory organizations with a mandate to collect information on the lake and its natural resources. Mandates and activities of specialized institutions (fisheries, hydrobiology, water, agricultural and land use) have been compiled (Plisnier and Marijnissen, 2010). It was observed that there is seldom a multidisciplinary approach and that monitoring activities are not sustained over a long time or are discontinuous. Many key parameters are not recorded regularly across the four countries, and various gaps, sometimes of 10 years or more, exist, even for important basic parameters such as water temperature. The absence of continuity is a serious problem when attempting to address environmental changes in a systematic way. The lack of data may lead to different opinions and management decisions by the riparian countries if stakeholders rely only on indirect indicators or individual perceptions and hypotheses for changes that may or may not occur. For example, the lack of fisheries data for the

Table 1
Examples of past and present environmental monitoring at Lake Tanganyika.

Period	Monitoring
1950's to present	National monitoring from various institutions with a specific mandate. Methods are not harmonised and observations not centralized. Monitoring of various parameters is not always continuous. Gaps of several years may exist for some parameters.
1993–1996	Four countries monitoring in the framework of the LTR (FAO/FINNIDA) project "Research for the Management of the Fisheries on Lake Tanganyika" (Lindqvist et al., 1999). Limnological and fisheries data were collected weekly or bi-weekly in addition to automatic weather using lake buoys and limnological measurements. In addition to regular measurements at three stations (Bujumbura, Kigoma and Mpulungu), several lake wide cruises and a fisheries aerial frame survey were implemented.
1995–2000	Four countries monitoring including all countries around the lake was implemented in the framework of the LTBP (UNDP/GEF) project "Pollution Control and Other Measures to Protect Biodiversity in Lake Tanganyika" (West, 2001). Water quality and biodiversity were the main topics of this project.
2002–2006	Two countries (Zambia and Tanzania) monitoring in the field of limnology, fishery and fish biology (Belgian funded projects CLIMLAKE and CLIMFISH)
2011–2014	Two countries (Zambia and DRC) monitoring of meteorology, limnology, bacteriology, phytoplankton, zooplankton, fish abundance, and remote sensing (Belgian funded project CHOLTIC).

whole lake may induce some countries to consider that overfishing is taking place while others may consider that the fisheries are underexploited and need more investments. This situation is problematic in developing common strategies for the management of shared resources.

Multidisciplinary monitoring is often lacking although an ecosystem approach for the monitoring is advised (Mölsä et al., 2002). Ecosystem-based fishery management (EBFM) is a holistic approach that considers the ecosystem rather than focalising mainly on target species in order to sustain healthy ecosystems and the fisheries they support. EBFM aims to understand not only the biological aspects of the species being studied or exploited, but also the environmental variables they are experiencing. It involves all relevant stakeholders in an integrated approach. It is flexible enough to allow changes to be made in the light of new knowledge and take into consideration any impacts management might have to conserve ecosystem structure and functioning to ensure sustainable use and development reflecting societal choices. EBFM management is based on the precautionary principle. It needs coordinated monitoring, assessment programmes, control and enforcement (Pikitch et al., 2004; Kolding et al., 2008; Cochrane and Garcia, 2009). For example, at Lake Tanganyika, fisheries data were often not integrated with limnological and climate data observations. Many fisheries investigations at Lake Tanganyika used almost exclusively other fisheries data which lead to often quoted "predator-prey" interpretations to explain changes in the abundance of fish species. However, multidisciplinary research has shown that limnological variability related to hydrodynamics plays a major role in fluctuating pelagic fish abundance (Plisnier et al., 2009). A clear understanding of various environmental issues at Lake Tanganyika is however still lacking as long-term data are often missing while data formats and methods are not regionally harmonised. Such steps are however necessary to reach an EBFM management based at Lake Tanganyika.

Present data are mainly collected in the frame of short-term projects leading to discontinuous time series. An example is provided in Fig. 4 with the thermal structure (0-100 m) and secchi depth transparency data in the southern Lake Tanganyika waters near Mpulungu (Zambia). Time series data are important to study the interannual variability of the southern upwelling (Coulter and Spigel, 1991). This hydrodynamic climate-related event induces important seasonal ecological and fisheries changes. In 1997–98, such data were however not recorded. During this period, a very strong El Niño event had been affecting various areas of East Africa (Plisnier et al., 2000; Ntale and Gan, 2004). This gap in the recording of temperature profiles and water transparency therefore precluded an important opportunity to progress in the understanding of the Lake Tanganyika ecosystem.

Continuous time-series of key parameter observations should be collected. This is the goal of LTRIEMP. A schematic representation of the present state of data acquisition (Fig. 5a) shows gaps in data time series, parameters being monitored mainly during short-term projects. A LTRIEMP monitoring should include key parameters on a continuous basis. Occasional short-term projects would not replace the main monitoring but complement it (Fig. 3b).

Methods

All mandated institutions/organizations involved at Lake Tanganyika were visited in the four riparian countries. Those institutions were indicated to the LTA by the national authorities of these countries. In addition, many institutions or organizations that have an interest (but not an official mandate) in Lake Tanganyika were visited or contacted, such as the University of Burundi (Plisnier and Marijnissen, 2010). Parameters, accuracy and frequency of measurement and monitoring sites for each of the five main environmental topics of LTRIEMP were discussed while previous studies were also taken into account (Chen et al., 2010; Sichingabula, 2010; Rutagemwa, 2010). Preliminary proposals were discussed during workshops organised by the LTA. Those included stakeholders (scientists, politicians, NGO's, et al.) from

Fig. 3. (From left to right): (A) Water sampling by the Department of Fisheries in Zambia, (B) zooplankton sampling by the Centre de Recherche en Hydrobiologie at Uvira in DRC, (C) water analysis by TAFIRI at Kigoma in Tanzania. (Photos: P.-D. Plisnier).

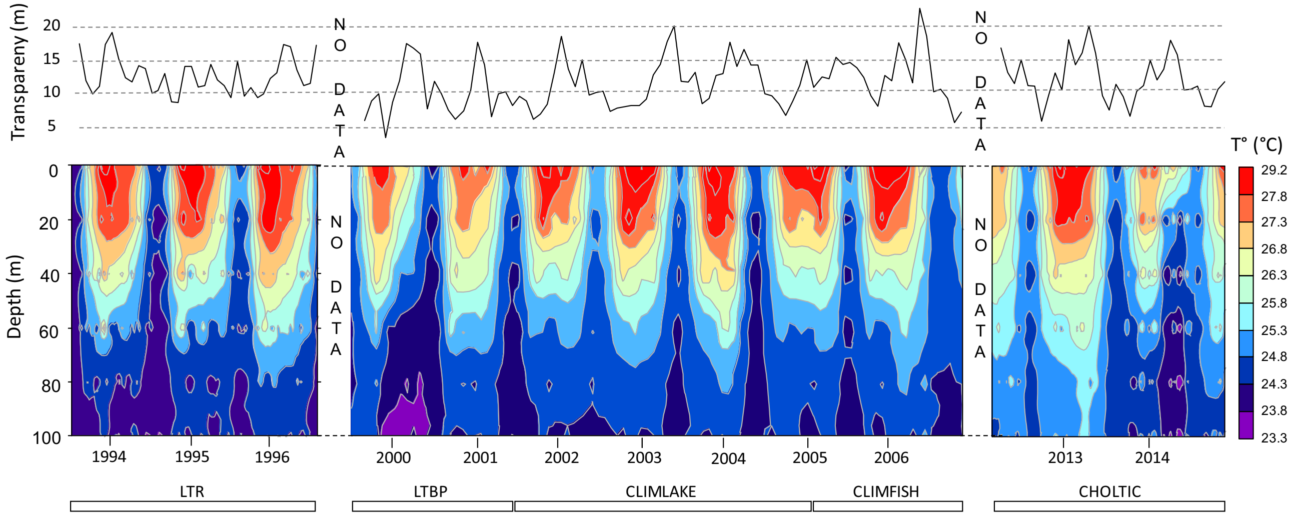

Fig. 4. Water temperature monitoring (0 to 100 m) in pelagic waters of southern Lake Tanganyika near Mpulungu (8°43.98′ S 1°02.43′ E) and water transparency (secchi disk) mainly during short-term projects: LTR (FAO/FINNIDA), LTBP (UNDP/GEF), CLIMLAKE & CLIMFISH (BELSPO) and CHOLTIC (BELSPO) in partnership with the Zambian Department of Fisheries (DOF). Such data were not available during the 1997–98 El Niño event. LTRIEMP aims to ensure continuous sampling of basic important parameters.

each of the four countries and experts from various organizations (Plisnier, 2012). The present proposal is mainly built on those workshop discussions. A plan for LTRIEMP could probably be improved provided that sustainability and low-costs remain key considerations to ensure the continuation of the monitoring.

Results

Long-term regional monitoring

The LTRIEMP aims to provide a long-term continuous monitoring of the most essential parameters. The sustainability of this monitoring programme in the long-term should be ensured even for periods when funding from short-term projects is not available. This is why it would be appropriate that national institutes ensure that main monitoring activities are included in the annual budgets of their mandated institutions. This is indeed the case for various parameters although monitoring interruption may be frequent. A restricted choice of key parameters only, with a reasonable frequency of measurement, is thus essential. It is preferable to build a continuous and low-cost time series of a few main parameters rather than a wide, frequent but expensive and unsustainable monitoring including too many parameters. It would be, however, of interest for a coordinating body such as the Lake Tanganyika Authority to apply to international organizations such as the

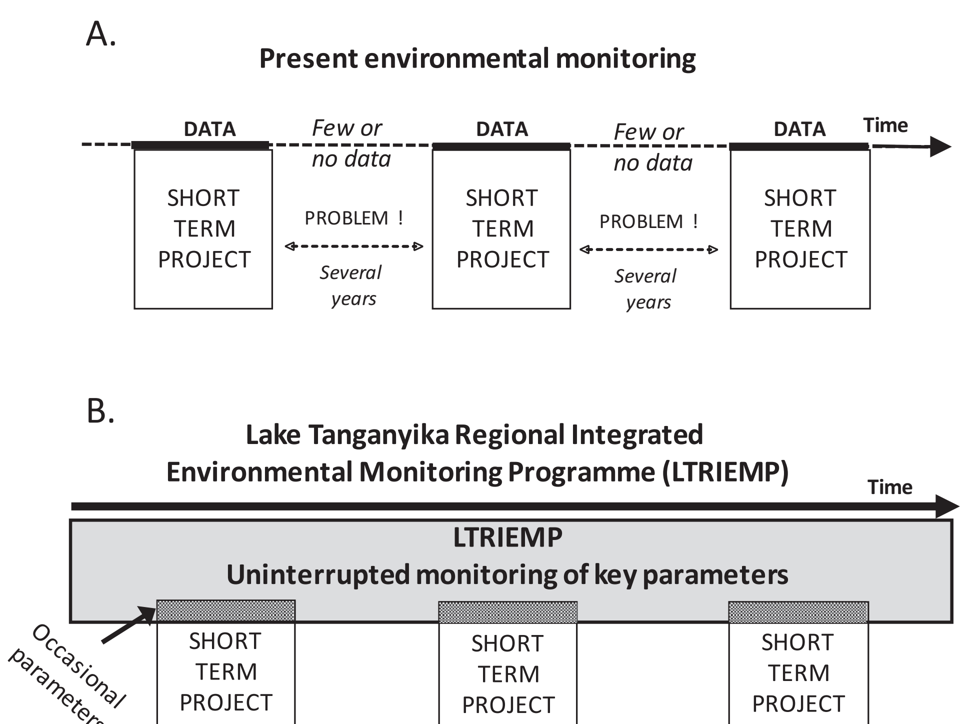

Fig. 5. Schematic presentation of the present monitoring at Lake Tanganyika showing (A) the discontinuous data collection mainly related to short-term projects and (B) LTRIEMP monitoring with uninterrupted monitoring of main parameters (short-term projects only as supports).

World Bank or its Global Environment Facility to support the comprehensive integrated long-term monitoring of this major ecosystem of the world providing invaluable services to the population. Such a programme could also be used to unify data storage and dissemination through a centralized archive and information portal.

To provide complementary information that LTRIEMP could not collect on a continuous basis, occasional specific monitoring could take place during short periods when additional funding is available, such as during international collaborative short-term projects as previously done. A proposed schematic presentation of parameters and measurement frequencies (Table 2) illustrates the complementarity between LTRIEMP and short-term projects. As an example, frequently measured parameters for fisheries during LTRIEMP should include catches per unit of effort of the main pelagic fish species while specific groups of littoral fishes could be surveyed during short-term projects as a minimal common strategy for the riparian countries. Riparian states could be encouraged to increase the level of monitoring intensity when funding opportunities arise, but should ensure these study results are available to LTRIEMP.

Meteorological monitoring

Meteorological data, as for agriculture, are essential to understand the various changes in water environment (Kapetsky, 2000). The main surface meteorological parameters needed to monitor climate change around the lake include air temperature (maximum and minimum), rainfall, rain intensity, wind speed and direction, humidity, solar radiation and atmospheric pressure. Whenever possible, upper air measurements should also be made (wind direction and speed, humidity, temperature and atmospheric pressure). Protocols of measurements should be regionally harmonised and follow recommendations of the World Meteorological Organization (Jarraud, 2008). Daily and monthly reporting should be shared among countries in the frame of the LTRIEMP as a tool to analyse impact of climate on various ecological issues.

A problem exists, however, as the spatial coverage of meteorological synoptic stations around Lake Tanganyika is not uniform. A meteorological coverage exists for the north east of the lake (main stations of Bujumbura in Burundi and Kigoma in Tanzania). In Zambia, the closest official meteorological station (Mbala) is situated too far from the lake (40 km) and 700 m higher in altitude. In DRC, there seems to be no operational meteorological monitoring at present in the lake area. This means that a great part of the lake is not covered by meteorological stations. This is really problematic since climate change is a major threat to Lake Tanganyika. The meteorological stations network in relation to the length of national shore along Lake Tanganyika should at least maintain one station in Burundi and Zambia and two in Tanzania and DRC close to the lake (Fig. 4). For the longest freshwater lake in the world (673 km), such a meteorological "network" (6 stations) seems to be a minimal requirement. Lakeside institutions such as the Department of Fisheries (DOF) in Zambia, the Centre de Recherche en Hydrobiologie (CRH) in Uvira, the Fisheries Department in Kalemie (DRC), the Tanzania Fisheries Research Institute (TAFIRI) and the Mahale station of the Tanzania National Parks (TANAPA) could usefully reinforce the meteorological monitoring after an ad hoc training and with close supervision by the Meteorological Departments in each country.

Automated stations could be useful but are fragile and need regular replacement and maintenance. However, technology is rapidly progressing. As longer lasting automated station become available, those could possibly be operated in the framework of collaboration with partners. Automated meteorological stations allow hourly or even sub-hourly observations which are desirable for meteorological monitoring, with real-time data transmission through cellular and satellite networks linked to the Internet (e.g. *Trans*-African Hydro-Meteorological Observatory (TAHMO http://tahmo.info)).

Installation of high frequency data loggers/sensors moored on lake buoys including meteorological instruments would be optimal. However, this is costly and, so far, only done in the framework of short-term projects (LTR/FAO-FINNIDA in the early 90's, CLEAT/DANIDA since 2016). Long-term collaboration with partners or groups of partners would be particularly helpful here as such equipment could be difficult to maintain for a continuous long-term monitoring without a sustained source of funding.

There is also a large potential for remote sensing (RS) data to alleviate some of the gaps caused by the lack of in-situ data (Thiery et al., 2015). This only holds for a certain number of variables such as precipitation. Tropical Radar Measuring Mission (TRMM) is an example of RS precipitation data but dozens of different products are available. For wind speed and direction over large water bodies, such as Lakes Tanganyika or Victoria, QUICKSCAT may be used (Docquier et al., 2016). Other variables that may be measured from space are cloud cover, surface net shortwave and longwave radiation, soil moisture, and lake and land surface temperature during cloud free conditions. For sea level pressure, atmospheric reanalysis, in particular ERA-Interim could be recommended. Although built around a model, with data assimilation, this variable appears to be a trustworthy output of reanalyses (Thiery, pers. com). However, for 2 m air temperature and 2 m relative humidity, there are no reliable products available yet, and *in-situ* data are needed to calibrate and improve the remote sensing (RS) data. *In-situ* measurements may not totally be replaced. However, satellite data analyses could, in the long term, be cost effective. For an efficient long-term regional monitoring, a RS service providing regular meteorological reports for a network of institutions involved in an observing system of the African Great Lakes (multi-lakes monitoring) could usefully be provided.

Fisheries monitoring

National stratified sampling programmes to estimate catches (C) and fishing efforts (E) for each main commercial species and fishing technique are essentials to follow closely the C/E. This fish abundance indicator is highly relevant to management (van Zwieten et al., 2011). Regional lake-wide frame surveys (to quantify craft, gear, fishermen and landing site facilities) are also essential. A periodicity of five years seemed appropriate from discussion among various stakeholders during preliminary workshops (Plisnier, 2012) but some flexibility in the frequency of such a part of the programme should be integrated in LTRIEMP since too intensive efforts might not be sustainable. Main sites for fisheries monitoring are presented in Fig. 6. It is advised that additional sites along the coasts are chosen by each country according to their possibilities. Monitoring capacities in the Kalemie area (DRC) and Kipili (Tanzania) could usefully be developed for better lake-wide coverage. Biological monitoring of main target fish species are part of

Table 2
Schematic representation of continuous LTRIEMP and occasional short-term project parameters list.

Parameters	Sampling	Time scale (e.g. months)																	Implementation
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	…	
most essential (few)	frequent	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		LTRIEMP (continuous)
	seasonal	x			x			x			x			x			x		
additional	occasional							x										x	Specific projects (not LTRIEMP)

the proposed LTRIEMP. Clupeids species *Limnothrissa miodon* and *Stolothrissa tanganicae* display very different biological characteristics and need to be separately studied in all investigations. Additional studies could be implemented for other biological parameters and other species in the frame of short-term projects. Main target fish species include *Stolothrissa tanganicae*, *Limnothrissa miodon* and *Lates*

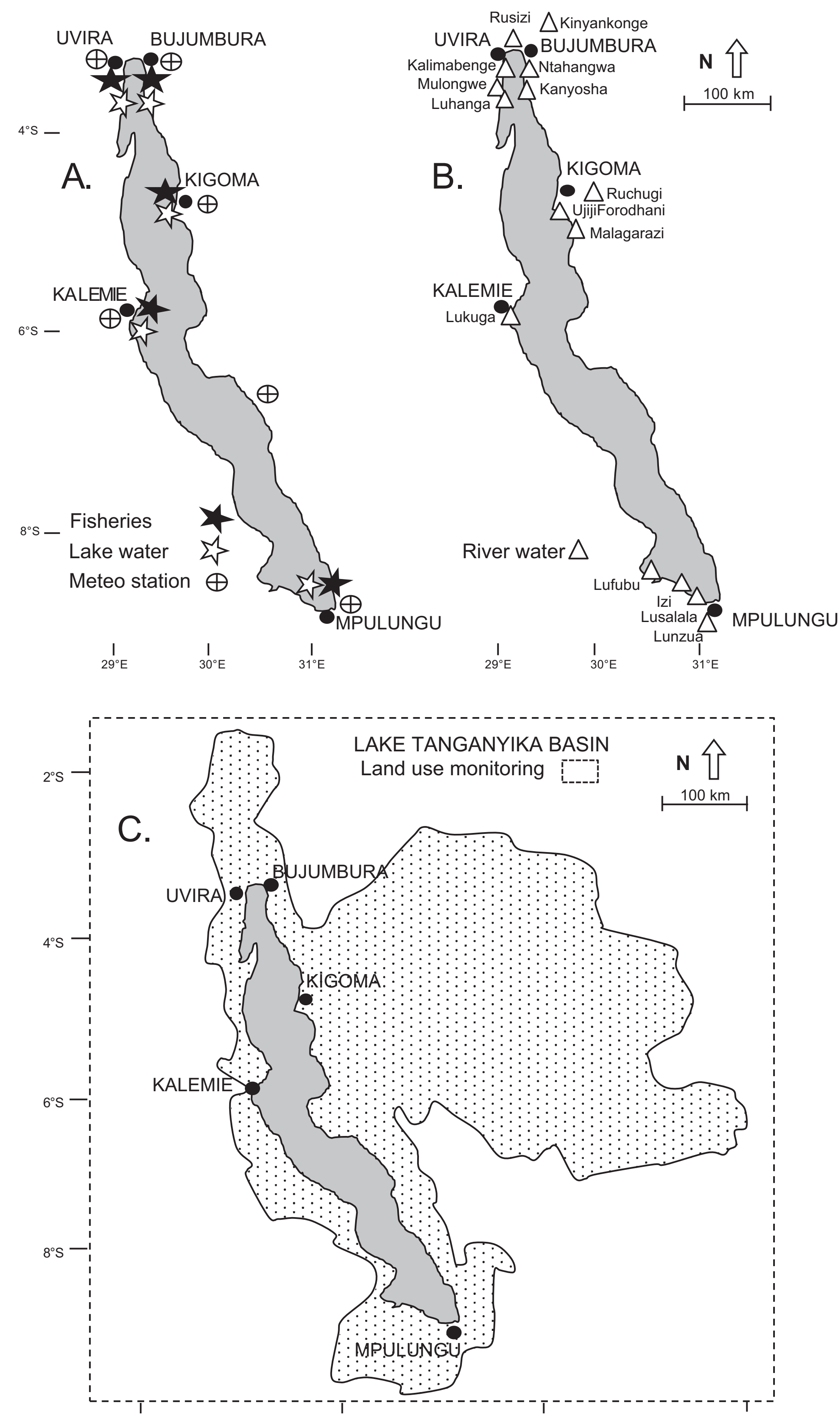

Fig. 6. Monitoring sites proposed for the LTRIEMP for (A) fisheries, lake water (pelagic, coastal and harbour) and meteorological stations (presently only in Bujumbura and Kigoma); (B) river water monitoring and (C) land use monitoring of the Lake Tanganyika Basin.

stappersii. Other targets could include species such as *Lates mariae*, *Lates microlepis*, *Lates angustifrons* and *Boulengerochromis microlepis* according to resource availability. A summary of fisheries monitoring components is presented in Table 3.

Water quality monitoring

Essential parameters for water quality continuous monitoring are presented in Table 4. Targets for water quality monitoring include limnological, chemical and sediments pollution in addition to the microbiological environment. Water quality monitoring is needed not only for its direct human use, particularly for drinking water, but also as habitat quality that affects fish stocks and the overall biodiversity. This is why limnological parameters such as chlorophyll *a* and transparency or temperature and oxygen profile measurements allowing thermocline and oxycline determination are important for LTRIEMP.

A systematic lake wide remote sensing monitoring including water temperature, chlorophyll *a* and turbidity would be appropriate for such a large lake (Ballatore et al., 2014). Spatiotemporal dynamics of phytoplankton in Lake Tanganyika have shown the usefulness of satellite-based analysis for research at Lake Tanganyika (Bergamino et al., 2010; Horion et al., 2010). A better understanding of the dynamic of some pelagic fish species may be gained also from remote sensing of chlorophyll *a* data (Plisnier et al., 2009). Remote sensing would be essential to detect surface pollution as in the case of oil spills. However, remote sensing may not replace *in-situ* investigation because only surface data are acquired (when cloud conditions allow it). Vertical profiles of water temperature, dissolved oxygen, pH, conductivity and chlorophyll *a* need to be measured *in-situ*, either from regular measurements or from automatic buoys (a technology not yet considered as low-cost). The integration of RS into LTRIEMP seems thus conditional either on a long-term sustainable funding or on short-term projects developed in addition to LTRIEMP.

Main water quality sites include pelagic, coastal and harbour sites located near main towns. Many sites along Lake Tanganyika are not easily reachable from land. For pelagic sampling of lake water, the choice of identical sites used in previous monitoring such as during the LTR project (FAO/FINNIDA) is advised for comparisons (Fig. 6a).

A few rivers identified by stakeholders for LTRIEMP are situated near those locations (Fig. 6b). The presence of a laboratory and staff near those sites is required to allow frequent sampling (Table 5). Sites adjacent to protected areas situated in more remote locations such as Mahale, Gombe and Nsumbu national parks should be occasionally sampled (short-term projects) to provide baseline data.

Frequency of monitoring for water quality and quantity depends on various aspects such as the parameters to be measured, the water use and other criteria such as the number of people using the water (e.g. drinking water for the population of Bujumbura needs more frequent analysis compared to water along the shores in rural areas).

Three types of sampling for water quality and quantity are proposed: 1) frequent, 2) seasonal and 3) occasional sampling (Chen et al., 2010; Rutagemwa, 2010; Sichingabula, 2010).

Table 4
Water quality and quantity parameters (LTRIEMP and non-LTRIEMP), units and type of sampling (coliform and faecal bacteria, *E. coli* = *Escherichia coli*, TDS = total dissolved solids, TSS = total soluble solids, BOD = biological oxygen demand, COD = chemical oxygen demand, NTU = nephelometric turbid unit), TP = total phosphorus, TN = total nitrogen. Remote sensing (RS) daily measurements are advised. (x) indicates recommended but not possible for all locations.

Parameters	Units	Type of sampling			
		LTRIEMP			Not LTRIEMP
		Daily	≤ Monthly	Seasonal	Occasional
Water temperature	°C	(x)	x	x	x
Surface temperature	°C	x (RS)			
pH			x	x	x
Electrical conductivity	μS/cm		x	x	x
Dissolved oxygen	mg/l		x	x	x
Turbidity profile	NTU		(x)	(x)	(x)
Surface turbidity	NTU	x (RS)			
Transparency	m	(x)	x	x	x
Coliform, faecal, *E. coli*	Col./100 ml		x	x	x
TDS, TSS	mg/l		x	x	x
Tributaries flow	m^3/s		x	x	
BOD, COD	mg/l			x	x
As, Ni, Pb,Cd, CN, Hg, Mn	mg/l			x	x
NO^{3-}, $PO_4^{- - -}$	mg/l			(x)	x
Fe	mg/l				x
Ca^{++}, Mg^{++}	mg/l				x
Na^{+},K^{+}	mg/l				x
Cl^{-}, $SO_4^{- -}$, F^{-}	mg/l				x
H_2S	mg/l				x
Pesticides	μg/l				x
Hydrocarbons	μg/l				x
Chlorophyll a	μg/l				x
Surface chlorophyll *a*	μg/l	x (RS)			
TP, TN	mg/l				x
SiO_2	mg/l				x
Alkalinity	mg/l ($CaCO_3$)				x
Total hardness	mg/l ($CaCO_3$)				x
Cr,Co,Sn,Cu,Zn,Ra,U,Al	mg/l				x
Ag,Be,Se,Ba,Sr,S,V,Au	mg/l				x

Frequent sampling (F) corresponds with weekly up to monthly frequency. This frequency is adequate for the monitoring of essential parameters known to vary in this range of time. Water temperature, pH, electrical conductivity, dissolved oxygen, turbidity, transparency, total dissolved solids (TDS), total soluble solids (TSS), bacteria (coliform, faecal, *E. coli*) and river flow are important parameters that are linked to water quality and quantity aspects including pollution aspects, erosion, human health, habitat and primary production. These parameters are important to interpret environmental changes taking place in the lake. For fish habitat, a useful limnological monitoring frequency is weekly because a clear lacustrine variability is linked to internal wave periodicity that is close to three weeks (Chitamwebwa, 1999; Plisnier et al., 1999). However, bi-weekly or monthly pelagic sampling could be a first goal of LTRIEMP. Frequent sampling is possible at locations where at least one operational laboratory, equipment, boat and staff are available. In this case, besides lake surface sampling, the measurement of water temperature, pH, electrical conductivity, dissolved oxygen and

Table 3
Fisheries monitoring components for LTRIEMP and/or during short-term specific projects (S.P.) depending on funding (Lt = length, W = weight, S = sex, M = maturity stage, GW = gonad weight, F = fecundity, St.C = stomach contents, Par. = parasites, Occ = occasional).

Fisheries survey	LTRIEMP/S.P.	Parameters	Frequency
A. Catch assessment survey (CAS)	LTRIEMP	Catch & efforts	Monthly
B. Biological analysis of main pelagic species	LTRIEMP	Lt, W, S, M, GW, F, St. C , Par.,…	3 months/occ.
C. Frame survey (FS)	LTRIEMP/S.P.	Boats and fishing gears	5 years
D. Biological fish cohort studies	LTRIEMP/S.P.	Length frequencies	Monthly
E. Gear selectivity	S.P.		Yearly/occ.
F. Biomass/stock assessments	S.P.	Biomass	Yearly/occ.

Table 5
Water quality and quantity monitoring suggested for LTRIEMP: sampling sites (lake and rivers) and frequency.

	Location name	Site	Frequency		
			Weekly	Monthly	Seasonal
Burundi	Bujumbura	Lake-coast	x		x
		Lake-pelagic		x	x
		Harbour		x	x
	Rusizi	River mouth		x	x
	Kinyankonge	Kinyankonge			x
	Kanyosha	River mouth			x
DRC	Uvira	Lake-coast	x		x
		Lake-pelagic		x	x
		Harbour		x	x
		Kalimabenge		x	x
		Mulongwe		x	x
		Luhanga		x	x
	Kalemie	Lake-coast		x	x
		Harbour		x	x
		Lukuga		x	x
Tanzania	Kigoma	Lake-coast	x		x
		Lake-pelagic		x	x
		Harbour		x	x
	Ujiji Forodhani	Ujiji		x	x
	Uvinza bridge	Malagarasi			x
	Uvinza	Ruchugi			x
Zambia	Mpulungu	Lake-coast	x		x
		Lake-pelagic		x	x
		Harbour		x	x
	Lusalala Village	Lusalala			x
	Mbete Village	Izi river			x
	Kabyolwe	Lufubu			x

turbidity could be done every 20 m down to 100 m since this depth generally includes the main thermocline and oxycline delimiting important biotopes in the lake. The use of conductivity-temperature-depth probe (CTD) would allow a complete vertical profile. However, this technology is not considered as low-cost and LTRIEMP sustainability should rely on long lasting, more affordable equipment. Frequent sampling sites near cities involve also some rivers crossing cities or situated in their vicinity (Table 5, Fig. 4b).

Seasonal sampling (S) corresponds to quarterly or semi-annual sampling for sites that are situated farther away and/or for the same sites as frequent sampling but for parameters that do not necessitate frequent sampling.

Occasional sampling (O) corresponds to parameters that are not part of LTRIEMP but that should be kept in mind for periods when additional funding is available (short-term projects). When such sampling is done, the same parameters as for frequent (F) and seasonal sampling (S) should be included in addition to new parameters. In some cases, such as severe pollution, occasional sampling (O) could also be very frequent. In all cases, occasional sampling allows flexibility in sites and parameters.

Land use monitoring

For the purpose of understanding sediment, nutrient and pollutant discharges it is important to monitor changes in land cover, agroforestry interventions, agricultural crop cover and sediment loads in rivers (Table 6). Two scales need to be considered when monitoring land use: i) The whole basin (Fig. 6c) for which remote sensing data is necessary (Cohen et al., 2005); and ii) landscape and demonstration sites, which may be monitored using participatory methodologies with local communities to validate remote sensing observations. Monitoring sites for *in-situ* land use monitoring still need to be precisely designated in each country. River flow measurement and suspended sediments should be measured for all major rivers but also smaller accessible rivers.

Table 6
Proposed parameters frequency for the environmental monitoring related to the land use topic in the Lake Tanganyika basin.

Parameters	Frequency
Surface use for agriculture, forest, pasture, savanna	2 years
Surface used on exposed soil by categories of slope	2 years
Erosion hazard risk assessment	2 years
Population and its distribution	4 years
Land use maps from remote sensing	3 years

Biodiversity monitoring

The overall objective of monitoring the status of biodiversity is to maintain a healthy ecosystem functioning and high levels of species diversity and endemism in Lake Tanganyika. It aims also to help control the invasive species threatening the lake habitats, biodiversity and productivity. As defined in the Convention on Biological Diversity:

- an alien species is a species, subspecies or lower taxon, introduced outside its natural past or present distribution. It includes any part, gametes, seeds, eggs, or propagules of such species that might survive and subsequently reproduce.
- an invasive alien species is an alien species whose introduction and/or spread threaten(s) mainly biological diversity but also habitat and fisheries productivity.

LTRIEMP monitoring should focus on taxa that play a key role in the aquatic ecosystem. Taxa should be easily identifiable by para-taxonomists and easily sampled, for instance using dipnets, snorkeling, or fishing gear. Reference collections (taxonomic guidelines, and preserved example specimens of key taxa) need to be established in strategic locations within each country. Collaborative networks with national, regional and international experts as well as ongoing training of selected para-taxonomists should ensure sustainability of a biodiversity monitoring programme in Lake Tanganyika. Short-term lake-wide biodiversity surveys of a wide range of taxa could take place periodically by teams of national and international experts. Long-term site-specific monitoring of limited key taxa could be done by lake based national survey teams (IUCN, 2012).

Biodiversity monitoring includes three types of species occurrence surveys (Table 7). Baseline monitoring would be a short-term regional survey that could be organised with national and international experts focusing on a wide range of taxa (e.g. including crustaceans, gastropods, etc.). Its frequency could be every five to 10 years depending on funding. This type of survey needs to be mentioned but is not part of the LTRIEMP. Changes from the baseline would be established by a long-term monitoring (LTRIEMP) of the habitat reflected by occurrence of key taxa, mainly fish species, by national survey teams with attention to possible introduced species. Key taxa should be easily identifiable

Table 7
Targets of surveys (LTRIEMP/not LTRIEMP) for biodiversity monitoring (species occurrence and relative abundance) and ideal frequency; ND: not defined.

Survey type	LTRIEMP	Group target	Frequency
Baseline survey	No	Littoral fish, phytoplankton, zooplankton, vegetation & all other possible taxonomic groups	10 years
Changes from baseline	Yes	Key species (particularly littoral fish)	2 years
		Riparian vegetation	5 years
Intermittent survey	No	Submerged macrophytes	2 years
		Phytoplankton & zooplankton	5 years
		Arthropods	5 years
		Mollusks	5 years
		Other species (animal & vegetal)	ND

by para-taxonomists and also easily sampled, for instance using dipnets, snorkeling, or fishing gear. Species diversity indices should be used. Frequency could be every two years. Intermittent surveys would be done when the possibility arises based on the availability of funding and participation of specialists. Intermittent surveys are thus not part of the LTRIEMP but need to be mentioned. For each type of survey frequencies (yearly, 5 to 10 years or intermittent), it is important to sample every 3 months or, at least, during the dry and the wet season. Various sites for biodiversity and invasive species monitoring should be included (Table 8). Previous monitoring activities and sites should be taken into account as possible guidelines for biodiversity and invasive species monitoring.

Stakeholders

The successful implementation of LTRIEMP will be closely linked to the active collaboration of stakeholders each of which would have an important role to play as summarized in the below.

The LTA has a mandate to oversee and coordinate regional activities aimed at sustainable management of Lake Tanganyika and its catchment basin given sufficient resources and human capacity both for regional coordination and national implementation. As a key regional institution, the LTA should play a main role in the organization of the LTRIEMP. The technical/scientific implementation of LTRIEMP could be delegated to an existing or a new institute which regularly reports to the LTA. Such a separate board would match with the suggestion presented below (Duda, 2002).

National and regional monitoring units formed in mandated governmental institutions in the riparian countries will implement the LTRIEMP in possible collaboration with other institutions and partners. In addition to the five main topics: (meteorology, fisheries, water quality, land use and biodiversity) a national coordination unit in charge of a national database should be set up. National topic coordinators from interministerial committees would link the national implementation of LTRIEMP with the regional coordination unit (Plisnier and Marijnissen, 2010; Plisnier, 2012).

National stakeholders formed from local stakeholders in the lake basin is necessary. These could include universities, research centers, local fishermen and NGO's specialized in various fields related to the LTRIEMP topics. As an example, fishermen communities, beach management units, farmers and schools could participate in some aspects of LTRIEMP after an adequate training and follow-up.

Regional stakeholders collaboration with other Great Lakes partners (e.g. the Lake Victoria Fisheries Organization, the Lake Victoria Basin Commission, the Nile Basin Initiative, the Kivu and Rusizi River Basin Authority) could be usefully developed with a possible goal of harmonizing monitoring procedures and observations toward a better understanding of climate and anthropogenic pressures and adapted management measures.

Table 8
Suggested sites or activity sectors and number of sites (N) for the monitoring of biodiversity and invasive species.

Types of site	N	LTRIEMP	
		Biodiversity	Invasive species
Rocky shoreline	2	x	x
Sandy beach	2	x	x
Pelagic waters	1	x	x
Landing-beach	1	x	x
River mouth	3	x	x
Lake-edge wetland/swamps	2	x	x
Basin catchment	2 to 6	x	x
Urban and port extensions/lake edge	All	x	x
Aquarium fish collectors	All		x
Aquaculture/ponds	10		x
Aquaculture/cage in the lake	All		x
Other pathways	Variable		x

Experience of North American Great Lakes has shown that complementary to the board of Ministry officials, a separate board representing the science community is useful to evaluate progress undertaken by each country in implementing its commitments to cleanup/prevention and to report this with recommendation to the Commission (Duda, 2002). A structured network of national/regional and international institutions/experts could form a consulting group to provide advice, analysis, comments or technical support to the LTRIEMP.

Various potential international partners could possibly support the LTRIEMP financially or by joining the advisory group. Such partners might include The World Bank (GEF), UNEP, UNDP, FAO, UNESCO and other organizations such as the Nature Conservancy, the International Union for Nature Conservation, the Critical Ecosystem Partnership Fund, the Albertine Rift Conservation Society, the Worldwide Fund for Nature, the MacArthur Foundation, among others. It would be highly advisable to establish a mechanism ensuring the long-term support of LTRIEMP.

Data flow, analysis and reporting

An important aspect of LTRIEMP is the database management and equipment for which the LTA Secretariat (or a dedicated regional institution for LTRIEMP implementation) and national partners' staff could be strengthened. In parallel to the database, a website data portal is essential. A firewall for internal use helps in the exchange of information and allowing partners to discuss shared issues among themselves. Various levels of data management and information sharing may be foreseen. Geographical Information System (GIS) would be useful to access and visualize data although this could also be implemented at a later stage. Remote sensing data processing could be developed internally in the LTRIEMP structure. However, a dedicated regional or international organization providing this service for the whole African Great Lakes region, including Lake Tanganyika, is advisable.

Yearly technical reports need to be produced for each topic. These could present physical, chemical and biological indicators in the five LTRIEMP themes: climate, fisheries, water, land use, biodiversity. Additional human indicators including economics, demography and societal aspects could usefully be added toward a holistic integrated ecosystem approach.

The predictive value of indicators increases with the length of the time series. For fisheries management and research, the traditional approach was often formed by top-down-driven single species steady-state assessment aimed at single gear licence-controlled fisheries but applied to an open access multispecies multi-gear fishery. This may largely result in uncertainties with the reality. Indicators represent major ecosystem state and processes to inform fisheries and ecosystem management decisions on important issues and concerns by stakeholders. Those indicators of ecosystem drivers give a comprehensive picture of states, trends and interactions of the ecosystem (Kolding et al., 2008; van Zwieten et al., 2011).

Research results and findings should not only be transferred to policy makers and managers, but also to the stakeholders and the wider public. Such results may be shared through policy briefs, brochures, radio messages, etc. (Van der Knaap and Munawar, 2014).

Discussion

The sustainability of a long-term monitoring programme such as LTRIEMP will be very dependent on the initial choice of parameters, sites and observation frequency. A good ratio between the value of information and the corresponding cost/effort to collect it will ensure the sustainability (Fig. 7). A monitoring strategy that is too intensive would lead to higher costs without providing significant additional information where a less sophisticated strategy (fewer parameters) could lead to the continuous build-up of important ecosystem indicators as required for lake managers.

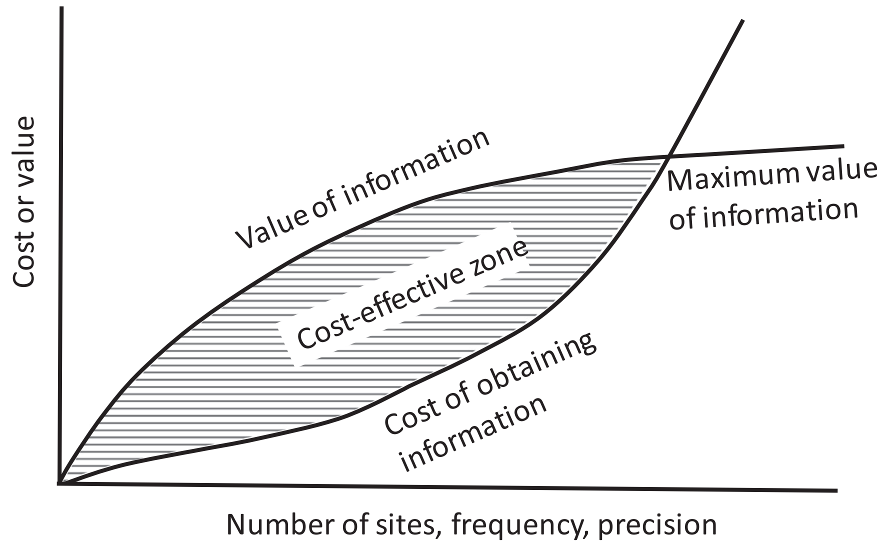

Fig. 7. Cost effectiveness of monitoring.
(After Biswas, 1988)

Various surface parameters may usefully be monitored using remote sensing. To reduce the cost of a regular remote sensing monitoring, the collaboration of international partners is advised, possibly including organizations such as UNEP, UNDP, the European Space Agency, or another network in the framework of a global lake observatory (Politi et al., 2016). The value of remote sensing is thus high for surface specialized studies as a spatial tool for developing ecological modelling for example. Remote sensing in the frame of a long-term monitoring could be considered if an LTRIEMP partner could sustainably support its cost. Such a service could be part of a general remote sensing monitoring service of the African Great Lakes region by an environmental agency. In case of oil exploitation, remote sensing monitoring should be considered as a necessity to track any oil spills and help with possible remedial measures. However, remote sensing may not be considered as a substitute for field monitoring in many aspects. For example, remote sensing (ground-truthed) may be appropriate for lake wide algal blooms monitoring, but not for primary production measurements (Van der Knaap and Munawar, 2014).

At the North American Great Lakes, a dense monitoring network of federal, state/provincial, academic and private institutions has been created including the Great Lakes Observing System (GLOS) (Gronewold and Stow, 2014). GLOS collects and collates existing physical, chemical, biological and geospatial data about the Great Lakes according to international standards and makes these data and information readily accessible, via a data portal, to the Great Lakes community and decision makers. This allows the monitoring of the ecological health of the Great Lakes using data that are both comparable and compatible. The experience of GLOS suggests that: (1) activities should support documented policy and management priorities and meet a requirement/mandate or serve multiple needs, (2) a group of users should identify/confirm needs, (3) efforts to develop such a monitoring should be well evaluated (complexity, execution, data accessibility, coordination) and costed (execution time/cost estimates, funding sources available, sustainability, leverages) (The Great Lakes Observing System. Blueprint. A strategy for data for decision-making. www.glos.us/wp-content/uploads/2016/03/GLOSBlueprint_2016-20.pdf accessed on 10-4-2018).

Could a modelling approach complement and strengthen the development of a monitoring strategy by enabling upscaling and interpolation in time and space? For African inland lakes, Musinguzi et al. (2017) noted that there is limited local and regional capacity for ecosystem modelling because of data deficiencies in addition to a need for specific training. Data deficiencies have limited most ecosystem models to specific time periods and areas (Nsiku, 1999; Kolding, 1993, 2013). The use of simulation models compared to common sense in decision-making was also the subject of debate among the science community in the North American Great Lakes. Uses and abuses of modelling, their over-reliance for decision-making, and limitation of application due to unverified assumptions were addressed by the Great Lakes Sciences Advisory Board (Duda, 2002). In accordance with the low-cost requirement of LTRIEMP, it is advisable that monitoring programmes first improve availability of data independently from a modelling approach until those may be developed as a validated management tool. Modelling in the frame of specific research topics is, however, useful (Naithani et al., 2012; Villanueva et al., 2008).

For Lake Tanganyika, a successful LTRIEMP would be favoured by the following points:

- A clear agreement between countries on questions that the long-term monitoring aims to answer
- Steps toward a long-term environmental regional integrated monitoring of Lake Tanganyika include identification of partners, collaboration agreements, preliminary methods, needs assessment, capacity building, common training to ensure regional harmonization, test period, evaluation and adjustment before starting the operational LTRIEMP monitoring
- Well defined tasks including a clear organigram for the various roles of each partner (e.g. national/regional topic coordinators)
- Common training, gathering observers from each of the countries for harmonization of methods and to favour communication between partners. Training should include data analysis to improve the supply of information to managers (West, 2001)
- Clear instructions including concise field manuals and reporting procedure using web networking
- Good information technology (IT) facilities including relevant software, sufficient data storage and processing capacity, and Internet access
- Collaboration between partners is essential and could include common sampling and sharing of laboratory facilities
- Clear communication and exchange of information including feedback to partners (advice on methods, database, providing additional information etc.)
- Maintenance of measuring instruments. Reserve instruments in each country or based in a regional coordinating office may supply temporary help. This includes, for example, essential monitoring equipment such as thermometers, dissolved oxygen/pH, conductivity/turbidity meters, weighing scales, etc. Gaps in time series should be avoided to allow LTRIEMP to reach its goals.

– Data should be collected in a harmonised way, which should be similar for all LTRIEMP partners (units, methods). In order to integrate, interpret and use data for informed management decisions at a regional level, an integrated data management and information sharing system is crucial.
– Regular evaluation by advising scientists could ensure the quality control of the LTRIEMP (methods, instruments calibration, analysis of specific parameters such as trace elements analysis in certified laboratories).
– As Lake Tanganyika is the subject of scientific interest from all over the world, because of its unique biodiversity, limnology, hydrodynamics, fisheries, and paleo-climatology, a scientific association or consortium including regional and international partners could reinforce the long-term effort of the LTRIEMP. This type of partnership should be based on mutual scientific benefits. This group of partners could reinforce the long-term monitoring of essential parameters in addition to researches and intense monitoring during short-term projects.
– A high level political commitment to support the Lake Tanganyika monitoring is strongly advised (West, 2001).

Conclusions

The second deepest lake in the world with its exceptional characteristics certainly deserves a Regional Integrated Environmental Monitoring Programme as indicated in the Lake Tanganyika convention. Developing such a LTRIEMP is a challenge but also a necessity for managers who need data-based information concerning the various threats from climate and anthropogenic pressure at Lake Tanganyika.

The monitoring programme could focus on a limited number of parameters in the field of climate change, fisheries, water quality, land use and biodiversity to ensure its long-term sustainability. Occasional short-term monitoring activities could complement the LTRIEMP by investigating additional parameters.

Various institutions are mandated in each country to monitor important lake parameters on a regular basis. It is important that international organizations support the launching of such a harmonised monitoring of LTRIEMP (with initial reinforcement of capacities including equipment and training). Various budgeted options would help countries before commitment. Continuous support would ensure the sustainability of LTRIEMP. This would be easily justifiable for an ecosystem of such worldwide importance. For its sustainability, a low-cost programme is a necessity to avoid failure of an overambitious programme. A consortium of partner institutions could reinforce the long-term implementation of LTRIEMP. The collaboration of LTRIEMP with other monitoring taking place on other African Great Lakes should be favoured to gain from other experiences and harmonise methods. A possible (even partially) common harmonised monitoring among some or all of the various African Great Lakes would be ideal as similar environmental problems are observed. Such a collaboration could be an incentive to develop a regional multi-lakes long-term monitoring network. This will increase cooperation and coordination particularly in international lake basins. The North American Great Lakes monitoring system could be inspiring for the development of an "African Great Lakes Observing System" (AGLOS) possibly linked to a regional institution with a mandate to facilitate multi-lakes collaboration and reporting to the authorities.

Long-term monitoring programmes are needed by managers to determine the impact of human activities and environmental changes around the lakes (Odada and Olago, 2006). This will bring a greater interest from the international scientific community and other interested parties worldwide for the sustainable use and conservation of Lake Tanganyika but also for all African Great Lakes facing serious natural and anthropogenic threats.

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