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Lake Turkana: Status, challenges, and opportunities for collaborative research

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ABSTRACT

Lake Turkana, located in northwestern Kenya and south-western Ethiopia, is Africa's fourth largest lake and the world's largest permanent desert lake. The lake lies in a closed basin and its limnology, ecology, and fisheries are driven by seasonal cycles of flooding from the Omo River, which provides more than 90% of the lake's inflow. Lake Turkana is a unique ecosystem and is home to at least 79 fish species (12 endemic), the world's largest remaining population of Nile crocodile, and hundreds of resident and migratory bird species. The lake has considerable fisheries resources that contribute to food security, employment, and the general wellbeing of local communities. Lake Turkana is also the least studied of the Great Lakes of Africa, due to its remoteness, the absence of necessary scientific infrastructure, and the scarcity of trained personnel in the field of aquatic sciences and fisheries in the region. Here, we present a review based on the available literature and on expert discussions and surveys to synthesize current knowledge, research gaps, and opportunities for increasing our knowledge on this unique ecosystem. Our literature review showed that there is a marked lack of interdisciplinary and applied research on Lake Turkana, and that much of the work published on the system (63.3%) focuses on previous geological periods rather than the current state of the ecosystem. We highlight four critical steps that need to be taken to improve research into this system: local capacity building, consistent monitoring and data sharing, sustainable financing, and strengthened collaborative networks.

Introduction

Lake Turkana, located in northwestern Kenya and south-western Ethiopia (Fig. 1), is the world's largest permanent desert lake and has been deemed a UNESCO World Heritage Site and an "Important Birdlife Area" (Birdlife International, 2021). Although the communities living around Lake Turkana are traditionally pastoralists (except for the El Molo), fishing provides an important alternative livelihood, particularly during periods of drought (Hopson and Ferguson, 1982; Kolding, 1989; Watson and van Binsbergen, 2008ab; Yongo et al., 2010; Carr, 2017). Lake Turkana is also considered the least studied and understood of the African lakes (Kolding, 1992). The knowledge base of the lake is highly localized, largely outdated, and only based on several short-term studies since the 1980s. The lake's limnology and fish ecology have been the focus of only five major studies (Worthington and Richardo, 1936; Hopson et al., 1982; Källqvist et al., 1988; Kolding, 1989), all of which have been externally driven and sponsored. Most of the research that has taken place has focused on small subsets of this vast and diverse ecosystem; and this work has primarily been conducted on the lake's central sector and specifically on a very small but highly productive portion of the lake, Ferguson's Gulf (size is highly variable but ~10 km^2; Kolding, 1993a). The physical and hydrological characteristics of the lake is presented in Table 1.

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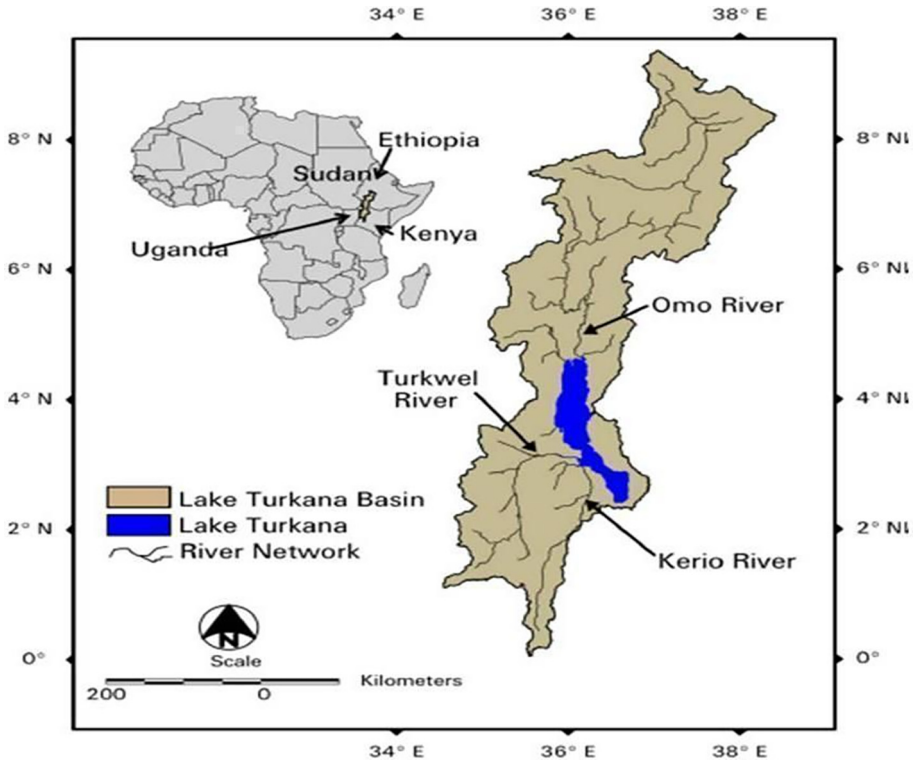

Fig. 1. Map of Lake Turkana Basin (Source: Velpuri et al., 2012).

Table 1
Physical characteristics of Lake Turkana. Modified from Hopson,1982; Kolding, 1989, 1992; Ogutu-Ohwayo et al., 2020)

Characteristic	Measure
Age (millions of years)	4.3
Position: Latitude and Longitude	3°29′N; 36°17′E
Altitude (m above mean sea level)	360
Catchment area (km^2)	130,860
Lake surface area (km^2)	7,560
Lake area as percentage of catchment (%)	5
Maximum length, North-South (km)	265
Maximum width, East-West (km)	32
Mean width (km)	31
Maximum depth (m)	114
Mean depth (m)	31
Volume (km^3)	203.6
Inflow ($km^3 yr^{-1}$)	19
Precipitation ($mm yr^{-1}$)	< 200
Annual fluctuations in level (m)	1 – 1.5
Residence time (yrs)	12.5
Country	Kenya, Ethiopia

Furthermore, except for global satellite products that can be used to infer lake level and some water parameter values (e.g., USDA/NASA G-Realm), the limited data on this system are not easily accessible. No central data repository exists to allow stakeholders to track the status of the lake and its resources. Local organizations, including the Kenya Marine and Fisheries Research Institute (KMFRI), Kenya Fisheries Service (KeFS) and Turkana County Government Department of Fisheries collect regular monitoring data on Lake Turkana and its fisheries (Schubert et al., 2022), but with limited spatial resolution, a lack of standardization, and sporadic funding. As a result, ongoing efforts to study this unique ecosystem remain scattered and uncoordinated.

The reasons for the lack of research conducted on Lake Turkana are, in part, due to the lake's harsh and remote setting and the absence of necessary infrastructure to support the logistical needs of a scientific research program (Johnson and Malala, 2009). Moreover, a lack of investments and scarcity of trained workforce in the fields of fisheries and aquatic sciences have exacerbated the situation. As a result, there is still much to be learned about the lake's limnology, ecology, and fisheries resources. The Ethiopian side of the lake and Omo Delta is even more remote than the Kenyan portion of this ecosystem and, as a result, even less studied. Though this region is likely to play a key role in the functioning of the entire ecosystem, our limited knowledge comes from accounts of short visits to the area and a few academic theses and publications of post-graduate students (Wakjira, 2016; Getahun et al., 2020).

This review paper discusses the threats posed to Lake Turkana and the knowledge gaps that exist on the system and explores ways to improve scientific understanding of the lake and its river basin through standardized, collaborative research. The paper summarizes past work, identifies current research priorities, and outlines a way forward for Lake Turkana researchers and managers.

Importance of and threats to Lake Turkana

The Omo-Turkana region is globally famed as the "Cradle of Mankind" due to the preponderance of early hominid fossils discovered there (Amin, 1981; Joordens, 2011). As a result of its archaeological importance, a national park was created on the lake's eastern shores in 1973, Sibiloi National Park. In 1983 and 1985, the Central and South Island National Parks were formed and, together with Sibiloi, these were designated a UNESCO World Heritage Site in 1997 (Ojwang et al., 2016). The lake, which is home to hundreds of resident and migratory bird species, is also an "Important Birdlife Area" (Birdlife International, 2021). Most recently, the Lake Turkana World Heritage Site was added to the "World Heritage in Danger" (UNESCO, 2018). The lake is presumed to support the livelihoods of roughly 200,000 people in Kenya and Ethiopia (Hodbod et al., 2019). Fisheries also act as an important

safety net during perennial droughts that lead to massive livestock loss (Ibid).

Over 90% of Lake Turkana's inflow comes from the Omo River, located in Ethiopia. The endorheic (closed basin) nature of the lake, desert location, sporadic rainfall, high evapotranspiration rates, and dominant singular source of inflow from the Omo River result in amplification of small climate changes. As a result, the lake's productivity, water quality, and habitat availability are highly sensitive to climate shifts and hydrological changes, with implications for its flora and fauna (Kolding et al., 2016; Gownaris et al., 2018; Tebbs et al., 2019). Changes to the ecosystem could become more rapid due to the current and planned construction of hydroelectric dams on the Omo River and associated agricultural expansion and irrigation (Hodbod et al., 2019). The region has also seen recent oil exploration activities and heightened conflicts over natural resources (Schilling et al., 2015).

The Turkana region is characterized by remoteness, low levels of development, high rates of poverty (>94 %), high illiteracy levels, and limited employment opportunities (Ojwang et al., 2011). Historically, local people have adapted and persevered despite intermittent natural droughts, but population growth, loss of livestock, migration constraints, and sedentary lifestyles have resulted in severe poverty and increasing dependence on food aid, and these debilitating conditions persist and will likely increase in response to continued natural and man-made changes unless novel adaptive solutions are found. Food aid has become a de facto drought coping mechanism in the region, further exacerbating the situation by attracting in-migration (Avery, 2010).

The impact of frequent droughts, increasing insecurity, restricted mobility, and cattle rustling has led to partial or complete loss of livestock in some years, with ensuing famine causing the community to take up fishing as an alternative livelihood (Kolding, 1989; Yongo et al., 2010; Derbyshire, 2020). This follows the general trend of humans migrating towards, and increasingly relying upon "open-access" water resources as access to alternative livelihoods, and other resources (such as crops and animal husbandry) become limited (Lawrence, 2015). As a result, the lake is seen as a strategic resource to address food insecurity through its provision of nutrient rich fish to combat hunger and malnutrition triggered by the harsh climatic environment (Kolding, 1989; Kolding et al., 2016). In spite of some donor support in the 1970s and 80s (Kolding, 1989), the communities living around the lake do not have the necessary means and facilities to utilize the resources adequately. There is great potential that fish production can be sustainably increased on Lake Turkana.

Methods

This review was written by scientists from institutions, organizations and universities in Kenya and Ethiopia with support from other international experts (from Norway, Canada, and the United States) through an ongoing collaboration within a formal group called the Lake Turkana Advisory Group (LTuAG). This group was formed during the African Great Lakes Stakeholders Network Workshop held in Entebbe, Uganda in 2019 by the African Center for Aquatic Research and Education (ACARE; https://www.agl-acare.org/2019-workshop-resources). Members of LTuAG with expertise in fisheries, water quality, biodiversity, ecohydrology/-modelling, remote sensing, climate and socio-economy meet virtually every month with the intended goals of bringing together multilateral agencies, academic and research institutions, the private sector, and non-governmental organizations to facilitate collaboration, strengthen capacity, inform policy and management with science and practice, and encourage basin-scale ecosystem management and biodiversity conservation. The goal of LTuAG is to harmonize research efforts on the lake through transition from short-term, parochial, sporadic funding and disparate approaches towards long-term data collection and monitoring (Plisnier et al., 2023). Ultimately, this group hopes to provide the basis for Kenyan and Ethiopian decision-makers to ensure the long-term health of the lake and the sustainable, and profitable, use of the lake's resources. For this paper, the members of LTuAG developed the priorities and way forward using the following approaches:

1. *Semi-formal and formal discussions:* Over 16 monthly virtual discussion sessions took place from the beginning of December 2019, until the paper conceptualization in mid-2021. At each meeting, we highlighted important issues and further discussed and considered recommendations. When appropriate, meetings considered some of these issues as formal agenda items and upon outlining this paper, those issues were considered for a more in-depth review and priority-setting.
2. *Survey administration*: With facilitation from ACARE, a 32-questions virtual survey was conducted that asked respondents to identify the most critical issues and state how to address them. This questionnaire was similarly used in other African lakes, so that comparisons among responses could later be made. The overall top issues raised and ranked among respondents (in no particular order) include:
   1) Climate change
   2) Insufficient knowledge and skills
   3) Biodiversity decline
   4) Fishery resources
   5) Land use/habitat destruction
3. *Secondary literature reviews* were used to support the above-described discussions and surveys taken by the LTuAG, to help to summarize previous research into Lake Turkana. We ran a search for any articles containing the term "Lake Turkana" in their abstract, keywords, and/or title on the Scopus database in July 2022. These articles spanned the period of January 1983 through June 2022. We downloaded bibliographic information for the resulting articles and reviewed the abstracts of each article to categorize them based on relevance, timeframe of focus, and field of study. Articles were deemed relevant as long as they represented an academic article and were focused on Lake Turkana. If publications focused on previous geologic time periods, we categorized them as "paleo", otherwise we categorized them as "current". We also categorized papers based on a broad (natural science, social science, applied science, interdisciplinary) and specific (e.g., geology, anthropology) field of study. It is important to note that this review would not have captured any key studies in the grey literature, such as the Hopson (1982) report, governmental reports, and the various thesis and dissertations that have focused on this ecosystem.

Results

Survey administration

The total number of respondents from within the LTuAG members was 5 out of 9. Insufficient knowledge and skills received the greatest number of 1st priority votes of all the issues (3 votes). Climate change received the greatest number of votes (4), but it had fewer top priority votes than "Insufficient knowledge and skills". Two other issues, "biodiversity decline" and "fishery resources", each received 3 votes, ranking as 3rd and 4th respectively. Biodiversity decline is ranked 3rd because it had more 1st and 2nd priority votes than did fishery resources. Land use received some 1st and 2nd priority votes, but overall was ranked last. Through formal-structured, monthly virtual meetings, the above results

were discussed and ranked in plenary, supported by literature search with the final ranked results of the survey shown below:

1. Insufficient knowledge and Skills
2. Climate change
3. Biodiversity status
4. Fishery resources
5. Land use/habitat destruction

Secondary literature review

Our literature search resulted in a total of 386 articles (Electronic Supplementary Material (ESM) Table S1 and Table S2). Of these, we categorized 26 as irrelevant because they were not focused on Lake Turkana or the surrounding regions (n = 14), they were duplicate records (e.g., an erratum to an article already categorized; n = 6), or they were for a news article or another non-academic article (n = 6). The remaining relevant articles were cited a total of 2,169 times. Most of these articles (n = 228 or 63.3 %) were focused on previous geologic time periods (paleontology, paleoanthropology, paleoclimatology, etc.). The proportion of articles representing the current state of the ecosystem increased over time (Fig. 2a). Of the articles focused on current time periods (n = 133) the majority (78.5 %) represented Natural Science studies (Fig. 2b); nearly all these studies (91.2 %) focused on geology, biogeochemistry, or biology. Due to the relevance of biological studies to conservation and management in the region, we also noted which of these studies focused on genetics, taxonomy, or the presence/absence of species in the region. These descriptive studies comprised 66 % of all biological studies; applied biological research (e.g., fisheries biology) or ecological studies (e.g., on species interactions or behavior) were rare.

Discussion

As it is a transboundary ecosystem, it is critical to address research on and management of Lake Turkana through national, regional, and international collaborations. This calls for the mobilization of resources from the global freshwater community and partners to help make this happen. The experts of the group are scientists, researchers, lake managers, policy makers and environmental enthusiasts, whose short-term goals are to harmonize the research and scientific priorities on the lake and then help the governments of Kenya and Ethiopia and others interested in studying the lake to focus resources and research efforts. In this way, LTuAG aims to decrease the disparate and often short-term nature of research conducted on this lake specifically and inform effective research networks for "Global South" lakes in general.

The LTuAG is administered and facilitated by ACARE which is an independent organization with the interest of strengthening science, research, and education on the African Great Lakes for positive lake management and livelihood improvement. It is intended that good lake and basin management will in turn address many of the United Nations Sustainable Development Goals, such as No Poverty (SDG 1), Zero Hunger (SDG 2), Quality Education (SDG 4), Decent Work and Economic Growth (SDG 8), Reduced Inequalities (SDG 10), and Life Below Water (SDG 14), Life on Land (SDG 15) and Partnerships for the Goals (SDG 17). ACARE intends to ensure that LTuAG survives in perpetuity as a scientifically oriented organization, building trust, confidence, and cooperation among lake stakeholders, creating information based on the scientific process, and engaging the decision-making community to propose positive policy and management changes on the lakes. The discussion below provides a synthesis of the current state of knowledge on Lake Turkana under the key categories expressed above and research and capacity-building priorities in each of these cate-

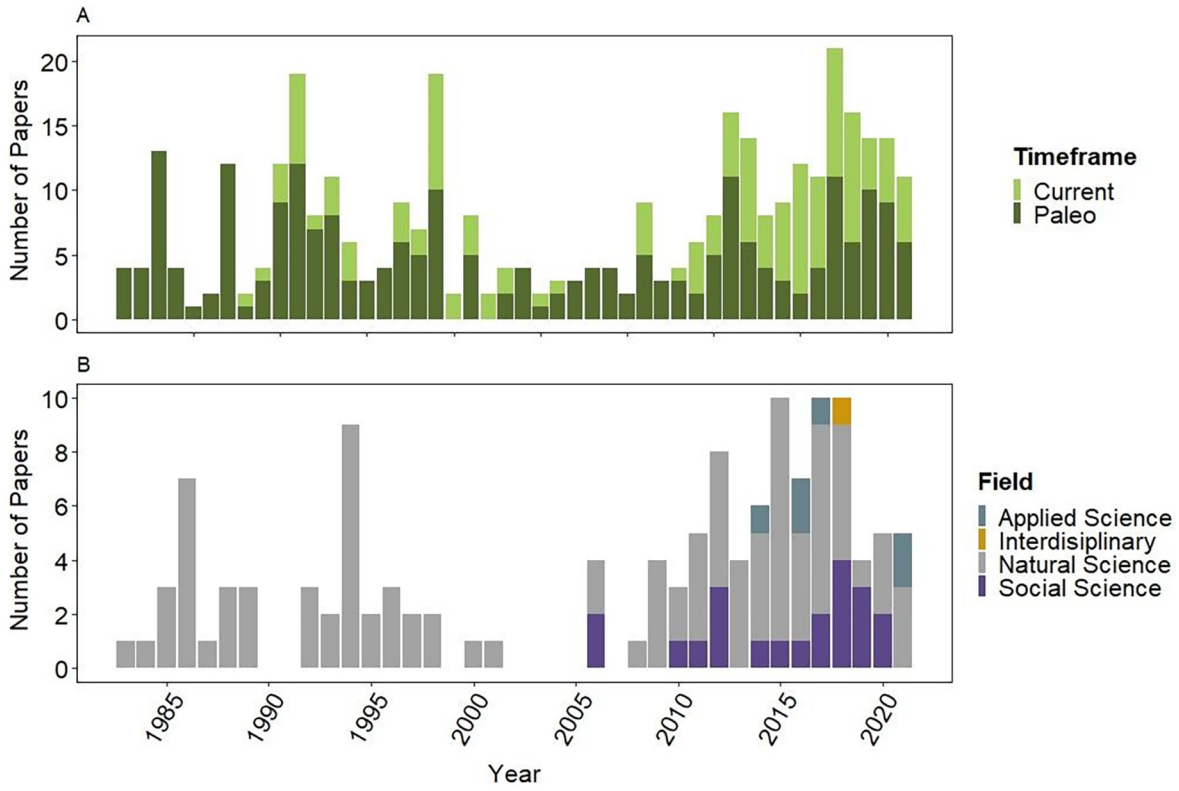

Fig. 2. The number of peer-reviewed publications (n = 360) on Lake Turkana over time as indexed on the database *Scopus*. Abstracts were reviewed to ensure relevance to this system and to group publications based on their timeframe of relevance (A; studies focused on the current system, "current", or on previous geologic time periods, "paleo") and on their field of study (B).

gories. Specific priorities listed under each section and the overarching priorities that follow are the result of ongoing discussions and our collective expertise on this ecosystem.

Insufficient knowledge and skills

Across the African Great Lakes, there is a general lack of sufficient basic information on biodiversity to effectively inform conservation and resource management. Short-term research efforts in the region lack standardized approaches, resulting in inconsistent and incomparable scientific data, and the disjointed nature of country-and-regional specific datasets hinders evidence-based formulation and implementation of regulations, policies, and conservation actions (Obiero et al., 2020). Our literature search revealed that research into the current state of this system is still deficient, with much of the research historically conducted in the region focused on paleoenvironments. There are few interdisciplinary or social science studies in the region and rarely do the studies take an applied approach to understanding the issues affecting the ecosystem.

Most of the biological research in the region has been focused on documenting the presence of species or novel species or morphological variation in species; there have been very few ecological studies or studies directly applicable to resource management in the region. The ecology and fisheries of Lake Turkana have been the focus of only four major research expeditions: the Cambridge University Expedition of 1930–1931 (Worthington and Richardo, 1936), the Lake Turkana Project of 1972–1975 (Hopson et al., 1982), the Lake Turkana Limnological Study of 1985–1988 (Källqvist et al., 1988), and the Turkana Fisheries Study (Kolding, 1989). The most comprehensive study, undertaken by Hopson et al. (1982), is nearly 40 years old.

Though there are ongoing efforts to study the lake, they remain uncoordinated and insufficient. Except for global satellite products, which can be used to infer lake level and some water parameter values (e.g., USDA/NASA G-Realm), the limited data on this system are not easily accessible (Velpuri et al., 2012). The limited biological data on the system kept on paper at the offices of KMFRI and other local research organizations are largely inaccessible. Published data on the system are not easily findable or searchable. Opportunities also exist to integrate Lake Turkana into pre-existing data collection frameworks (e.g., national bird surveys conducted by the National Museums of Kenya), improved data-collection by fishers on the lake (e.g., Enhanced Fish Market Information Systems) and an open-source information portal developed by UNEP, based in part on satellite imagery data, land cover, water quality and soil moisture, and various climate change scenarios for the basin (UNEP-DHI, 2021).

The need for a standardized and centralized repository of user-friendly data on the African Great Lakes is a persistent request of scientists working in the region. For example, key issues highlighted by a 2017 workshop entitled "Strategy for Conservation and Sustainable Development of the African Great Lakes (AGL) Region in a Changing Environment" include the lack of standard methods for the collection, analysis, and archiving of ecological data and the need for improved monitoring and assessment (Cowx and Ogutu-Owhayo, 2019). These gaps in data availability are further highlighted in a recent publication resulting from a collaboration among scientists in Malawi, Uganda, Kenya, Austria, and the United States (Obiero et al., 2020). A recent study by Plisnier et al. (2023) proposed a multi-lake approach to harmonizing data collection modalities. This approach would allow for cross-system comparisons and promote a better understanding of regional and global environmental impacts on the AGL.

To promote better understanding on Lake Turkana, there is need to enhance knowledge and skills through the following priorities:

- Training research scientists to conduct various monitoring and research studies, including frame surveys, remote sensing, water quality monitoring, and fish stock and environmental impact assessments.
- Technical and infrastructural capacity building by modernizing existing research stations and training of technical personnel to ensure successful long-term monitoring of environmental and climatic parameters.
- Effective environmental education and improved communication between scientists, policymakers, and the public through exchange visits and multi-stakeholder workshop to raise awareness of environmental issues and disseminate research findings.
- Develop multi-year research projects and conduct regular field educational programs for undergraduate and post graduate students, interns, in collaboration with global freshwater experts to addresses environmental issues.

Climate change

The earliest comprehensive limnological and geological assessments of the lake are attributable to the Lake Turkana Project (Hopson, 1982). The comprehensive project dealt with the geological and chemical aspects, algal dynamics and primary productivity, and zooplankton of the lake (Ferguson and Harbott, 1982; Harbott, 1982). In the late 1980s, a study funded by the Norwegian Agency for Development Cooperation (NORAD) produced a more comprehensive summary of the major geological and limnological aspects including physicochemical characteristics, major and minor ions, and primary and secondary productivities (Källqvist et al., 1988).

Climatic conditions and water level fluctuations of the lake have been studied since the end of the 1960s and the beginning of the 1970s (e.g., Butzer et al., 1969). After a relatively long period of paucity, a couple of more recent studies have also re-addressed the geologic, water level fluctuations, and climatic conditions (e.g., Avery, 2010; Brown and McDougall, 2011; Feibel, 2011; Tebbs et al., 2019; Velpuri et al., 2012; UNEP-DHI, 2021). Satellite-derived data on the lake's water levels are freely available in near real-time from the G-REALM project.

The lake shows pronounced inter-and intra-annual fluctuations in water level as a function of the rainfall in distant upland areas, opposed by a high evaporation rate (Kolding, 1992). An influx of about 19 km^3/year is required to maintain balance (Avery, 2010). Generally, the lake level fluctuates annually with an amplitude of 1–1.5 m (Gownaris et al., 2018; Kolding, 1989; Tebbs et al., 2019), but it also undergoes considerable long-term variations, which exceed that of any other world lake of natural origin (Butzer, 1971) (Fig. 3). The closed basin and high evaporation create saline conditions in the long-term, and Lake Turkana is close to the borderline of 3 g/l defining saline waters (Williams, 1981).

Rainfall is the most unpredictable feature of the Turkana climate, yet it is also the most disruptive when it does occur. The Lake Turkana basin has four distinct seasons with two dry periods (December–February and July–August) and two rainy seasons (March–June and September–November). The average rainfall over the lake is less than 200 mm yr^{-1} (Halfman and Johnson, 1988). Heavy rainstorms, often localized and scattered, are preceded by violent winds and dust storms, accompanied by a marked fall in air temperature of up to 8 °C. Up to 70 mm precipitation over a few hours have been observed (Kolding, pers. obs.), resulting in sudden flash floods of ephemeral rivers, sweeping trees, animals, and even people out into the lake.

Over the past decade, studies have been undertaken to assess any potential impacts of the hydrological modifications owing to the development activities taking place in the lake's Omo River

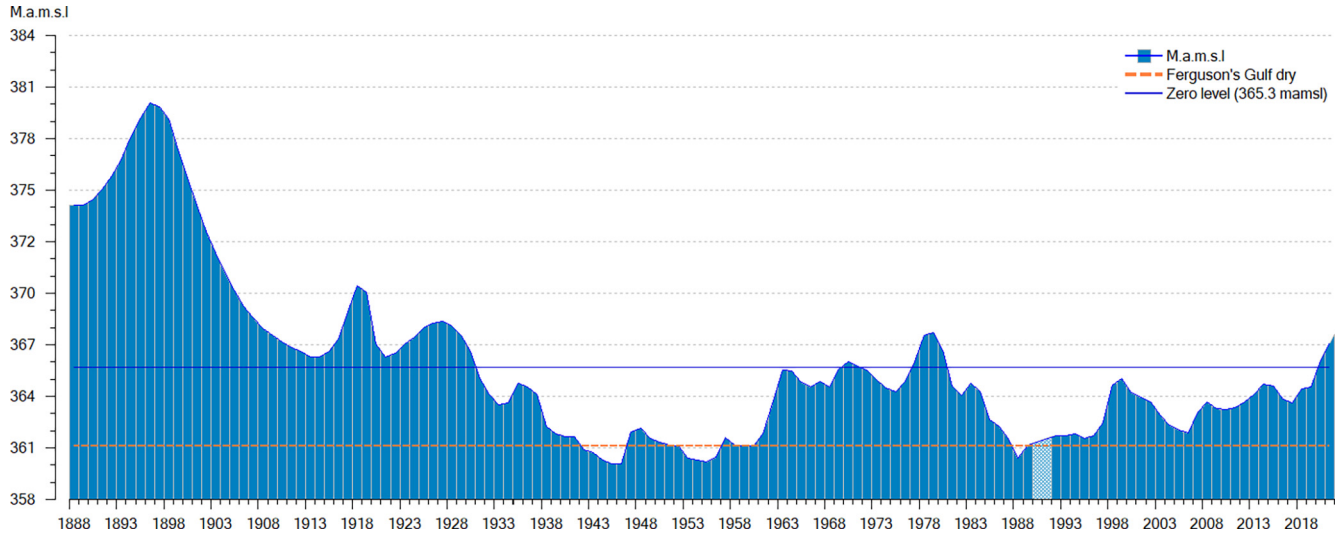

Fig. 3. Fluctuation in the lake levels of Lake Turkana in meters above mean sea level (m.a.m.s.l). Data from 1888 to 1989 are from Butzer (1971; Ferguson and Harbott 1982; Källqvist *et al.*, 1989, and Kolding 1989). Data from 1992 to 2021 are from USDA G-Realm satellite monitoring. 1989 to 1992 are interpolated. Red dotted line at 361 m.a.m.s.l is when the productive Ferguson's Gulf is dry, and blue line at 365.3 m.a.m.s.l is the 1972 Zero level (Hopson 1982). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

basin. For instance, a study by the African Development Bank (AfDB) documented the potential impacts of the development activities on the basin's fish fauna and the downstream fishing communities (Avery, 2010). Recent studies have reported changes in the volume and seasonality of inflows from the Omo River, owing to the upstream dams and irrigation schemes, significantly influencing the ecology of the Lower Omo River and Lake Turkana (e.g., Carr, 2017; Gownaris et al., 2017; Hodbod et al., 2019; Tebbs et al., 2019).

In addition to hydrological development, predictions suggest that, due to climate change, differences in precipitation between wet and dry seasons in Africa will widen and that extreme flood and drought events will become more prominent, intensifying seasonal fluctuations (IPCC, 2013). There is already evidence that such changes are emerging. A recent study by the United Nations Environment Programme (UNEP) predicts that, over the next 20 years, climate change could likely lead to heavier rains over Lake Turkana's inflowing rivers, which would raise water levels in the lake and increase the likelihood of severe flooding (UNEP-DHI, 2021). The past several years have already been marked by increasing lake level due to these precipitation increases. Gownaris et al. (2018) analyzed long-term changes in seasonal and interannual relative lake level fluctuations in 13 African lakes and reservoirs in association with general ecological attributes. The temporal trends in seasonal water level fluctuations were overwhelmingly positive, with significant increases in eight of the systems studied and decreases in only two. All the lakes situated in drylands showed a significant positive increase in seasonal water level fluctuations, thus supporting the IPCC predictions of intensified seasonal oscillations.

To advance knowledge of Lake Turkana's response to climate change, priorities include:

- Regular monitoring of environmental conditions, including annual lake water levels, land cover, water quality nutrient levels, soil moisture and salinity.
- Linking environmental variation to variation in the lake's ecology.
- Modelling of potential future environmental states given ongoing hydrological change at local to global scales.

Biodiversity status

Documenting and characterizing biological diversity are vital for species conservation and sustainable development (Boden et al., 2004). The Turkana basin was first explored for its ichthyofaunal diversity towards the end of the 19th Century during Dr. Donald Smith's Lake Turkana expedition of 1894–1895 (Günther, 1896). Though several subsequent expeditions to the lake provided piecemeal updates, the British Lake Turkana Project (1972–1975) laid the foundation for much of the contemporary knowledge of Lake Turkana's Nilotic ichthyofaunal diversity (Hopson and Hopson, 1982). Kolding (1989; 1992) also provided an update on the ichthyofaunal list that focused mainly on the lake's fisheries. Recent studies on the ichthyofaunal diversity of the Omo River and Lake Turkana on the Ethiopian side have been undertaken as part of Joint Ethio-Russian Biological Expedition (JERBE) and PhD projects (Golubtsov and Darkov, 2008; Prokofiev and Golubtsov, 2013; Gownaris, 2015; Wakjira, 2016; Wakjira and Getahun, 2017).

The Lake Turkana Project (Hopson, 1982) provided the first in-depth study of the biology of Lake Turkana's fish populations as well as the abundance of the commercially important fish species and, to this day, remains the most comprehensive study. A snapshot update on the status of the fish stocks was conducted by Muška et al. (2012) in the open water of the central part of the lake through a hydroacoustic survey and supplementary gill net investigation. Around this time, Gownaris (2015), Gownaris et al. (2015) and Gownaris et al. (2017) collected data on the lake's food web and water quality as part of her PhD study from 2011 to 2013. From the limited data that do exist, many ecologically unique and scientifically interesting characteristics have emerged, such as the intimate ties between the lakes' drastic water level fluctuations and its fauna (e.g., tilapia production: Kolding, 1993a; primary productivity: Tebbs et al., 2019; overall fisheries catch: Gownaris et al., 2017), the semi-saline chemistry of the system, the low flora and fauna diversity for its size, a mid-scattering layer of small endemic characins (*Alestes* spp.), and intermittent phenomenal peaks in production of tilapia (*Oreochromis niloticus*) (Kolding, 1993a).

The ichthyofauna of Omo- Turkana basin is dominated by Nilotic riverine species (Lowe-McConnell, 1987; Snoeks et al., 2011).

Thirty of the species found in the lake are spread over the Nilo-Sudan region, eight are found in the lake only and twelve species are endemics, i.e. *Barbus turkanae* (Hopson and Hopson, 1982), *Neobola stellae* (Worthington, 1932), *Brycinus ferox*, *Brycinus minutus* (Hopson and Hopson, 1982), *Chrysichthys turkana* (Hardman, 2008), *Aplocheilichthys jeanneli* (Pellegrin, 1935), *Aplocheilichthys rudolfianus* (Worthington, 1932), *Haplochromis macconneli* (Greenwood, 1974), *Haplochromis rudolfianus* (Trewavas, 1933), *Haplochromis turkanae* (Greenwood, 1974), *Hemichromis exsul* (Trewavas, 1933) and *Lates longispinis* (Worthington, 1932). The endemic species nearly all live in the offshore demersal or pelagic zone (Hopson, 1982, Lowe-McConnell, 1987).

Over the past two decades, fisheries surveys and expeditions have been carried out (KMFRI, 2008; Ojwang et al., 2011), yet few published reports of fishes in the Omo-Turkana basin exist from these later expeditions. Ojwang et al. (2016) noted that the less saline Omo Delta and the fringing riverine wetlands are home to species that are rarely and/or hardly found in the lake proper including species of Mormyridae, Arapaimidae, Gymnarchidae, and Polypteridae. Together with the riverine fish species, the delta hosts representatives of more than 15 different fish families (Ojwang et al., 2011).

Fish spawning migrations are synchronized with the ecoregion's seasonal flooding, which occurs from June through September. During this time, various potamodromous species migrate up the Omo River (*Hydrocynus forskalii, Alestes baremoze, Citharinus citharus, Distichodus niloticus* and *Barbus bynni*) and other ephemeral affluents (*Brycinus nurse, Labeo horie, Clarias gariepinus* and *Synodontis schall*) to breed, for periods of both long and short duration. However, information on these migrations and the ecology of the lake's fishes remains extremely limited and outdated, with little use of current tools and technologies to better understand the system except for the hydroacoustics study completed by Muška et al. (2012) and some stable isotope work completed by Gownaris et al. (2015). In 2011, a study was initiated to examine fine-scale movement data of the lake's tilapia species using acoustic tags, but the acoustic receivers were removed from the lake due to mistrust by local fishers. Given the several anthropogenic activities taking place upstream of the basin (dams, irrigation schemes, deforestation, etc.), these migrations may be seriously impacted or impaired. The endemic planktivorous pelagic fishes are also at risk due to reductions in the primary production of the lake's open waters, which is highly seasonal and driven by nutrient inflow from the Omo River (Tebbs et al., 2019).

While knowledge of the lake's fishes is lacking, even less is known about the lake's other resident fauna and flora. The Omo-Turkana basin supports over 350 resident and migratory bird species, making it an Important Birdlife and Biodiversity Area (BirdLife International, 2021). Yet only two studies have been published on the lake's waterbirds (Fasola et al., 1993; Borghesio and Biddau, 1994). Limited studies suggest 110 phytoplankton species, 32 zooplankton species, and several benthic species (Cohen, 1986; Hopson, 1982; KMFRI, 2008). The algal diversity in the open water is low (ca. 8 main species) and the cyanobacterium *Microcystis aeruginosa* is usually dominating, sometimes to the exclusion of other species (Hopson and Ferguson, 1982; Källqvist et al., 1988). However, *Microcystis* appears uncropped by either fish or crustaceans and most of the primary carbon produced passes through decomposition before being consumed (Hopson and Ferguson, 1982). A pelagic detritus-based food chain, therefore, appears to play an important role in the Lake Turkana ecosystem, and a relatively high proportion of the primary produced carbon might thus be lost to respiration and recycling processes before entering into higher trophic levels and fish production (Kolding, 1992). The importance of organic detritus is reflected in the high abundance of detritivore zooplankton (*Trophodiaptomus banforanus*) (Worthington and Richardo, 1936; Ferguson, 1982; Källqvist et al., 1988) and small, detritus-feeding prawns (*Macrobrachium niloticum* and *Caridina nilotica*) (Hopson, 1982). In addition, the absence of rich benthic fauna and the unusually poor organic carbon content in deep water sediments suggest the recycling of organic matter and nutrients in the open water (Cohen, 1984, 1986; Yuretich, 1976).

Although new species including fish, turtles, and parasites are still being discovered in and around the lake, many species remain incompletely described (Ojwang et al., 2011; Přikrylová et al., 2012). Other aquatic animals in the ecoregion include *Hippopotamus amphibious*, *Crocodylus niloticus*, and an endemic freshwater turtle, the recently discovered and imperiled Turkana mud turtle (*Pelusios broadleyi*). Lakes Abaya and Chamo support notably large populations of *Crocodylus niloticus* and *Hippopotamus amphibious*. Three frog species are endemic to the ecoregion (*Bufo chappuisi*, *B. turkanae* and *Phrynobatrachus zavattarii*). Because many species found in and around the lake are endemic, the ongoing hydrological and environmental changes are likely to threaten their existence (Muška et al., 2012), potentially before they are even discovered. To track and conserve Lake Turkana's biodiversity, key priorities include:

- Identifying and mapping critical habitats, including those rich in fish biodiversity and developing strategies to mitigate human impacts.
- Documenting the biological diversity in Lake Turkana to establish an accurate baseline for future monitoring and environmental impact assessment.
- Updating existing records (e.g., FishBase) to account for this biological diversity.
- Using novel tools and technologies e.g., video cameras, echosounders and multi-beam sonars to develop a more nuanced understanding of the behaviours (breeding, foraging, movement) of the lake's fauna.
- Further investigation of driving forces that can be used to better predict the outcomes of socioeconomic and environmental change in the region.
- Develop the Lake Turkana Management Plan to guide implementation and sustainable resource utilization

Fisheries resources

Subsistence fishing has taken place for at least 10,000 years on Lake Turkana (Owen et al., 1982). Early explorers of Lake Turkana said that the lake had an "inexhaustible wealth of food" and in particular was "marvelous in its fertility of fish" (Neumann, 1898). The first attempts to create a commercial fishery occurred during the 1940s (Kolding, 1989; KMFRI, 2008). Intensive efforts to develop the fishery were initiated during the 1970s and 80s, but international support stopped in the mid-1980s (Kolding, 1989), and the fishery has since remained largely underdeveloped with rudimentary infrastructure and processing facilities. There have been several failed attempts to promote fishing on the lake; for example, a fish processing facility was built on the lake in 1980 but failed by late 1981 due to a lack of access to freshwater resources and insufficient deliveries of fish (Kolding, 1989). On the Ethiopian side, there has never been any large-scale fisheries development support.

The fishery of Lake Turkana is artisanal and practiced mainly by the Turkana, the Dassanech, and the El Molo communities. Fishing activities deploy both traditional fishing vessels (dugout canoes or rafts made from 4 pieces of doum palm logs tied together) and more modern vessels (wooden boats or short-life span fiberglass due to the disintegration by the perennial desert sun). Gears deployed include spears, harpoons, basket traps, multifilament gill

nets of various ply ratings, and, increasingly, monofilament nets of various meshes (KMFRI, 2008). The artisanal and small-scale commercial fisheries concentrate on littoral fish resources, while the pelagic fish community is practically unexploited due to a lack of proper boats and the strong south-easterly winds that blow over the lake (Kolding, 1989; Yongo et al., 2010). Of the 22 species that are regularly caught in the lake, 17 support the commercial fishery. Only 8 species, namely *Alestes baremose, Oreochromis niloticus, Lates niloticus, Lates longispinis, Labeo horie, Hydrocynus forskahlii, Distichodus nefasch, Citharinus citharus,* and *Synodontis* spp. contribute to over 80 % of the fish landed by tonnage and value (KMFRI, 2008).

There is a lack of an effective and consistent monitoring plan for Lake Turkana's fish stocks. Even when fisheries data do exist, they are not readily available, and their reliability is questionable (Fig. 4). These data are collected from the lake's Beach Management Units and are dependent on reporting by these units, which generally does not include catches for local consumption or fishes captured with illegal mesh sizes. Due to the large size of the lake and the relative dearth of available fisheries officials, not all landing beaches are covered by this monitoring. As a result, the true catch on the lake since the late 1980s is likely to be at least double that reported here (Fig. 4) and in the Annual Statistical Fisheries Bulletin. In some years, the difference between the official statistics and reported statistics is much larger. For example, local officials who are members of this expert group recounted a year where local estimates of fisheries catch were 10,000 MT, while the Fisheries Bulletin reported catches of 500 MT. In addition to the limitations above, Lake Turkana fisheries data are generally very coarse, lacking information on seasonal and spatial trends and species composition. Effort data are similarly uncertain. For example, though we know that effort has increased on the lake as fishing has become a more widespread livelihood in the region, fisheries records from 2004 to 2015 suggest no change in the number of fishers (Fig. 4). Because the standing fish biomass and potential production are unknown, the few historic estimates of maximum sustainable yield range with a factor of 10—from 15,000 to 150,000 tons per year (Kolding, 1989). Bayley (1977) labeled these predictions to be "at worst very mistaken and at best very conditional". In any case, the lake's resources remain underexploited (Kolding et al., 2019). In addition to the potential for local use, there is increased demand for salted sun-dried fish, the main method of preservation for Lake Turkana fishers, in the Democratic Republic of Congo.

There are strong indications that the standing biomass and fisheries productivity fluctuates with the lake levels, which must be taken into account when considering the lake's potential yield (Kolding, 1989; 1992; 1993a,b; Gownaris et al., 2017). Recent pelagic fish density estimates are lower than those from the 1970s and 1980s (Hopson, 1982[§]), but the overall biomass indices remain relatively unchanged (Muška et al., 2012). The lake's fisheries composition and production changes spatially and seasonally (Kolding,

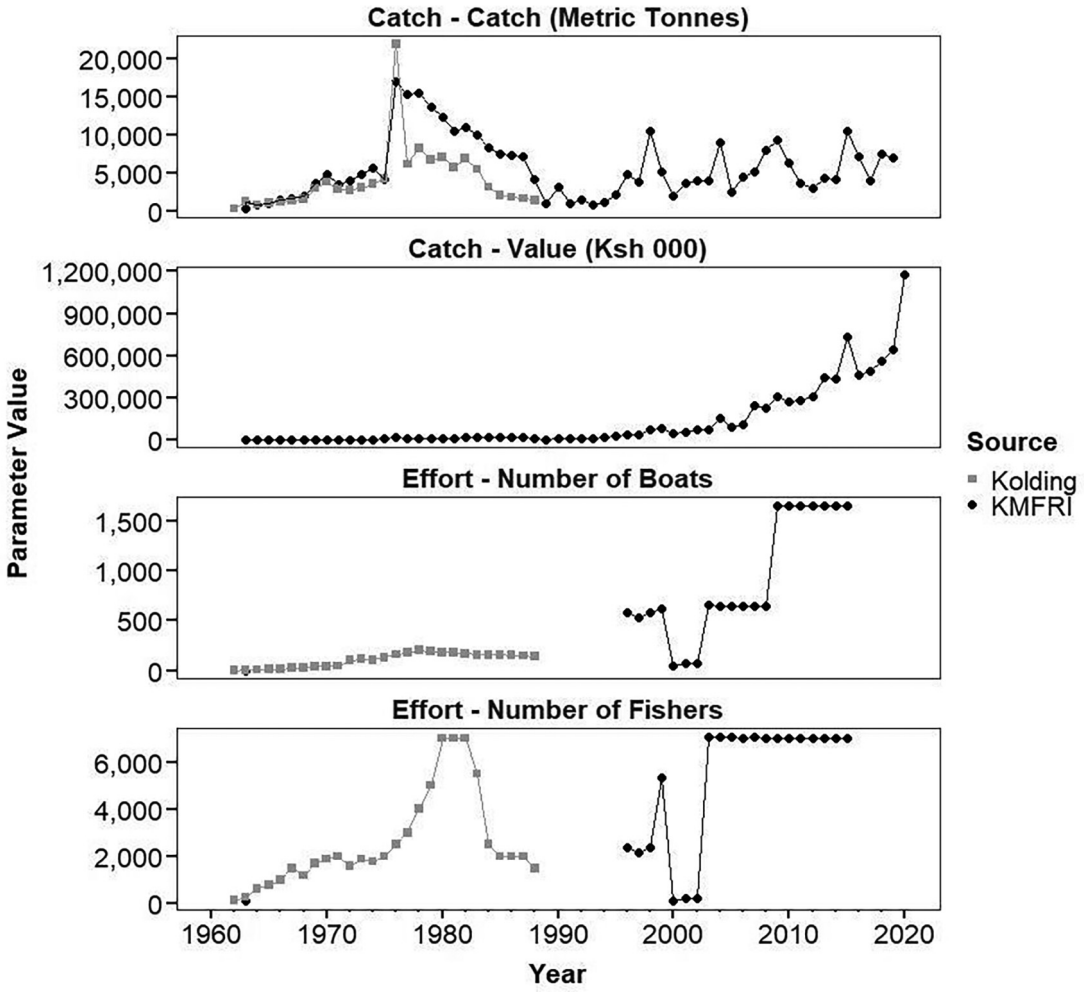

Fig. 4. Trends in Lake Turkana's fisheries showing catch and value and effort in terms of the number of boats and fishers from 1960 to 2020. Data Sources: KMFRI (2008); Kolding (1989).

1992), and the lake fauna composition and structure seem to undergo strong interannual changes (Kolding, 1993b, 1995), but data on these patterns and their drivers are lacking. For example, there is some evidence that the lake's small, endemic fishes, which act as a key food web link and diet item for predatory fishes like Nile perch, have declined and have been replaced by the generalist catfish *Synodontis schall,* which cannot easily be consumed due to its large pectoral spines (Muška et al., 2012, Gownaris et al., 2015).

In addition to a lack of adequate and reliable data to guide sustainable use and optimize the fishery, several other factors limit the use of this resource. Fishers do not have access to proper markets or methods to preserve their catch. Consequently, they are forced to sell their products, even high-value fishes such as Nile perch, at very low prices often to the traders or local restaurants (Getahun et al., 2020), and there are high rates of postharvest loss (up to 60 %; KMFRI, 2008). The major reasons for the postharvest loss are contamination by sand and a slow drying process, resulting in a low-quality final product with a short shelf life. There have been efforts to introduce improved, low-cost fish drying systems (KMFRI, 2008). In Ethiopia, a recent study indicates that the socioeconomics and management conditions of fisheries are poor with only a few NGOs providing minimal support to the fishers via provisions of a fishing boat, gears, and refrigerators (Getahun et al., 2020). Moreover, the effective development of fisheries in these localities is marred by sporadic conflicts arising between the Ethiopian and Kenyan fishers in an apparent competition over a fertile fishing ground and a lack of effective management measures (Getahun et al., 2020; Yongo et al., 2010).

Beyond managing the lake's fishery, there also remain understudied implications for public health in the region. Tropical contaminant research and ecotoxicology is an emerging field, particularly in Africa where published research is scarce. Major contaminants causing concern are lead and mercury. Previous studies by Campbell et al. (2003) have consistently indicated low concentrations of total mercury (THg) in *Lates niloticus* and other important fish species from Lake Victoria and other East African lakes. In Lake Turkana, two *Hydrocynus forskahlii* had high THg concentrations (490 and 636 ng g^{-1}) which are above the international marketing limit of 500 ng g−1 (Campbell et al., 2003). Because of the importance of the fishery to both domestic consumption and export, any exposure to mercury is a primary concern.

To optimize the Lake Turkana fishery, key knowledge and management priorities include:

- Developing reliable and relatively easy-to-track indicators of fish stock status and providing adaptive estimates of sustainable yield based on these indicators.
- Investigating the drivers of spatial and temporal (short-term and long-term) variability in fish stock productivity, value, and composition.
- Determining how to optimize the use of the lake's fish resources (e.g., balance littoral and pelagic fishing, set species-specific targets, improve fish preservation techniques).
- Minimizing conflict that leads to unequal access to fish resources.
- Monitoring levels of mercury and other contaminants in fish stocks.

Land use and habitat destruction

Recently, Lake Turkana has been thrust into the spotlight due to the discovery of oil through test drilling, which identified considerable commercial quantities of hydrocarbon trapped in the geological structures of the Turkana Rift basin (Ojwang et al., 2016). In addition, significant investments in constructing a cascade of Gibe dams to expand hydropower and support extensive irrigation projects is likely to impact several water-related sectors both in Ethiopia and Kenya (Table 2), yielding social and international tensions (Guiliani et al., 2022). The construction of a new mega-dam named Koysha started in 2016 with an installed capacity of 2200 MW to the cascade. The Ethiopian government is also planning to develop large-scale agricultural production in two separate districts, with about 175,000 ha designated for irrigated sugar cane plantations, recently reduced to 100,000 ha, and about 80,000 ha for private commercial irrigated agriculture (Avery and Eng, 2012; Guiliani et al., 2022).

Even though the constructions of dams and related irrigation projects on the Omo River have significant socio-economic importance (Guiliani et al., 2022), they have also had an impact on the ecology of the aquatic biota and the riparian environment. The change from a lotic to a standing reservoir system in the vicinity of the dam will result in an altered aquatic food web involving change of dominant functional groups and the establishment of disease vectors such as mosquitoes and snails in such systems. There will be impacts on the natural vegetation during the construction phase of the dams and irrigation projects. These impacts are related to the physical clearance, or disturbance, of natural vegetation for the operation of quarry and burrow areas, construction of access roads, construction of temporary campsites, etc. In addition, nutrient-rich suspended run-off material will sediment inside the dams and no longer reach the lake. The Lake Turkana ecosystem is inextricably linked to the activities occurring nearby on land.

Future development plans include the Lamu Port South Sudan Ethiopia Transport Corridor (LAPSSET) and related development (roads, railways, pipeline, powerlines, and resort cities) that will strategically connect northern Kenya with emerging markets in South Sudan. These major development projects are likely to strongly affect existing resources (water, land and livestock) and create new resources in the form of revenues, business opportunities, employment and infrastructure (Cormack and Kurewa, 2018; Schilling et al., 2016). Lind et al. (2020) reported that infrastructure developments and investments have already ignited intense competition for and revaluation of land, as local elites, and other domestic and foreign investors, jostle to claim tracts of land. The authors argue that the likely impacts from investment project on land range from the consequences of speculation and the economies of anticipation to the direct results of dislocation and dispossession, to the indirect effects on local economies, employment opportunities and service provision. Further, unmet community expectations for water, employment and development pose a significant risk for violent conflict between local communities and the operating oil company (Schilling et al., 2015). Therefore, to decrease the conflict potential and to maximize benefits, it is critical for any project to closely include the local communities in a fair and transparent manner. Therefore, to understand the lake ecosystem requires:

Table 2
Dams and power plants of the Gibe cascade. (Data source: Guiliani et al., 2022)

Dam	Year of construction	Hydraulic Head (m)	Installed/planned capacity (MW)
Gibe 1	1999-2004	40	180
Gibe II (power plant)	2004-2009	550	420
Gibe III	2006-2015	250	1870
Gibe IV	Not built	-	1470
Gibe V	Not built	-	560
Koysha	2016- In progress	178.5	2200

- Monitoring and research to generate information that will support informed sustainable management of the aquatic resources by various stakeholders in agriculture, conservation, livestock, fishery, power production and urban development sectors.
- Further investigation of the synergistic effects of all ongoing development in the region.
- Creating avenues for productive discussions among stakeholders to reduce resource use conflict.

Overarching recommendations

Though we have separated the research and management needs for Lake Turkana into themes above, meeting any of these needs will require large-scale changes to harmonize research approaches and infrastructure in this region. This section describes our overall recommendations for sustainably managing Lake Turkana's aquatic resources, wildlife and livelihood support systems. These overall recommendations include local capacity building, standardized and accessible monitoring systems, sustainable financing, and strengthening collaborative networks. A matrix of Lake Turkana issues and suggested management strategies for long term sustainable resource use is presented in Table 3.

Capacity building

To address key knowledge gaps and sustainably manage and conserve Lake Turkana resources, it is necessary to have trained experts to improve the ability of decision-makers and scientists to respond to the complex, multifaceted challenges that are rapidly arising in this region. There is a need to train professionals and the necessary resources to conduct various monitoring and research studies, including frame surveys, water quality monitoring, and fish stock and environmental impact assessments. Frame surveys includes the number of landing sites, boats, fishing gears, processing facilities, and fisheries related service found near the landing sites (Plisnier et al., 2023). Local communities and institutions should be empowered with the necessary skills and facilities so that they are aware of the aquatic resources and actively participate in co-managing the resources, including planning and implementation of planned activities. These facilities would enable coordinated and sustained research at both sides of the lake (Kenya and Ethiopia) to guide informed lake-wide decision-making processes.

Given the harsh and arid environment of the Lake Turkana region, where people live on the edges of the natural carrying capacity, competence building for monitoring and assessing climate change adaptation is greatly needed. In addition, greater research cooperation between Kenyan and Ethiopian scientists is required to strengthen international links in this transboundary basin. There is currently no gathering of regular data from the lake and the rivers. The only institutions of higher education in the region include Turkana University College located 60 km from the lake and the recently established Jinka University, located more than 250 km from the lake. There also exists KMFRI, the main government agency for innovative research in marine, fisheries and the Blue Economy which has a station located 5 km from the lake, and the Turkana Basin Institute, which focuses on paleoanthropology and is located 100 km from the lake (Table 4). Though their work is crucial, these government institutions and the officers tasked with research and resource management are not equipped with sufficient human capacity, skills, and facilities to conduct accurate and monitoring and environmental impact assessment studies.

Technical resource capacity can be improved by modernizing existing research stations and to support and train technical personnel to ensure successful long-term monitoring and gauge the implications of climate change. The foreseeable impacts of the hydropower projects such as the ones on River Omo (Avery, 2012; Tebbs et al., 2019) should motivate ecological and limnological research and monitoring to document and evaluate the impacts. Effective environmental education and improved communication between scientists, policymakers, and the public is also required to raise awareness of environmental issues and disseminate research findings. There is an urgent need to strengthen and modernize the existing KMFRI facility in Kalokol and to establish a new research station in Ethiopia at the shore of Omo River at Omorate.

Initiatives for community-based capacity building could greatly alleviate the problems with the management practices in Lake Turkana. This would first call for tactics including performing training requirement assessments, involving stakeholders in capacity development, and putting capacity development measures into action. To establish trust, confidence, and promote cooperation for ecosystem restoration, transboundary water management (TWM) capacity building and conversation activities are required. Strategies like sustainable irrigation and lake water abstraction could help maintain a stable water level as the effects of climate change become more apparent. Additionally, education on reforestation initiatives and water and soil conservation programs could lessen the effects of climate change. However, to direct planning and development activities at the basin size, these plans call for a competent framework for stakeholder interaction.

Consistent monitoring and data sharing

Short-term research efforts in the Omo-Turkana region lack standardized sustainable approaches, resulting in inconsistent and incomparable scientific data. The disjointed nature of country-and-regional specific datasets hinders evidence-based formulation and implementation of regulations, policies, and conservation actions (Obiero et al., 2020). The limited data collected by local research organizations are scattered, haphazard, insufficiently processed, documented and stored, and thus largely inaccessible. Similarly, published and unpublished data collected by international researchers have not been collated and systemized since the mid-1980 s. Scientists working in the Omo-Turkana region have persistently voiced the need for a standardized and centralized repository of user-friendly data on this system (Obiero et al., 2020).

It is also necessary to ensure that both Kenyan and Ethiopian universities, research stations, and governments harmonize efforts and work together in collaboration with international researchers to have research and data that is more comprehensive, comparable, accessible, has fewer gaps and hence minimizes duplication of efforts in the region. A necessary first step is collating the data that do exist into one central repository that can be easily accessed by local scientists, which would help to motivate synthesis studies and novel research. Cooperative approaches to any bi- or multinational resource are essential to adequately address the issues on these shared resources.

Lake Turkana is the least studied of the Great African lakes, and the collection, analysis, dissemination and use of data and information are central for fisheries management. To support this, a regular program on stock monitoring, assessment and investigation of ecosystem interactions aimed specifically at providing management advice on the key lake fisheries must be undertaken. Socioeconomic monitoring and studies should be carried out to assess the impact of upcoming challenges related to climate change, hydropower dam construction, and population growth. Furthermore, information from fish marketing surveys in major supply areas and information on regional and domestic fish trade will complete the essential sources of information from the fish pro-

Table 3
A matrix of Lake Turkana issues and suggested management strategies for long term sustainable resource use

Thematic Area	Critical driving forces and pressures	Strategic management recommendations
Biodiversity and Ecosystem Status	■ Limited studies and publications on biological diversity and fisheries of the Lake Turkana basin. ■ Extremely limited and outdated information on potamodromous fish species migration and the ecology of the lake's fishes. ■ Lack of knowledge on the lake's fishes and other flora and fauna, including basic functioning of the ecosystem. ■ Human-induced rapid hydrological and environmental changes in the Lake Turkana basin.	■ Documenting the biological diversity in Lake Turkana basin to establish an accurate baseline for future monitoring and environmental impact assessment ■ Updating existing records (e.g., FishBase) to account for this biological diversity ■ Using novel tools and technologies to develop a more nuanced understanding of the behaviors (breeding, foraging, movement) of the lake's fauna. ■ Developing ecosystem models to better predict the outcomes of socioeconomic and environmental change in the region. ■ Capacity building to monitor and assess climate change adaptation. ■ Enhancing research cooperation between Kenyan and Ethiopian scientists and strengthen international linkages. In part, by raising awareness of the lake and its unique environs among the international community. ■ Strengthening the existing Kenyan research facility in Kalokol and establishing a new research station in Ethiopia at the shore of Omo River at Omorate. ■ Enhancing technical resource capacity by modernizing existing research stations and training technical personnel to ensure successful long-term monitoring, gauge climate change implications and develop appropriate adaptation strategies. ■ Local expert's trainings (decision makers and scientists) for increasing response and adaptation capacities to the challenges arising from changing climatic conditions. ■ Empowering local communities with the necessary skills and facilities to enhance awareness of their resources and actively participate in its well-being, including planning. ■ Lobbying for sustainable funding schemes on a local level, especially to the research institutions to support livelihoods, research and management of Lake Turkana basin.
Fisheries Resources	■ Lack of effective and consistent monitoring plan for Lake Turkana's fish stocks. ■ Unreliable and inaccessible fisheries data in the Lake Turkana basin, which is generally coarse, lacking information on seasonal trends and species composition ■ Lack of data on the standing fish biomass (fluctuating with varying lake levels) and potential productivity (patterns and their drivers), aggravating unsustainable use of the fisheries and other lake resource. ■ Reducing fish stocks due to use of unregulated fishing gears such as spears, harpoons, basket traps, multifilament gill nets of various ply ratings, and, increasingly, monofilament nets of various meshes. ■ Lack of proper markets or methods to preserve catches leading to low prices by the local fishermen. ■ High rates of post-harvest losses due to contamination by sand and a slow drying process, resulting in a low-quality final product with a short shelf life. ■ Sporadic conflicts between the Ethiopian and Kenyan fishers over a fertile fishing ground and lack of effective management measures. ■ Lack of tropical contaminant research and ecotoxicology ■ Lack of standardized approaches for short-term research efforts resulting in inconsistent and incomparable scientific data and datasets hindering evidence-based formulation and implementation of regulations, policies, and conservation actions in Lake Turkana basin. Inadvertently, published and unpublished data collected by international researchers have not been collated and systemized	■ Developing reliable and relatively easily tracked indicators of fish stock status and providing adaptive estimates of sustainable yield based on these indicators. ■ Understanding the drivers of spatial and temporal (short-term and long-term) variability in fish stock productivity, value, and composition. ■ Determining how to optimize use of the lake's fish resources (e.g., balance littoral and pelagic fishing, set species-specific targets, improve fish preservation techniques). ■ Minimizing conflict that leads to unequal access to fish resources. ■ Monitoring levels of mercury and other contaminants in fish stocks. ■ Train professionals to conduct various monitoring and research inquiry e.g., frame surveys, water quality monitoring, and fish stock and environmental impact assessments, among others, to be able to sustainably conserve, utilize and manage the aquatic resources of Lake Turkana. ■ Creating cooperative approaches for developing central online data depository system that can be easily accessed by local scientists, which would help to motivate synthesis studies and novel research. ■ Ensuring that both Kenyan and Ethiopian universities, research stations, and governments harmonize efforts and work together to have research and data that is more comprehensive, comparable, and have fewer gaps ■ Implementing regular program of work on stock assessment and investigation of ecosystem interactions to providing management advice on the key lake fisheries. ■ Undertaking socio-economic monitoring and studies to assess the impact of emerging challenges related to climate change, hydro- power dam construction, and population growth. ■ Packaging and disseminating information and data gathered to all stakeholders in appropriate forms and in a timely manner i.e., websites, briefs, newsletters etc. ■ Acquiring sustainable financing of the fisheries institutions to facilitate management, including resource and socio-economic monitoring. ■ Advocating for increased engagement of and collaboration with local fisheries, students, and other community members.
Limnology and Ecohydrology	■ High salinity and alkalinity of the lake's water make it unsuitable for drinking and irrigation and limits biodiversity. ■ Unpredictable and disruptive rainfall, resulting in sudden flash floods of ephemeral rivers, sweeping trees, animals, and even displacement of people. ■ Changes in the volume and seasonality of inflows from the Omo River, significantly influencing the ecology of lower Omo River and Lake Turkana.	■ Linking environmental variation to variation in the lake's ecology ■ Regular monitoring of environmental conditions, including water levels, nutrient levels, and salinity ■ Modeling of potential future environmental states given ongoing hydrological change at local to global scales. ■ Implementing ecological and limnological research and monitoring to evaluate impact and gather data for improved communication between scientists, policy makers and the general public. ■ Undertaking monitoring studies to assess the impact of emerging challenges related to climate change, hydropower dam construction, and population growth. ■ Strengthening bilateral arrangements for funding biodiversity and environmental conservation, fisheries management, water resources, planning, development and assessments in Lake Turkana basin.

(*continued on next page*)

Table 3 (*continued*)

Thematic Area	Critical driving forces and pressures	Strategic management recommendations
Land Use	▪ Alteration of Lake Turkana's ecosystem balance due to increasing development (water abstraction, oil exploration, wind and hydropower productions and the development of a resort city) with high demands for land marred with concerns over indigenous land rights, access to resources, and uncertain identification of the projects. ▪ Facilitated run-off and further accumulation of sediments in the Omo River and ultimately in Lake Turkana through impacts of clearing natural vegetation during construction phase of the dams and irrigation projects. ▪ Resource use conflicts between fishers and conservationists resulting from fishing in protected areas. ▪ Species loss, soil loosening, rapid erosion and sediment transportation into the lake due to slashing and burning of the available few wetlands and macrophytes dominated areas to support shifting farming and for livestock access. ▪ Lack of information on land use and habitat degradation leading to destruction of habitats for both juvenile, breeding and foraging fishes in Lake Turkana basin.	▪ Monitoring and research to generate information that will support conflict reduction, informed sustainable management of the aquatic resources by various stakeholders in agriculture, conservation, livestock, fishery, power production and urban development sectors ▪ Reducing conflicts and empowering stakeholders ▪ Undertaking Socio-economic monitoring and studies for assessing the impact of emerging challenges related to climate change, hydro- power dam construction, and population growth ▪ Implementing ecological and limnological research and monitoring to evaluate impact and promote effective environmental research and education and improve communication between scientists, policy makers and the general public. ▪ Prioritize local population welfare, ecosystem research and management in awareness raising.

duction chain. The information and data gathered must be packaged and disseminated appropriately to all stakeholders in appropriate forms and on time. A new website can be developed containing all information related to Lake Turkana research activities for dissemination and should be regularly updated and maintained.

Currently, biodiversity data on the Omo-Turkana ecosystem is insufficient to adequately determine conservation priorities and to define baseline conditions from which to track the impacts of ongoing perturbations. There is a need to establish and empower information hubs for the acquisition, mobilization, integration and provision of data across all areas of freshwater biodiversity research on the Lake Turkana. This can be accomplished through development of an open-access repository of information on the biodiversity distribution of the Omo-Turkana ecosystem and the environmental drivers of these distributions according to the FAIR principles of Findability, Accessibility, Interoperability and Reusability (Wilkinson et al., 2016). The end-users of this open-access database include fisheries officers, researchers, conservationists, academicians, and other local and international stakeholders. Coupled with this is the need to build capacity by training local research organizations and university students in collecting, cleaning, and analyzing biodiversity data using open-source programs, thereby reducing barriers to ongoing data collection. These efforts will improve decision-making in the Lower Omo-Turkana region and promote understanding and conservation of this understudied, rapidly changing ecosystem by improving access to, and use of, data on biodiversity and its drivers.

The Omo-Lake Turkana basin is under immense pressure from human-related activities including unsustainable agriculture, climate change, oil and drilling activities, deforestation and riparian land degradation, water pollution, overexploitation of natural resources including through illegal fishing, and the introduction of invasive non-native species. Therefore, managers and researchers need a set of ongoing indicators to evaluate trends in socioeconomic and environmental changes to better understand those complex ecosystems. The socio-economic monitoring should focus on collection of information on fishers (population statistics, income), fish abundance, size and prices at the market (main species), specific surveys (variable topics related to fisheries, lake and human population) as indicators of anthropogenic pressure and surveys linked to the human environment related to the lake (Plisnier et al., 2023).

Short-Term and Sustainable Funding

Sustainable financing of the fisheries institutions is essential to facilitate resource management, including regular environmental and socio-economic monitoring. Three of the 'Great Lakes of the World' (Victoria, Malawi, Tanganyika) have received Global Environment Facility funding and other support sionce the 1990 s through bilateral arrangements for biodiversity and environmental conservation, fisheries management, water resources, planning, development and assessments (Ogutu-Ohwayo and Balirwa, 2006). In part, this goal will require raising awareness of the lake and its unique environs among the international community. For Lake Turkana, similar to other Great Lakes, the immediate welfare of the population is a priority, and ecosystem research and management can be justified in this context. There is a need to obtain sustainable funds on a local level, especially to the research institutions to support the research and management of Lake Turkana. Funding requests should focus on building capacity for long-term, consistent research into Lake Turkana that is driven by local-scale engagement (e.g., local outreach, building local scientific human capacity, infrastructural development).

Table 4
Role of national institutions/organizations and actors related to Lake Turkana in Kenya and Ethiopia (L= Lake; B = Basin). Modified from Plisnier et al., 2023.

Institution/Organization	Mandate and Role	Fisheries	Biodiversity	Water	Land Use	Socioeconomics	Climate
Kenya							
Kenya Marine and Fisheries Research Institute (KMFRI) https://www.kmfri.co.ke/	Generate and disseminate scientific data and information for sustainable development of fisheries and aquaculture resources	L + B	L + B	L + B		L + B	L + B
Kenya Fisheries Service (KeFS) http://www.kenyafisheriesservice.go.ke/	Conserve, manage and develop Kenya fisheries and aquaculture resources	L					L + B
State Dept for Fisheries, Aquaculture & The Blue Economy (SDFA&BE) https://kilimo.go.ke/	Co-ordinate development of policy, legal, regulatory and institutional framework for the fisheries industry and the blue economy	L		L		L	L + B
Kenya Coast Guard Service (KCGS) https://kcgs.go.ke/	Enforce maritime law on security, safety and protection of maritime resources within Kenya's	L					L + B
Turkana County Government (Department of Fisheries) https://www.turkana.go.ke/	Provide an enabling environment for the development of the fisheries subsector	L	L				L
National Museums of Kenya https://www.museums.or.ke/	Collect, preserve, study, document and present Kenya's past and present cultural and natural heritage		L + B				L + B
Kenya Wildlife Service (KWS) http://www.kws.go.ke/	Conserve and manage wildlife in Kenya, and to enforce related laws and regulations.	L	L + B	L		L + B	
National Environment Management Authority (NEMA) https://www.nema.go.ke/	Ensure sustainable management of the environment through exercising general supervision and coordination over matters relating to the environment		L + B	L + B		L + B	
National Land Commission (NLC) https://www.landcommission.go.ke/	Secure and manage public land and exercise oversight on use of land for the benefit of all Kenyans				B		
Water Resources Management Authority (WARMA) https://wra.go.ke/	Manage and develop water resources in the whole country and ensure equal access to water for the various stakeholders	L + B					L + B
Kerio Valley Development Authority (KVDA) https://kvda.go.ke/	Initiate, plan and develop resources along the Kerio River basin.	L		L + B	B	B	
Turkana University College https://tuc.ac.ke/	Research and community outreach and engagement						
Friends of Lake Turkana https://www.friendsoflaketurkana.org/	Foster participation of indigenous communities to achieve social and environmental justice	L + B	L + B	L + B	L + B	L + B	
Turkana Basin Institute (TBI) https://www.turkanabasin.org/		L + B	L + B	L + B	L + B	L + B	L + B
Turkana University College (TUC)		L + B	L + B	L + B	L + B	L + B	L + B
Ethiopia							
Jinka University https://www.jku.edu.et/	Research and community outreach and engagement	L + B	L + B	L + B	L + B	L + B	L + B
Jimma University https://ju.edu.et/	Research and community outreach and engagement	L + B	L + B	L + B	L + B	L + B	L + B
Addis Ababa University http://www.aau.edu.et/	Research and community outreach and engagement	L + B	L + B	L + B	L + B	L + B	L + B
Ministry of Agriculture (Livestock and Fisheries Department) http://moa.gov.et/	Extension and policy issues	L + B			L + B	L + B	L + B
Ministry of Water and Energy https://www.mowe.gov.et/	Water level/flow control, flooding and irrigation uses			L + B		L + B	L + B
Daasanach Woreda (District) Administration	Overall administration, close regulation of activities over the lake	L			L + B	L + B	L + B
Daasanach Woreda (District) Cooperative Office	Organization and management of Fishermen's Cooperatives	L			L + B	L + B	L + B
Kenya and Ethiopia							
Omo-Turkana Research Network (OTuRN) https://www.canr.msu.edu/oturn/	Research impacts of hydrological, agricultural, and social change on the people and ecosystems surrounding the Lower Omo Valley and Lake Turkana	L + B	L + B	L + B	L + B	L + B	L + B

Strengthened collaborations

Transboundary cooperation on the regional, national and local management of land and aquatic resources has great potential for creating long-term benefits for both upstream and downstream users of the Lake Turkana Basin. Recently formed collaborative research networks within the region and beyond (e.g., LTuAG, the Omo-Turkana Research Network) have an excellent potential for efficiently advancing knowledge on Lake Turkana through harmonized information sharing, a collective agreement on priorities and reduced redundancies. Several institutions and organizations in Kenya and Ethiopia are involved in gathering information related to fisheries, water quality, biodiversity, land use, climate change and socioeconomics (Table 3). The need for collaboration, however, extends beyond the scientific to the borderland communities. Activities such as early warning systems for floods and rehabilitating degraded land could benefit from a coordinated borderland approach. While the potential for unmanaged exploitation of natural resources, and conflict, is high, there is scope for transboundary collaboration given that cultural practices often have stronger regulatory force than national laws in the region. Noteworthy, is that different ethnic groups have shared livelihood practices and cultural values for generations, hence there is potential to find common ground and work together on joint initiatives. There is potential for peacebuilding through transboundary community-based natural resources management in borderlands. There is also a need for increased engagement of and collaboration with local fishers, students, and other community members and awareness creation through citizen science by holding discussions with key stakeholders on a micro-catchment level. Citizen science is the non-professional involvement of volunteers in the scientific process, commonly in data collection, but also in other phases, such as quality assurance, data analysis and interpretation, problem definition and the dissemination of results (De Rijk, 2020). Integration of, for example, citizen science apps like e-Bird (Faizah et al., 2021), which are commonly used elsewhere in Africa, is critical since there are currently very few observations in the Omo-Turkana region.

Conclusion

Lake Turkana is the fourth largest but least studied of the African Great Lakes, and there are still major gaps on even the basic functioning of this ecosystem, which is distinctly different from the other Great African lakes in most physical, chemical and biological features. A lack of baseline data and ongoing monitoring make it nearly impossible to track changes and develop sound decisions on how to optimize the use of the lake's resources. Yet, this lake offers immense promise; its unique ecosystems make it scientifically interesting, and its fisheries have the potential to increase food security in a highly food insecure region. To reach the expert-identified goals that we have listed in this review will require improved capacity, standardization, accessibility, financing, and collaboration. An updated management plan for the lake, guided by the priorities outlined above, should be developed as soon as possible, and made available for discussion among all local, national, regional and international stakeholders.

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.2022.10.007.

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