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Challenges and strategies for management and conservation of water resources and freshwater biodiversity in the Lake Victoria Basin

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The Lake Victoria Basin (LVB) is an important economic growth zone, sustaining the livelihoods of more than 42 million people. The economies of the five countries in the LVB (Burundi, Kenya, Rwanda, Tanzania and Uganda) rely heavily on the rich array of natural resources and ecosystem services provided by the basin. However, significant alterations of terrestrial and aquatic ecosystems have occurred over the past century. This human-led transformation is evident in the areal reduction of native vegetation and wetlands, giving way to expanding agriculture and human settlements. Human activities have further manifested in observable declines in water quality, unregulated water abstractions, eutrophication, infestation of exotic and invasive species, dwindling fisheries, and biodiversity declines. These challenges are exacerbated by growing conflicts over resource access and use, and shortcomings in policies, laws, and institutional structures, posing unsustainable threats to ecosystem vitality and resilience. To address these multifaceted challenges, comprehensive management strategies are essential for the well-being of future generations. This paper critically reviews existing literature, elucidating the primary human impacts and threats jeopardizing water resource sustainability and biodiversity conservation in the LVB. It also proposes corresponding management measures to either be implemented or enhanced, aiming to counteract the ongoing degradation of natural resources and safeguard biodiversity. Coordinated management actions at the river catchment and regional scales are imperative, operating within the frameworks of regional cooperation. Priority should be accorded to a cohesive Integrated Water Resources Management (IWRM) approach, reinforced by harmonized regional laws and regulations. Emphasizing participatory approaches through co-management, enhanced gathering and dissemination of research findings, mainstreaming climate change considerations, implementing sustainable environmental monitoring protocols, and introducing novel strategies like

Payment for Ecosystem Services (PES) are crucial steps to reduce reliance on donor funds. The paper also underscores the need for additional research to bridge existing knowledge gaps concerning the status of water resources and biodiversity conservation in the region.

KEYWORDS

human threats, biodiversity conservation, lakes, rivers, management strategies, water quality, ecosystem services, freshwater ecosystems

1 Introduction

Worldwide, freshwater ecosystems have witnessed the greatest transformation, leading to significant reductions in biodiversity, ecosystem structure and function and a decline in ecosystem services (Dudgeon et al., 2006; Reid et al., 2019). Parallel to this transformation, the complexity of social, economic, and ecological demands has increased, exerting multiple, and often interlinked, stressors on aquatic ecosystems at different spatial and temporal scales (Ormerod et al., 2010; Sabater et al., 2019; Birk et al., 2020). Major stressors on freshwater ecosystems are due to human population growth, land use and land cover changes, waste disposal, over-abstraction of water resources (both surface and groundwater), introduction of alien species, and overextraction of natural resources such as overfishing (Allan, 2004; Vörösmarty et al., 2010; Nyamweya et al., 2023a). Other emerging threats to freshwater biodiversity include changing climates, infectious diseases, eutrophication and harmful algal blooms, expanding hydropower, emerging contaminants, engineered nanomaterials, micro- and nano-plastic pollution, light and noise pollution, freshwater salinization, declining calcium and multiple stressors (Reid et al., 2019; Ahmed et al., 2022). In the face of these threats, the challenge is increasingly one of reconciling human needs, attitudes and perceptions with ecological requirements of healthy and resilient ecosystems, while also considering their critical role in support of aquatic biodiversity (van Rees et al., 2021; Bonar, 2021).

For over a century, the Lake Victoria basin (LVB) has experienced fundamental changes to both terrestrial and aquatic ecosystems. This is exemplified by declines in the extent of native vegetation and wetlands to expanding agriculture and human settlements, introduction of exotic species and pollution of surface waters (Verschuren et al., 2002; Hecky et al., 2010; Masese and McClain, 2012). These developments have resulted in significant declines in the integrity of water resources and are a threat to biodiversity (Ogutu-Ohwayo, 1990; Darwall et al., 2005; Sayer et al., 2018). This jeopardizes the potential of these systems to sustain ecosystem services deriving to over 42 million people in the LVB (Nyamweya et al., 2023a). For effective management of aquatic resources in the LVB, there is a constant need to update our knowledge on the changing relationships between human activities and the well-being of ecosystems. Several studies have looked at different aspects of freshwater ecosystems in the LVB that have given a broad understanding of their structure and functioning, and how they are responding to the multiple stressors arising from the human use of the basin (Chapman et al., 2022; Njagi et al., 2022; Nyboer et al., 2022).

The development and livelihoods of majority of the citizens of emerging economies overwhelmingly depend on the sustainable use of freshwater ecosystems (Nel et al., 2011; Barbier, 2019). Most countries in the LVB have established common principles and structures for sustainably managing water resources, regional cooperation, and protection of the environment. However, there is often a disconnection between management guidelines and the development plans of individual countries, including expanding the area of irrigated agriculture, building of dams and increasing overall water use for agriculture, industry and hydropower (McClain, 2013). Given these pressures, sustainable water use in many African countries is becoming a major concern, since many people in rural areas depend almost entirely on the integrity of freshwater ecosystems to support their livelihoods and sustenance.

This review explores the current status of aquatic ecosystems in the LVB in terms of the major threats or challenges they face, and at the same time, presents management strategies to mitigate these threats. The review also explores future research needs to fill the gaps in our current understanding of the influence of human activities on the well-being of ecosystems in the LVB. The target audience of this review include postgraduate students of fisheries and aquatic sciences, academicians, aquatic ecologists, environmental practitioners, land use planners and water resource managers.

2 Survey methodology

To compile this review, we searched published literature in Scopus, PubMed, Web of Science, Google Scholar and OpenAlex. We searched for studies and reports on human impacts or threats on water resources and biodiversity in the LVB. To obtain relevant results, we used the Boolean Operators: ((Lake Victoria OR Lake Victoria basin) AND (pollution OR degradation OR human impacts OR threats OR biodiversity loss OR land use change OR overharvesting OR habitat loss OR eutrophication OR invasive OR exotic OR introduced) AND (wetland OR river OR stream OR lake) AND (threatened, vulnerable, red list, endangered)). The survey was conducted by searching titles, keywords, and abstracts. Where possible, we ordered the search results by relevance. We retained peer-reviewed publications that discussed the mentioned impacts on water resources and biodiversity in streams, rivers, wetlands and lakes in the LVB, including Lake Victoria. Given that this review focuses on surface waters, publications pertaining to groundwater were excluded. Furthermore, only studies published in English were considered. Although the search period was restricted to between 1990 and 2024, relevant literature and citation classics published prior to the year 1990 were also included, but these were not many.

Data extracted from the selected articles included information on human threats or impacts to water resources and aquatic biodiversity in the LVB and suggested management measures for their sustenance. The papers were analyzed to identify the main threats to water resources and biodiversity and the relevant management measures. We also identified research gaps that hinder a comprehensive understanding of the status, structure and functioning of the various aquatic ecosystems of the LVB and need to be filled to guide their sustainable use and management.

3 The Lake Victoria basin in context

The Lake Victoria Basin (LVB, Figure 1), located in East Africa, has a total catchment area of over 180,000 Km^2, and is shared amongst Burundi (7%), Kenya (22%), Rwanda (11%), Tanzania (44%) and Uganda (16%) (Masese and McClain, 2012; Nyamweya et al., 2023a). Lake Victoria is Africa's largest and the second-largest freshwater lake in the world. The lake has a mean depth of 40 m with a maximum depth of around 80–90 m (Awange and On'gan'ga, 2006). The lake is transboundary and shared among Kenya (6%), Uganda (43%) and Tanzania (51%). The lake is the source of the Nile River, which is the longest river in the world. However, the distribution of water resources varies significantly within the basin. The lake is fed by an array of freshwater sources comprising 19 major rivers and shoreline streams (Table 1). The lake's primary water source is direct precipitation, constituting about 80% of the water input (Sutcliffe and Petersen, 2007; Swallow et al., 2009). Discharge by rivers and underground inputs contribute 20%, with the Kagera, Nzoia, Gucha, Sondu-Miriu, and Simiyu rivers contributing over 60% (Table 1; LVEMP, 2002). Approximately 75% of the water is lost through evapotranspiration, 18% exits through the White Nile, and the rest is abstracted or lost through groundwater seepage.

The LVB hosts over 42 million people with a population density of about 250 per km^2, although some areas very have high human population densities of over 1000 persons per km^2 (Sayer et al., 2018; Nyamweya et al., 2023a). The lake is very important for each of the three riparian East African countries because of foreign revenue earned from capture fisheries. In 2021, approximately 1.5 million metric tons of fish were captured from the lake, with an estimated value of over USD 1.1 million (LVFO, 2022). The fishery, which is by the far the largest among the African Great Lakes,

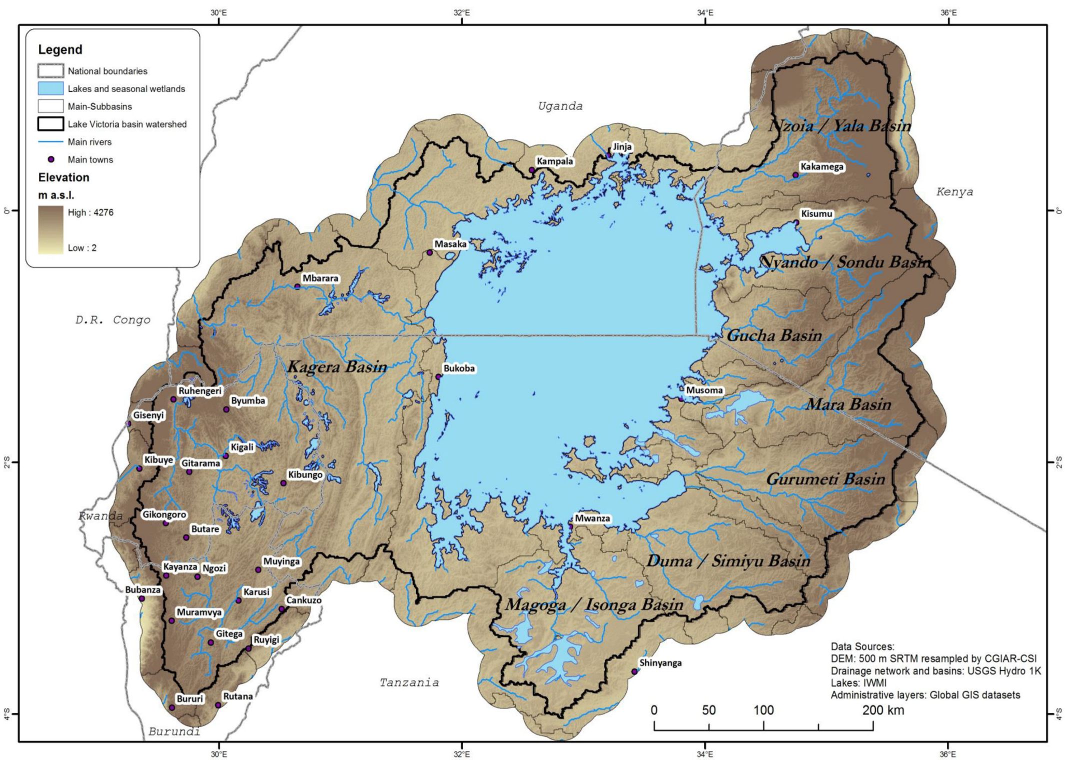

FIGURE 1
A map of Lake Victoria and its basin showing the major influent rivers.

TABLE 1 Catchment area sizes, mean annual rainfall and discharge of the major rivers in the Lake Victoria basin.

Country	River Basin	Catchment area (km^2)	Mean annual rainfall (mm) ♯	Mean discharge (m^3/s) ♯	Percentage (%) of total discharge ♯
Kenya	Nzoia	15143	1492	116.7	14.8
	Nyando	3517	1307	18.5	2.3
	Sondu-Miriu	3583	1511	42.2	5.4
	Gucha	6612	1519	58.0	7.5
	Sio	1450	1560	11.4	1.5
	Yala	3351	1589	37.6	4.7
	South Awach	780	–	5.9	0.8
	North Awach	760	–	3.7	0.5
Kenya/Tanzania	Mara	13915	1040	37.5	4.7
Tanzania	Grumeti	13392	879	11.5	1.4
	Mbalageti	3591	766	4.3	0.5
	E. Shore streams	6644	–	18.6	2.3
	Simiyu	11577	804	39.0	4.8
	Magoga-Muame	5207	842	8.4	1.0
	Nyashishi	1565	–	1.6	0.2
	Issanga	6812	897	31.0	3.9
	S. Shore streams	8681	–	25.7	3.2
	Biharamulo	1928	–	17.8	2.2
	W. Shore streams	733	–	20.7	2.6
Burundi/Rwanda/Uganda/Tanzania	Kagera	59682	1051	260.9	33.5
Uganda	Bukora	8392	–	3.2	0.4
	Katonga	15244	–	5.1	0.7
	N. Shore streams	4288	–	1.5	0.2
Kenya, Tanzania, Uganda	Lake Edge	40682	–	1077	–

Data are from COWI Consulting Engineers (2002) and Shepherd et al. (2000).
#rainfall and discharge are for the period from 1950 to 2000.

employs over 3 million people directly and indirectly (Awange, 2021). The lake supplies water to millions of people living on its shores and is a major biodiversity hotspot because of the large number of endemic fishes (Darwall et al., 2005; 2011; Kishe-Machumu et al., 2018).

The LVB experiences a diverse climate, ranging from wet and humid tropical to dry-wet savannas. In a typical year, there are two peak rainfall periods: the long rains from March to May and the short rains from October to December. These contribute around 39% and 26% to the total annual rainfall, respectively (Kizza et al., 2009). Rainfall varies from approximately 0.8 m in the lowlands to over 2 m in the highlands, with a catchment average of 1.2 m. Spatial variation in rainfall is influenced by relief features, with mountainous areas receiving more rainfall than low-lying areas, including those near the lake (Kizza et al., 2009). However, there have been reported variations characterized by delayed onset of rainfall and increased duration and frequency of droughts (Ogutu et al., 2008).

The LVB encompasses a myriad of terrestrial and aquatic ecosystems that collectively bolster the environmental integrity and livelihoods of local communities. Major terrestrial ecosystems in the region include Afromontane forests and savannas hosting large populations of wildlife, and other ecosystems within protected areas such as the Maasai Mara National Reserve and Serengeti National Park. Aquatic resources include Lake Victoria and its satellite lakes, rivers and wetlands. Although, the LVB is one of the most studied freshwater ecosystems in the tropics, especially in terms of its geology and paleolimnology, water pollution, biodiversity, ecological changes and fisheries (Verschuren et al., 2002; Odada et al., 2004, 2009; Kolding et al., 2014; Sayer et al., 2018; Nyboer et al., 2022), the available information is often fragmented. For instance, there are huge gaps in the time series data on important fisheries and ecological indicators on the lake and influent rivers, and there are conflicting reports on the status of the fisheries and the importance of different drivers of ecosystem change and fish production, such as eutrophication and overfishing (Kolding et al., 2008; Nyamweya et al., 2020, 2023b). Many studies only provide short-term results, which makes it difficult to understand long-term trends and the impact of human activities, including climate change (Plisnier et al., 2023). For instance, long-term studies on water quality and the influence of land use change on run-off and discharge in streams and rivers are limited (Jacobs et al., 2018; Jacobs and Breuer, 2024; Masese et al., 2025a). Similarly, data on fish catches on influent rivers in Kenya was discontinued in the late 1950s and early 1960s (e.g., Cadwalladr, 1965; Whitehead, 1959). This makes it difficult to predict the influence of human activities and climate change on water quality, availability and fish production.

4 Major threats to water resources and biodiversity in the LVB

The LVB has undergone through a series of negative environmental and ecological changes over the past century. The most infamous is the introduction of exotic fishes such as *Lates niloticus* in the 1950s and 1960s, which caused the extinction of many species of native haplochromine cichlids (Ogutu-Ohwayo, 1990; Witte et al., 1999; Marshall, 2018; Nyamweya et al., 2020, 2023). The introduction of *Lates niloticus* in the lake took place at a time the lake was already experiencing increased nutrient loading and a progressive change in its trophic status (Hecky, 1993; Verschuren et al., 2002; Hecky et al., 2010). The ecological changes in the lake, largely driven by nutrient and sediment loading from the basin, are correlated with human population growth and land-use and land cover changes in the catchment area (Witte et al., 1999; Verschuren et al., 2002; Hecky et al., 2010). Over the years, growth in the scale and intensity of agriculture, urbanization and industrialization, and water pollution have increased parallel to the growth of human population in the basin (Scheren et al., 2000; Verschuren et al., 2002). The rivers have been at the fore of environmental change by experiencing change themselves through modifications of water quality and biotic characteristics (Masese and McClain, 2012; Masese et al., 2025a), and at the same time being agents of the change as conduits of sediments, nutrients and other pollutants from converted lands into the lake (Jacobs et al., 2018; Kroese et al., 2020a, b; Jacobs and Breuer, 2024; Oyege et al., 2024).

A number of studies, surveys, and reviews have documented the status and trends in environmental conditions, ecosystem function, and the status of aquatic biodiversity, including fisheries, in the LVB (e.g., Ntiba et al., 2001; Balirwa et al., 2003; Njiru et al., 2008; Hecky et al., 2010; Njiru et al., 2014; Sayer et al., 2018; Nyamweya et al., 2023a; Muthoka et al., 2024). The number of studies have shown a positive trend since 1990 implying that the influence of human activities on the structure and functioning of aquatic ecosystems has received increased attention over the years (Figure 2, Appendix 1). Prior to 1990, only a limited number of studies investigated the effects of human activities on aquatic ecosystem in the LVB – data

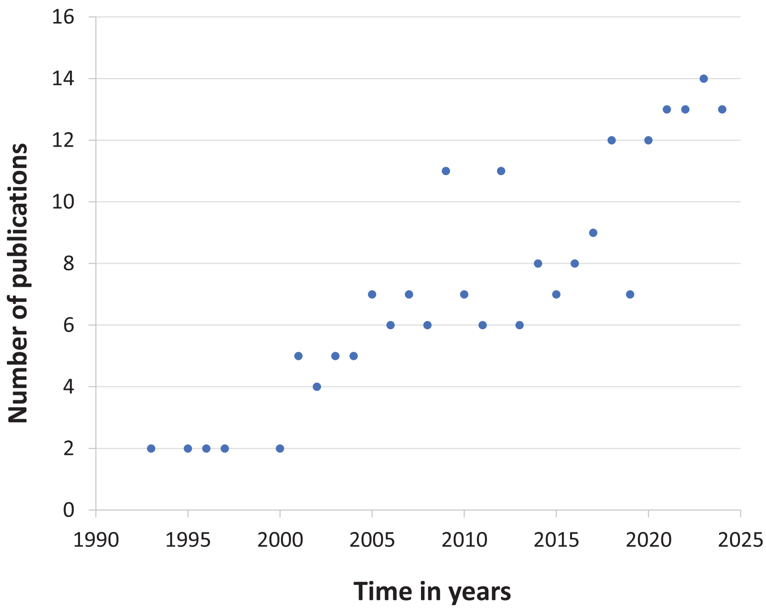

FIGURE 2
Growth in the number of publications from 1990 to 2024 on the influence of human activities on aquatic ecosystems in the Lake Victoria basin.

not shown. From the review of 190 publications and reports on the influence of human activities on aquatic ecosystems in the LVB (Appendix 1), ten (10) major challenges or threats and ten (10) corresponding management options or strategies were identified (Figure 3). The major threats to biodiversity and resilience of aquatic ecosystems identified include: land use and land cover changes in many river basins; pollution from domestic and industrial wastewater, solid and agricultural wastes, pesticides, and agrochemicals; agricultural expansion and intensification and the resulting soil erosion, increasing sediment and nutrient inputs into surface waters; overharvesting of fish resulting in growth and recruitment overfishing; introduction of exotic species, which include eight fish species and the red swamp crayfish *Procambarus clarkii* Girard, 1852; building of dams and over-abstraction of water from waterways causing ecosystem disconnectivity and modification of natural flow regimes of rivers; and climate change and variability, among others (Ogutu-Ohwayo, 1990; Witte et al., 1999; Scheren et al., 2000; Verschuren et al., 2002; Darwall et al., 2005; Njiru et al., 2008; Hecky et al., 2010; Sitoki et al., 2010; Masese and McClain, 2012; Masese et al., 2017; Sayer et al., 2018; Nyamweya et al., 2020, 2023a; Muthoka et al., 2024). Collectively, these threats have led to a decline in in water quality and freshwater biodiversity in the LVB. Recent assessments indicate that nearly 20% of freshwater biodiversity in the LVB are threatened by pollution, overexploitation (mainly overfishing), agriculture and invasive species (Sayer et al., 2018). Table 2 presents some of the aquatic species that are threatened by human activities in the LVB. Although some fish species, such as *Oreochromis esculentus*, *O. variabilis* and *Labeo victorianus*, were recently considered critically endangered (e.g., Sayer et al., 2018), their populations have significant recovered (Natugonza and Musinguzi, 2022; Tweddle and Bragança, 2023).

Here we discuss ten (10) most pervasive threats and management challenges (Figure 3A) that are a threat to biodiversity and its contribution to human well-being, and must be addressed in planning and management to protect the environment and biodiversity and guarantee the sustainable provision of ecosystems services deriving to the people. This is followed by a discussion of ten (10) suggested management strategies or options (Figure 3B) to address the threats and preserve water resources and biodiversity of the LVB.

4.1 Pollution

As a result of the human population growth, waste production has grown proportionally in the LVB. However, waste management mechanisms in place are unable to effectively handle the generated solid and liquid wastes in many cities, towns and municipalities (Scheren et al., 2000; Mugidde et al., 2003; Nyenje et al., 2010). For instance, many of the existing sewerage facilities in major towns and cities are old, poorly maintained and often operating above capacity (Ntiba et al., 2001; Juma et al., 2014). Many industrial and artisanal activities such as agroprocessing, gold mining, quarrying and brewing of traditional brews, have been highlighted as sources of wastewater, heavy metals such as mercury, major ions and nutrients into surface waters in the LVB (Oguttu et al., 2008; Nyenje et al., 2010; Oyoo-Okoth et al., 2010; Musungu et al., 2014).

Agricultural intensification in catchments areas of major rivers has also been linked to increased levels of pesticides and other agrochemicals in water and sediments (Getenga et al., 2004; Madadi et al., 2005; Musa et al., 2011). Small-scale gold mining, leather, and metallurgy industries have been identified as sources of heavy metals in Lake Victoria and its tributaries (Campbell et al., 2003; Kishe and Machiwa, 2003; Oguttu et al., 2008; Ongeri et al., 2009). Heavy metal pollution has been identified to be a potential threat to 6% of freshwater fish species native to the LVB (Kishe-Machumu et al., 2018). Although low concentration of heavy metals and agrochemical residues (especially pesticides) have been found in fish tissues (Campbell et al., 2003; Ssebugere et al., 2014; Nthusi, 2017), there is still a threat to food webs and humans because of bioaccumulation and biomagnification (e.g., Oyoo-Okoth et al., 2010; Mataba et al., 2016).

The conversion of native forests into smallholder farmlands and large-scale plantations is another pervasive problem that is a major source of sediments and nutrients in streams and rivers in the LVB (Defersha et al., 2012; Masese et al., 2017; Jacobs et al., 2018; Kroese et al., 2020a, b). Expanding human settlements, unpaved roads, and high livestock densities in grazing areas have also led to soil degradation and overgrazing, resulting in widespread erosion of top soils and increased turbidity in streams and rivers (Defersha et al., 2012; Dutton et al., 2018a; Iteba et al., 2021). Increased turbidity is detrimental to aquatic communities. Data show that 88.9% of the indigenous fish species in the LVB are threatened by soil erosion and high turbidity (Kishe-Machumu et al., 2018).

Many urban centers (municipalities, towns and cities) in the LVB are unable to effectively manage their solid and liquid wastes because of the constant influx of people from rural to urban areas. The increasing human population in many towns and settlements along the shores of Lake Victoria are not served with sewerage facilities and the few that have them cannot cope with the high amounts of wastes generated. Manufacturing of textiles, sugar, alcohol and food products, and informal activities such as breweries release large amount of wastewater and solid wastes that are released to streams, rivers and Lake Victoria with limited (Bootsma and Hecky, 1993; Calamari et al., 1995; Scheren et al., 2000; Verschuren et al., 2002; Kobingi et al., 2009; Muyodi et al., 2010; Nyenje et al., 2010). The growing human populations in urban areas are major sources of emerging organic micropollutants such as pharmaceuticals and personal care products that are discharged into rivers (K'oreje et al., 2018). Non-point sources of pollution from urban runoff, farmlands, human and livestock footpaths, and unpaved roads also pose significant threats to streams and rivers. These human activities have the greatest potential to degrade water quality and threaten biodiversity in rivers, wetlands and lakes (Sayer et al., 2018).

TABLE 2 List of threatened aquatic species of the Lake Victoria basin.

Common Name	Scientific Name	IUCN Status	Ecosystem	Reference
Singida tilapia (Ngege)	*Oreochromis esculentus*	NT	Lake (endemic)	Natugonza and Musinguzi, 2022
Victoria tilapia (Mbiru)	*Oreochromis variabilis*	NT	Lake/satellite lakes	Natugonza and Musinguzi, 2022
Ningu (Victoria carp)	*Labeo victorianus*	LC	Lake & rivers	Tweddle and Bragança, 2023
Lake Victoria deepwater catfish	*Xenoclarias eupogon*	CR	Lake (deep waters)	Froese and Pauly, 2025
Grant's haplo	*Haplochromis granti*	CR	Lake (endemic cichlid)	IUCN, 2025
Ishmael's haplo	*Haplochromis ishmaeli*	CR	Lake (endemic cichlid)	IUCN, 2025
Martin's haplo	*Haplochromis martini*	CR	Lake (endemic cichlid)	IUCN, 2025
Parvidens haplo	*Haplochromis parvidens*	CR	Lake (endemic cichlid)	IUCN, 2025
Nyeri's haplo	*Haplochromis nyererei*	LC	Lake (endemic cichlid)	IUCN, 2025
Thereuterion haplo	*Haplochromis thereuterion*	VU	Lake (endemic cichlid)	IUCN, 2025
Rainbow Sheller	*Ptyochromis* sp. "rainbow sheller"	CR	Lake (endemic cichlid)	IUCN, 2025
Rusinga Oral Sheller	*Ptyochromis* sp. "Rusinga oral sheller"	CR	Lake (endemic cichlid)	IUCN, 2025
Barthi's gabbiella snail	*Gabbiella barthi*	CR	Lake (benthic snail)	IUCN, 2025
Subtle snail	*Afrogyrorbis subtilis*	CR	Lake (benthic snail)	IUCN, 2025
Teesdale's hydrobia snail	*Incertihydrobia teesdalei*	CR	Lake (benthic snail)	IUCN, 2025
Cridland's cleopatra snail	*Cleopatra cridlandi*	CR	Lake (nearshore snail)	IUCN, 2025
Victoria pea clam	*Eupera crassa*	CR	Lake (bivalve)	IUCN, 2025
Rothschild's freshwater mussel	*Coelatura rothschildi*	CR	Lake (bivalve)	IUCN, 2025
Spoke Escarpment mussel	*Coelatura rotula*	VU	Lake (bivalve)	IUCN, 2025
Kenya Jewel (damselfly)	*Platycypha amboniensis*	CR	Lake wetlands	IUCN, 2025
Radiate sprite	*Zingis radiolata*	CR	Lake wetlands	IUCN, 2025
Scheffler's Ethulia	*Ethulia scheffleri*	EN	Wetland (marsh herb)	Beentje, 2017a
Narrow Hygrophila	*Hygrophila asteracanthoides*	VU	Wetland/stream edges	IUCN, 2025
Mann's Juncus	*Luzula mannii*	VU	Wetland/riverine	Juffe Bignoli and Beentje, 2017
Hydrilla-like pondweed	*Lagarosiphon hydrilloides*	EN	Lake (submerged plant)	IUCN, 2025
Narrowleaf floating-heart	*Nymphoides tenuissima*	EN	Lake backwaters	Ghogue, 2017
Angustissima sedge	*Carpha angustissima*	EN	Wetland (sedge marsh)	Beentje, 2017b
Axil-flower psilotrichum	*Psilotrichum axilliflorum*	EN	Wetland (riparian shrub)	IUCN, 2025

IUCN Red List threat levels: LC, least concern; NT, near threatened; VU, vulnerable; EN, endangered; CR, critically endangered.

4.2 Habitat loss and degradation

Habitat loss and degradation have been identified as some of the major threats to freshwater biodiversity globally (Dudgeon et al., 2006; Reid et al., 2019). In the LVB, habitat loss and degradation are caused by drainage or conversion of wetlands to other uses such as woodlots, grazing areas and farmlands, clearance and conversion of riparian areas along streams and rivers to other uses, water pollution caused by liquid and solid waste disposal and introduction of exotic species. Wetlands are among the aquatic habitats that have been lost and degraded thereby threatening biodiversity (Okeyo-Owuor et al., 2012; Masese et al., 2012). Wetlands perform many important functions that are beneficial to the environment and biodiversity, such as water storage, aquifer recharge, water quality improvement, and wildlife habitat (Mitchell, 2013). Wetlands are also important hotspots of biogeochemical transformations in a landscape, such as carbon sequestration and nutrient removal from runoff (Mitsch and Gosselink, 1993).

However, the degradation and loss of wetlands as a result of human activities is the LVB is a widespread concern. Many wetlands

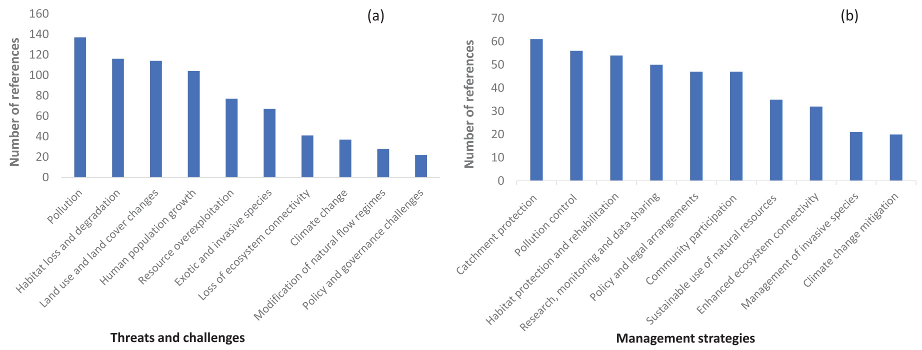

FIGURE 3
Identified management challenges **(a)** and suggested management strategies or options for addressing the challenges **(b)** from 190 publications and reports on the Lake Victoria basin.

have been lost to human activities and the remaining ones continue to be degraded (Okeyo-Owuor et al., 2012; Masese et al., 2012). LVB's wetlands are essential for reducing pollution from agriculture, industry, and cities as well as providing millions of people with a variety of ecosystem services such as dry-season grazing areas for livestock, farming during the dry season, building materials and biomass for household use, and sources of water (Kansiime et al., 2007; Masese et al., 2012). However, these wetlands are increasingly being modified by human encroachment, development projects that alter their water supply, introduction of exotic species, invasive species, disposal of wastes and chemicals from human settlements, industries and agricultural areas (Kairu, 2001; Masese et al., 2012).

The modification of the hydrology of wetlands alters the natural disturbance and flooding regimes. For instance, dam construction permanently alters the flooding and sediment dynamics and permanently disrupt the crucial ecological balance of floodplains. Furthermore, the hydrology of wetlands is impacted by extensive projects involving the construction of drainage canals. For instance, the Yala Wetlands in western Kenya have been drained, highlighting the consequences of such interventions (Kondowe et al., 2022). In many places in the LVB, riverine and palustrine wetlands have been transformed into grazing and agricultural lands, and woodlots featuring exotic tree plantations like *Eucalyptus*. Also, the reported unsustainable harvesting of papyrus plants exacerbates wetland loss in some areas, impacting biodiversity and ecosystem functioning (Owino and Ryan, 2007; Morrison et al., 2012).

Other activities that cause habitat loss and degradation in aquatic ecosystems include land use and land cover changes in catchments and riparian areas. Streams and rivers have also been degraded by human activities such as sand mining, water diversions for irrigation and other uses, and livestock watering (Masese et al., 2009a, b; Iteba et al., 2021). Livestock access to streams and rivers is especially detrimental to instream habitats as they cause bank-slumping, increase turbidity and water temperature and loading of nutrients and organic matter (Masese et al., 2020a; Iteba et al., 2021), which alter the diversity and composition of aquatic communities. These can disadvantage sensitive invertebrate and other taxa causing local losses of biodiversity (Owade et al., 2025).

4.3 Land use and land cover changes

Land use and land cover changes in the LVB is linked to human population growth and the need to convert natural forests, grasslands and wetlands into settlements, urban areas and agricultural farms for crop cultivation and livestock grazing (Mugo et al., 2020). These changes have led to habitat loss and fragmentation, adversely affecting the region's ecological integrity. For instance, the Yala Swamp in Kenya, a critical habitat for the endangered Sitatunga antelope and various bird species, has been extensively reclaimed for agriculture, leading to biodiversity loss and disruption of ecosystem services. In the upper Mara and Sondu-Miriu river basins, conversion of native forests to smallholder agriculture and tea plantations has been linked increased levels of sediments and nutrients in streams and rivers (Kilonzo et al., 2014; Masese et al., 2017; Jacobs et al., 2017; Kroese et al., 2020a, b). Land use change in riparian areas is also accompanied with the introduction of exotic species such as *Eucalyptus* species, which alter litter input dynamics, organic matter processing rates, flow regimes, and energy sources and flow in food webs (Cooper et al., 2013; Masese et al., 2014a, b). Land use change linked to changes in community composition has also been noted in headwater streams where forested streams have recorded a higher diversity of macroinvertebrates, especially leaf-litter shredders, compared to streams influenced by agriculture and urbanization (Masese et al., 2014a; Sitati et al., 2021).

Deforestation and unsustainable agricultural practices have exacerbated soil erosion and increased sedimentation in water bodies. Approximately 45% of the LVB's land is prone to water erosion, contributing to the siltation of rivers, wetlands and Lake Victoria. This sedimentation degrades water quality and disrupts aquatic habitats, posing challenges for both biodiversity and human livelihoods (Ochola, 2006). Climate variability, coupled with land cover changes, has also influenced water quality. Increased precipitation can heighten erosion risks, transporting more nutrients into the streams, rivers and the lake and promoting harmful algal blooms that deteriorate water quality (Nakkazi et al., 2024).

4.4 Human population growth

The human population in the LVB has grown by over 40 million people in the last century. The LVB is one of the most densely populated rural areas in Africa, with some areas having over 1200 people per km^2 (Masese and McClain, 2012). As the population increases, so does the demand for land, food, water, and energy—putting intense strain on the region's fragile ecosystems. Human population growth is a driver of many activities that have negative effects on the environment and biodiversity, such as increased conversion of natural forests and wetlands for food production, increased extraction of natural resources such as overfishing, and overharvesting of biomass for fuel and construction, urbanization and industrialization and the linked increase in waste production and disposal in aquatic ecosystems, increased intensification of agriculture and the resultant soil erosion and nutrient loading in surface waters, and other impacts (Scheren et al., 2000; Verschuren et al., 2002; Nyenje et al., 2010).

One of the most direct impacts of population growth is land use change. Expanding human settlements and the conversion of forests and wetlands into farmland are among the leading drivers of habitat loss. Large areas of wetlands, which are vital breeding grounds for fish and home to diverse flora and fauna, have been drained for agriculture or encroached upon by informal settlements in urban areas (Masese et al., 2012; Okeyo-Owuor et al., 2012). This destruction not only leads to the displacement of species but also disrupts natural water filtration systems and carbon storage functions. Additionally, increased agricultural activity to feed the growing human population has resulted in widespread deforestation and soil degradation. Farmers often clear forests for crop cultivation, especially in densely populated areas where land is scarce. This leads to a decline in forest-dependent species and exacerbates soil erosion, further reducing the land's productivity and ecological resilience (FAO, 2016). The use of chemical fertilizers and pesticides, often poorly regulated, also pollutes soil and water bodies, contributing to aquatic biodiversity loss (UNEP, 2012).

The pressure on fisheries is another major concern. Lake Victoria has historically supported one of the world's largest freshwater fisheries, but overfishing—driven by the needs of a growing human population—has drastically reduced fish stocks, particularly indigenous species like the cichlids. The introduction of the Nile perch, combined with increased fishing intensity and the use of illegal gear, has further threatened the lake's ecological balance (Njiru et al., 2008). As more people depend on fishing for their livelihoods, unsustainable practices become more common, creating a cycle of resource depletion and poverty.

Human population growth has also led to increased waste generation, much of which ends up in the lake due to inadequate sanitation and waste management infrastructure. Urban centers such as Kisumu, Mwanza, and Kampala continue to grow, often without corresponding investment in environmental services. The increased demand for protein to feed the increasing human population has led to the introduction of cage fish farming in Lake Victoria and some of the satellite lakes. While cages can increase fish production, there is increasing evidence that they can have negative effects on the ecosystem due to organic matter and nutrient loading (Orina et al., 2018; Lubembe et al., 2024; Nyakeya et al., 2022; Okechi et al., 2025). Nutrient and organic matter loading cause eutrophication and oxygen depletion—conditions that are harmful to aquatic life and further degrade biodiversity (Nyenje et al., 2010; LVEMP, 2011). Fish kills are increasingly occurring in Lake Victoria (Aura et al. 2024), and, although, there is no direct evidence linking them to cage fish farming, there is a likelihood of their contribution to oxygen depletion in the lake, especially when located in shallow areas where water mixing is limited.

4.5 Resource overexploitation

Overexploitation of natural resources in as a result of increased human population and over-reliance on natural resources for livelihoods. Unsustainable resource extraction threatens the long-term viability of the natural ecosystems. For instance, studies show that fish stocks in Lake Victoria have declined by over 50% in the past three decades due to overfishing and habitat destruction (LVFO, 2022). Apart from the fisheries, other resources that have faced threats of overexploitation include the wetlands (biomass harvesting) and water resources. Wetlands play a major role in maintaining water quality and the functioning of linked aquatic ecosystems. Most of the expansive wetlands in the LVB are those found in the floodplains of influent rivers (Masese et al., 2012; Mpopetsi et al., 2025). The inshore areas of Lake Victoria are also fringed by extensive wetlands that host diverse plant and animal species (Sayer et al., 2018). The wetlands and the associated influent rivers are important seasonal habitats for migratory fish species. For instance, several fish species make period runs from Lake Victoria into influent rivers for spawning during the rainy season (Whitehead, 1959; Manyala et al., 2005; Masese et al. 2020b). These migrations help maintain populations of migratory fish species both in the lake itself and in the influent rivers where they form important fisheries, particularly during the rainy season.

4.6 Exotic and invasive species

Lake Victoria is infamous for the decimation of indigenous cichlids by the introduced Nile perch (*Late niloticus*) and the cichlids *Oreochromis niloticus*, *O. leucostictus, Coptodon zillii* and *C. rendalli.* These introductions further endangered the indigenous tilapiine flock through interspecific competition and hybridization (Kwikiriza et al., 2023). Before the exotic introductions, native cichlids constituted >80% of the fish biomass in the lake (Graham, 1929; Marshall, 2018). The fishery is currently dominated by two exotic species, *L. niloticus* and *O. niloticus*, and the native cyprinid *Rastrineobola argentea* (Wasonga et al., 2017; Outa et al., 2020), whereas the tilapiine species have disappeared from catches. The exotic fishes in the lake have also invaded influent rivers. The Kenyan rivers draining into Lake Victoria have recorded nine exotic fishes (*Oreochromis niloticus*, *O. leucostictus*, *Coptodon zillii*, *C. rendalli*, *Gambusia affinis*, *Micropterus salmoides*, *Lates niloticus*, *Salmo trutta*, and *Oncorhynchus mykiss* (Masese et al. 2020b), further highlighting the threats posed to native fishes by exotic introductions.

Another exotic introduction in the LVB is the water hyacinth (*Eichhornia crassipes*). *Eichhornia crassipes* was first reported in Lake Victoria in 1989 (Twongo, 1991) and then spread to the entire lake, the satellite lakes, pans and reservoirs, and the lower reaches of major rivers. The growth of the plant is rapid, with a doubling time of 6 to 10 days under favorable conditions of enough light and nutrient supply (Denny, 1993). It is a very successful mat-forming species and, efforts to eliminate it in Lake Victoria by mechanical removal and biological control have failed. At its peak, thick floating mats covered over 10% of the lake's surface (Güereña et al., 2015; Mugidde et al., 2005). High nutrient levels have enabled its success and establishment in Lake Victoria (Mugidde et al., 2005). Its negative ecological effects include the formation of anoxic conditions during the decomposition of senescent mats (Nassali et al., 2020). It's also a navigation hazard that hinders fishing and other movements in the lake. The weed has also been detrimental to cage fish farming as the free-floating mats are carried by waves and end up smashing into and smothering fish cages and sweeping them away. Interestingly, the proliferation of the water hyacinth in the lake has also been attributed to the resurgence of some haplochromine species that were once thought to be extinct. Seemingly, the mats provide a refuge for the fish, and the low oxygen conditions within make it difficult for Nile perch, which prefers high dissolved oxygen concentrations, to access and predate on the fish.

4.7 Loss of ecosystem connectivity

Physical and biological connectivity among rivers, wetlands and Lake Victoria are critical to health of these ecosystems, given their interdependency for energy and nutrient flows that sustain food webs and support their functionality. Migrations of fish between the lake and peripheral wetlands, as well as along river corridors, are critical for accessing habitats and food resources needed for migration and reproduction (Cadwalladr, 1965; Ochumba and Manyala, 1992). Access to such spatially discrete resources is critical for sustaining populations of threatened and vulnerable species. However, the practice of targeting migrating populations of fishes along rivermouths of major rivers, and the use of illegal fishing methods has been condemned in the past as contributing to major declines and near collapse of the riverine fishery (Whitehead, 1959; Cadwalladr, 1965).

Recent evidence suggests that the LVB rivers still maintain populations of basin-scale migratory fishes, such as *Labeobarbus altianalis* and *Labeo victorianus* (Masese et al. 2020b). The wellbeing of these and other migratory species is at risk if longitudinal connectivity in gene flow and organic matter are lost. Many populations are becoming locally extinct or being reduced to small fragmented stenotopic populations (Ojwang et al., 2007; Chemoiwa et al., 2013). Similarly, the building of dikes has reduced the lateral linkage and reciprocal flows of organic matter and sediments between rivers and their floodplains (e.g., Junk et al., 1989; Winemiller and Jepsen, 1998). By confining rivers to their channels and limiting water, sediments and nutrient flows to floodplain lakes, pans and wetlands, many species that are dependent on seasonal flooding for survival and reproduction are placed at a higher risk of becoming locally extirpated (e.g., Wildekamp et al., 2014; Kishe-Machumu et al., 2018).

With the increasing demand for water for irrigation, hydroelectric energy and water for domestic and industrial uses, many river reaches have been earmarked for dam construction. Often, such developments do not put in place safeguards for environmental and biodiversity protection, especially for migratory fish. For instance, damming of the Sondu-Miriu River prevented the movement of fishes because a fish passage was not constructed (Owiti et al., 2013). A large amount of water is diverted from the river for hydropower generation, and this reduces the volume of water in river reaches below the dam significantly. The changes in flow velocities, habitat availability and water quality caused by the diversion are likely to negatively affect flow-sensitive species of macroinvertebrates and fishes. Declines in the populations of migratory fish is likely to negatively affect food sources for piscivorous animals such as otters, monitor lizards and crocodiles inhabiting the rivers, as well as people who depend on the riverine fishery for a significant fraction of their nutrition.

4.8 Climate change

Climate change poses significant threats to global biodiversity. There is increasing evidence that climate change is affecting ecosystems in the LVB, including the spatial and temporal distribution of water and its quality (Chapman et al., 2022; Nyboer et al., 2022). Local activities and processes linked to climate change that have altered the hydrological cycle of streams and rivers include clearance of native vegetation and forest fires, reduced infiltration, degradation of top soils and soil erosion (Mango et al., 2011; Nassali et al., 2020). Further projections from downscaled climate models show that some areas in the LVB will record 3-4°C increase in mean monthly temperature by 2055 (Sewagudde, 2009; Platts et al., 2015). In the lake, data shows that average surface water temperature has increased by 0.5°C over the last 30 years (Deirmendjian et al., 2021). Recent climatic data has also shown a 10–40% reduction in precipitation since the peak levels of the 1960s, with projections showing potential for further decrease into the future (Nassali et al., 2020).

The effects of climate change on flow regimes and water quality in rivers are compounded by local human activities such as land use and land cover change and excessive water abstractions. Many river basins in the LVB have reported changes in their natural flow regimes that are likely linked to climate change (e.g., Mango et al., 2011; Shinhu et al., 2023). Increased evaporation and evapotranspiration due to elevated air temperature caused by climate change may influence the soil–water balance and run-off process, which would then have an impact on river flows and water availability during the dry seasons and droughts. Increased runoff is a major driver of soil erosion, especially from converted lands, and this causes siltation of streams and rivers with significant effects on aquatic communities (Sayer et al., 2018). Some invertebrates such as shredders living in their thermal optima in forested streams face the greatest risk of extinction by warming of streams and rivers as a result of climate change and land use change (Yule et al., 2009; Taniwaki et al., 2017). In the headwaters of the Mara River basin, seven species of invertebrates were restricted to cooler forested streams, likely as a response to the warming (agricultural streams that were up to 4°C warmer) and poor water quality in adjoining agricultural streams (Masese et al., 2014a).

4.9 Modification of natural flow regimes

Maintenance of water levels in lentic ecosystems and natural flow regime in streams and rivers are important for regulating environmental conditions and the diversity and distribution of aquatic communities (Poff et al., 1997; Bunn and Arthington, 2002; Poff and Zimmerman, 2010). However, there is increasing evidence of altered flow regimes of streams and rivers and the resultant change in water levels of lentic ecosystems in the LVB as a result of land use change, excessive abstractions and impoundments (Sangale et al., 2005; Melesse et al., 2008; Hoffman et al., 2011; Dessu et al., 2014). For instance, the amount of water in the Mara River and its major tributaries has become erratic, with significant flow variation characterized by base flows during the dry season, and peak discharges during the wet season (Melesse et al., 2008; Mango et al., 2011; McClain et al., 2014). Also, the Sio, Nzoia and Yala rivers recorded increased peak discharge of 8%, 31% and 38%, respectively (Sangale et al., 2005). This increase is attributed to increased amount of rainfall of about 8% between 1960 and 1990 (Conway, 2002), and land use and land cover changes in the LVB. Increased runoff and peak discharge, and reduced interception and evapotranspiration have occurred in rivers where natural forests have been cleared for agriculture and other uses (Guzha et al., 2018; Jacobs et al., 2018). Flow data from rivers that have experienced widespread deforestation of their catchments show increase in flooding and reduced baseflows compared to catchments with less deforestation (Melesse et al., 2008).

There is a relationship between the amount of water and water quality in rivers, especially those receiving organic pollution (Mandal et al., 2010; Wen et al., 2017). For this reason, a given minimum discharge, called the reserve or environmental flow, should be maintained in rivers after all abstractive needs have been met to maintain water quality and protect biodiversity and water use by wildlife (Declaration, 2007; Arthington, 2012). For instance, excessive water abstractions in the Mara River, coupled with excessive organic matter and nutrient loading by hippopotami and livestock, have led to hypoxic conditions in the river and subsequent fish kills (Dutton et al., 2018b). Reduced discharge, especially during the dry season, increased water temperature and conductivity reduce the concentration of dissolved oxygen. The abundance of macroinvertebrates that are not tolerant to these conditions, such as orders Ephemeroptera, Trichoptera and Plecoptera, are negatively affected while that of tolerant taxa, such as Chironomidae and Oligochaeta, increase (Mathooko et al., 2005; Masese et al., 2009a, b; Masese and Raburu, 2017). In cases where a river ceases to flow, the diversity of sensitive macroinvertebrates has been found to significantly decrease (Shivoga, 2001; Masese et al., 2009b). With increasing human populations and the concomitant increase in water abstraction, many rivers are likely to experience modified flow conditions and deterioration in water quality, which will continue to threaten riverine biodiversity.

4.10 Policy and governance challenges

Policy and governance challenges among riparian countries of the LVB have hindered effective conservation and sustainable management of the basin's natural resources. One of the most pressing issues is the weak implementation and enforcement of environmental policies. Although the countries surrounding Lake Victoria have laws and frameworks aimed at protecting the environment, these regulations are often not enforced effectively. Regulatory agencies are underfunded, lack adequate technical capacity, and sometimes face political interference or corruption. As a result, practices such as illegal, unrestricted and unreported (IUU) fishing, deforestation, and pollution continue largely unbated (Etiegni et al., 2017; Nyamweya et al., 2023b). The unchecked discharge of untreated industrial and domestic waste into the lake, for example, has led to severe water pollution, contributing to ecological changes in the lake, including a decline of native species of fishes (Scheren et al., 2000; Kobingi et al., 2009; Nyenje et al., 2010; Nyamweya et al., 2020; 2023a).

Another significant challenge is the fragmented nature of regional governance. Lake Victoria is a shared resource, yet the riparian countries that border it often operate in isolation when it comes to environmental management. There is a lack of harmonized policies and coordinated enforcement, which undermines efforts to manage the lake sustainably. Although institutions like the Lake Victoria Basin Commission (LVBC) and Lake Victoria Fisheries Organization (LVFO) exist to promote regional cooperation, they often lack the authority, funding, and political support needed to make a meaningful impact.

Corruption and political interference further complicate governance in the region. Land use regulations are frequently bypassed through corrupt practices, leading to the conversion of forests and wetlands into agricultural land or urban developments. In some cases, politicians have opposed or weakened environmental regulations to gain favor with local populations or powerful business interests. Such actions undermine conservation efforts and encourage unsustainable exploitation of natural resources. Public participation in environmental governance is also limited. Local communities, who are often the most affected by environmental degradation, are frequently excluded from decision-making processes. The community-led beach management units that should represent local communities in decision making concerning the management of fisheries resources are not working effectively (Etiegni et al., 2019). Their limited participation in decision making results in policies that fail to consider indigenous and local needs and knowledge. Without a sense of ownership or involvement in conservation efforts, communities may continue harmful practices such as overfishing or wetland and forest encroachment, further endangering terrestrial and aquatic biodiversity. Conflicts over land tenure and resource ownership also pose challenges to biodiversity conservation. In many areas, land and water rights are unclear or contested, leading to unregulated use of resources. Without secure tenure or clear benefit-sharing arrangements, local communities have little incentive to conserve biodiversity or adopt sustainable practices.

5 Suggested management strategies for biodiversity conservation

The changes in environmental and ecological conditions in the LVB continue to test the resilience of ecosystems and their ability to sustain the provision of ecosystem services to people of the region. Here, we highlight the management measures and strategies suitable for mitigating the negative effects of human impacts on water resources and biodiversity in the LVB (Figure 4 and Table 3). If implemented at various spatial and temporal scales, these management measures will help address the identified management challenges or threats (Figure 4), and help maintain the ecological integrity of aquatic ecosystems and prevent biodiversity loss.

5.1 Catchment protection

Given the complex environmental challenges in the LVB, adopting an integrated catchment-scale approach for watershed protection holds great promise. Integrated Water Resources Management (IWRM) is a coordinated process aimed at developing and managing water, land, and related resources to maximize economic and social welfare equitably, without compromising vital ecosystem sustainability (GWP, 2000). In the LVB, IWRM should prioritize meeting human water needs while safeguarding ecosystem sustainability and biodiversity conservation. It provides various management tools, including the promulgation of water rights, institutional reforms, economic incentives, capacity building, gender considerations and scientific approaches such as assessing environmental flows and payment for ecosystem services (Naiman et al., 2007).

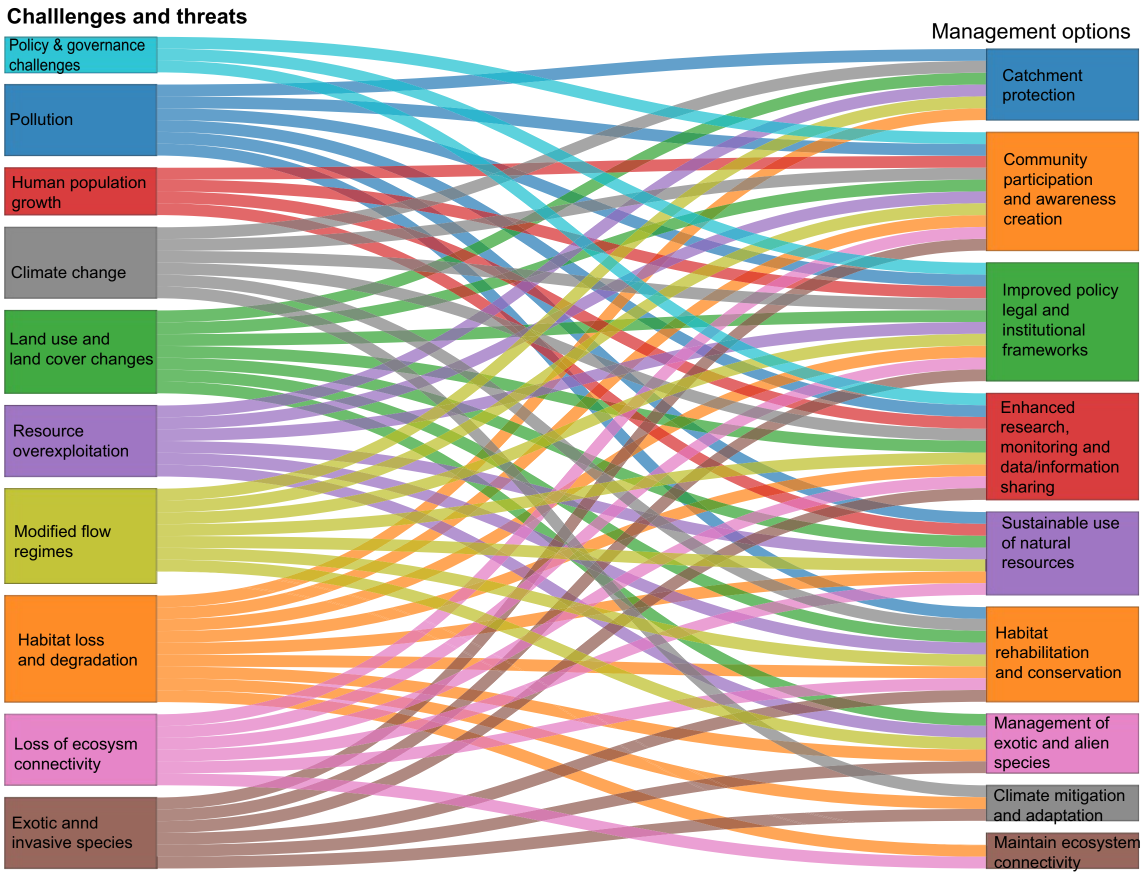

FIGURE 4
A linkage between the challenges or threats facing water resources and biodiversity in the LVB and the suggested corresponding management strategies or options to address them.

TABLE 3 Human and other threats or challenges, sub-challenges, causes, effects on water resources and biodiversity and the suggested management options to address the challenges in the Lake Victoria basin.

Human threats or challenges	Sub-challenges	Main causes	Main ecological and environmental effects	Management options	Examples of references
Pollution	Water pollution	• Land use change - deforestation • Soil erosion and increased turbidity • Agricultural and urban runoff • Municipal and industrial discharges • Nutrient loading • Pharmaceutical wastes • Artisanal mining	• Alteration of aquatic community composition • Ecological effects • Alteration of ecological processes and functions • Bioaccumulation and biomagnification of heavy metals and chemicals	• Watershed management • Sustainable agriculture • Treatment of sewage and wastewater • Wetland engineering	-Bootsma and Hecky, 1993; Calamari et al., 1995; Scheren et al., 2000; Verschuren et al., 2002; Hecky et al., 2010; Nyenje et al., 2010; Kilonzo et al., 2014; Jacobs et al., 2017, 2018; Nassali et al., 2020
	Chemical pollution	• Runoff from farmlands • Discharge of untreated or poorly treated industrial and municipal wastewater • Lack of monitoring, assessment and abatement of chemicals • Landfill and sewage leaching	• Surface and groundwater contamination • Persistence, bioaccumulation and toxicity • Risks to aquatic life • Endocrine disrupting effects on aquatic organisms • Antimicrobial/ antibacterial resistance development • Disruption of ecological processes and functions • Ecological effects	• Treatment of industrial and municipal wastewater • Monitoring, assessment and abatement of chemicals, including pharmaceuticals, personal care products, pesticides, herbicides and industrial chemicals • Proper site selection for landfills • Infrastructure (sewage facilities) improvement	Osano et al., 2003; Rosi-Marshall et al., 2015; Su et al., 2018; Ebele et al., 2017; Richmond et al., 2017; Sandegren, 2019; Nantaba et al., 2020; Kandie et al., 2020
	Soil erosion and sedimentation	• Deforestation of indigenous forests • Unprotected farmland • Overgrazing • Poor road construction • Unpaved tracks and gullies • Urban runoff • Clearance of riparian vegetation • Cultivation of fragile soils	• Increased sediment loads/turbidity • Reduced primary production • Loss of sensitive species • Faecal contamination	• Watershed management • Halt deforestation • Farm soil and water conservation • Law enforcement • Land adjudication • Management of livestock densities • Controlled livestock movements – zero grazing • Deferment, reforestation, controlled burning • Road drainage maintenance Infrastructure improvement • Resitting of roads and tracks	-Shepherd et al., 2000; Scheren et al., 2000; Masese and McClain, 2012; Kroese et al., 2020a, b; Jacobs et al., 2018
	Eutrophication	• Nutrient loading • Land use change • Agricultural intensification • Poor waste management	• Water pollution • Proliferation of algal blooms – including harmful algae • Ecological changes • Changes in fish and algal composition • Biodiversity loss	• Watershed management • Sustainable agriculture • Treatment of sewage and wastewater • Wetland engineering	-Bootsma and Hecky, 1993; Calamari et al., 1995; Scheren et al., 2000; Verschuren et al., 2002; Hecky et al., 2010; Nyenje et al., 2010; Kilonzo et al., 2014; Jacobs et al., 2017, 2018
Human population growth	Urbanization, industrialization and poor waste management	• Migration from rural to urban areas • Poor maintenance of waste handling and treatment facilities • Inadequate infrastructure for waste management • Housing	• Wastewater point source pollution • Leakages of sewage and landfills • Water pollution • Habitat disturbance • Diversion or burial of streams • Wetland reclamation and degradation	• Waste management by recycling and prohibiting plastic bags • Provision of adequate infrastructure and housing • Urban planning to curb proliferation of informal settlements. • Rehabilitation and maintenance of wastewater	Nyenje et al., 2010; Darwall et al., 2011; Okot-Okumu, 2012; Ravina et al., 2021; Elame, 2023

(Continued)

TABLE 3 Continued

Human threats or challenges	Sub-challenges	Main causes	Main ecological and environmental effects	Management options	Examples of references
		shortages • Poor or inadequate service provision (sewerage, garbage collection and other amenities) • Unplanned informal settlements • Poor or lack of urban planning • Poor enforcement of urban guidelines and regulations	• Channelization of rivers for navigation and flood control • Deforestation • Altered natural flow regimes • Altered ecosystem structure and function • Altered aquatic community composition through loss of sensitive species • Light pollution • Biodiversity loss	treatment facilities • Proper site selection of landfills to avoid leakage and groundwater contamination • Decentralization of services and opportunities to minimize rural-urban migration • Improved enforcement of urban guidelines and regulations	
Resource overexploitation	Overfishing	• Increased fish demand • Illegal, unrestricted and unreported fishing • Overdependence on capture fisheries	• Reduction in fish catches- reduced recruitment • Local extinctions • Ecological changes • Loss of livelihoods	• Increased fish production through aquaculture • Monitoring fishing effort • Enforcement of fishing regulations	Balirwa et al., 2003; Nyamweya et al., 2020
	Clearance of riparian zones	• Deforestation • Agricultural intensification • Exotic tree species – mainly *Eucalyptus* • Livestock watering in streams and rivers • Devegetation of streambanks • Poor soil conservation practices in proximity to streambanks	• Poor water quality • Nutrients and sediment loading • Eutrophication • Alteration of basal resources for food webs • • Altered community composition - invertebrates. • Biodiversity loss	• Reduce run-off and load upstream • Wetland engineering • Riverbank revegetation & grazing control • Conservation tillage up to 1 km from streambank • Borehole and stock tank construction • Controlled livestock movements – zero grazing	-Shepherd et al., 2000; Masese and McClain, 2012; Iteba et al., 2021; Nyamweya et al., 2023a
Land use and land cover changes	Land use and land cover changes	• Deforestation • Expansion of agriculture and settlements • Burning of vegetation	• Increased peak discharges and reduced base flows. • Water shortages • Poor water quality • Massive floods • Very high run-off, sheet, rill, gully erosion, land-slides • Raw sewage and agrochemical point source pollution • Aerosol emission	• Land use planning- land adjudication • Watershed management • Deferment, reforestation •	-Mati et al., 2008; Mugo et al., 2020; Guzha et al., 2018; Jacobs et al., 2018
Loss of ecosystem connectivity	Damming and dyking (channeling)	• Increased demand for water and hydropower (building of dams) • Flood control	• Disruption of longitudinal and lateral connectivity of rivers • Disruption of fish migrations • Population declines and extinction of migratory species • Collapse of riverine fisheries • Alteration of natural	• Provision of fish passages • Off-channel storage of water for irrigation, domestic and industrial supply • Development of environmentally friendly sources of energy such as solar, wind and geothermal • Management of water releases from dams	-Cadwalladr, 1965; Junk et al., 1989; Masese and McClain, 2012; O'Brien et al., 2019; Masese et al., 2020b

(Continued)

TABLE 3 Continued

Human threats or challenges	Sub-challenges	Main causes	Main ecological and environmental effects	Management options	Examples of references
			flow regimes of rivers • Sedimentation (upstream of dams) and sediment removal (downstream of dams)	• Environmental and social impacts assessments of dams	
Modification of natural flow regimes	Modification of water levels and flow regimes	• Overabstraction of water • Construction of dams • Water diversions - inter-basin water transfers (IBTs) • Land use change (deforestation)	• Ecological effects (disruption of feeds in and migrations of rheophilic species) • Water shortages • Declines in water quality	• Water allocation planning • Management of water releases from dams • Environmental flow assessments • Watershed management – water conservation • Land adjudication • Deferment, reforestation • Management of inter-basin transfers	-Sangale et al., 2005; Declaration, 2007; Mati et al., 2008; Melesse et al., 2008; Arthington, 2012; Dessu et al., 2014; McClain et al., 2014; Guzha et al., 2018; Jacobs et al., 2018;
Habitat loss and degradation	Habitat loss and degradation	• Burning and draining • Waste (both solid and liquid) disposal • Conversion to other uses (farmlands, grazing lands, settlements) • Building of dams and dykes • Overgrazing • Introduction of exotic species – e.g., *Eucalyptus* • Over-harvesting of biomass • Socio-cultural factors- poor perceptions • Lack of regulated use Lack of knowledge about the functions and values of wetlands • Weak or inadequate policy, legal and institutional frameworks • Poor enforcement of regulations	• Loss of wetland areas • Wetland degradation and loss of ecological functions • Alteration of natural water balance • Water scarcity/wetland drying • Flooding and soil erosion • Alteration of community composition (macrophytes, invertebrates) • Habitat and biodiversity loss	• Watershed management • Management of land use - land adjudication • Restoration and rehabilitation of degraded wetlands • Reducing overgrazing • Development of management plans • Banning exotic introductions • Increased monitoring of wetland status and ecosystem functioning • Developing adequate policy, legal and institutional frameworks • Awareness creation among communities • Strengthening enforcement of existing guidelines and regulations on wetland use and conservation	Denny, 1993; Chapman et al., 2001; Kairu, 2001; Kansiime et al., 2007; Masese et al., 2012; Owino and Ryan, 2007; Morrison et al., 2012; Okeyo-Owuor et al., 2012; Mitchell, 2013; Rongoei et al., 2014; Mulei et al., 2016
	Inadequate monitoring	• Lack of guidelines, indices or biocreteria for bioassessment • Lack of funds for water quality and quantity monitoring • Lack of equipment and infrastructure • Inadequate policy and	• Continued degradation of water resources • Lack of knowledge/data on impacts of human activities • Alteration of ecosystem structure and functions • Biodiversity loss	• Development of biological criteria for regional biomonitoring • Standardization of sampling and monitoring protocols • Increased funding for infrastructure and research • Enhancing biodiversity surveys • Data sharing • Training adequate personnel	Dickens and Graham, 2002; Raburu et al., 2009a, b; Raburu and Masese, 2012; Masese et al., 2013; Kaaya et al., 2015; Achieng' et al., 2021; Dallas, 2021; Masese et al., 2025b

(Continued)

TABLE 3 Continued

Human threats or challenges	Sub-challenges	Main causes	Main ecological and environmental effects	Management options	Examples of references
		guidelines for biomonitoring • Limited qualified personnel			
Exotic and invasive species	Exotic and invasive species	• Aquaculture (in case of fish) • Sport fishing • Biomanipulation • Aesthetics • Biological control • Poor monitoring • Lack of or limited control measures • Inadequate enforcement of guidelines and regulations • Lack of knowledge or data on potential effects of exotic introductions	• Ecological changes- biomanipulation • Threats to indigenous species • Extinctions of native species- case of haplochromine cichlids in Lake Victoria • Interspecific competition, hybridization and genetic swamping • Ecosystem effects	• Halting exotic introductions • Biological control (in case of water hyacinth) • Developing guidelines and regulations for exotic introductions • Enhanced surveys and monitoring • Awareness creation and community involvement – citizen science	- Ogutu-Ohwayo, 1990; Twongo, 1991; Mugidde et al., 2005; Masese et al., 2021a; Kwikiriza et al., 2023
Climate change	Climate change	• Increased emissions of greenhouse gases (GHGs) at the global and local scales • Burning of fossil fuels • Industrial emissions	• Variability in rainfall • Increased frequency and intensity of rainfall and droughts • Excessive flooding and drying of streams and rivers • Increased water temperature • Browning effect caused by excessive dissolved organic matter • Ecosystem effects • Biodiversity loss	• Minimizing emissions of GHGs to the atmosphere • Management of water quality • forestation and reforestation • Curbing deforestation and land use and land cover changes	-Awange et al., 2008; Dessu and Melesse, 2013; Platts et al., 2015; Roy et al., 2018; Mwanake et al., 2019, 2022; Seeteram et al., 2019; Nassali et al., 2020; Deirmendjian et al., 2021
Policy and governance challenges	Inadequate and poor enforcement of regulations	• Inadequate policy, legal and institutional frameworks • Inadequate capacity/qualified personnel • Lack of funds and resources • Poor training of natural resources managers • Laxity or lack of capacity in enforcement • Poor monitoring of natural resources • Lack of data/ limited knowledge • Lack of or poor harmonization and coordination of enforcement	• Increased human impacts on water resources. • Overexploitation of water/natural resources • Overfishing • Loss and degradation of fragile ecosystems such as wetlands and ecotones • Tragedy of the commons	• Harnessing of local innovations to reverse species loss • Increased regional cooperation, • Public awareness and participation • Enhanced training in natural resources and biodiversity conservation • Harmonization of policy, legal and institutional frameworks • Strengthening co-management	-Ntiba et al., 2001; Lelo et al., 2005; Sayer et al., 2018; Kishe-Machumu et al., 2018

Effective catchment protection based in IWRM principles requires management actions that recognize and uphold nature-based processes crucial for enhancing the self-cleansing capacity of rivers, like dilution, filtration, sedimentation, and biodegradation (McClain, 2002; Keesstra et al., 2018). To achieve this, efforts should focus on conserving and restoring essential components of natural systems such as riparian zones and similar ecotones, natural channel forms and riverine and fringing wetlands, and revitalizing degraded systems through restoration, effective deployment of nature-based solutions and phytotechnologies. Initiatives such as reforestation, agroforestry, and soil and water conservation in catchments can mitigate soil erosion and nutrient runoff into streams and rivers, ultimately benefitting the lake (Pavlidis and Tsihrintzis, 2018; Zhu et al., 2020).

There has been a progressive shift from top-down or voluntary watershed management programs to incentive-based approaches in many countries and regions (e.g., Wunder, 2005; Kagombe et al., 2018; Ola and Benjamin, 2019). Payments for Ecosystem Services (PES) involve providing monetary compensation for ecosystem services like carbon sequestration, biodiversity, scenic beauty, and watershed protection. Successful PES implementation requires identifying and evaluating environmental services and establishing payment mechanisms to encourage continued service provision. At the watershed scale, Payment for Watershed Services (PWS) provides alternative income sources for upstream farmers, reducing reliance on agriculture alone for food and family incomes. PWS involves downstream communities, the government, or other financial sources paying upstream farmers for maintaining land use activities that preserve water quality and quantity. While PES is established globally, its adoption is growing in eastern Africa (Masiga, 2011). Because of its success in areas where it has been implemented, PES represent an innovative approach that can be integrated into existing legal and institutional frameworks to incentivize sustainable land use and conservation practices. In the Mara River basin mechanisms have been established that will enable its implementation (Bhat et al., 2014; Hashimoto et al., 2014), and the same framework can be applied in other rivers in the LVB.

5.2 Pollution control and waste management

In many urban areas within the LVB, planning remains outdated and largely ineffective. Planning regulations often rely on frameworks developed decades ago when human populations were significantly lower and environmental sustainability was not a central concern. As a result, many towns and cities continue to grow without integrated environmental considerations. Poor urban planning, combined with weak enforcement of building codes and limited environmental monitoring, has led to the development of urban centers lacking essential sewerage and sanitation infrastructure. Despite the East African Community (EAC) member states having the technical capacity to revise and update urban planning systems, the continued deterioration of urban infrastructure poses a serious threat to both water resources and biodiversity across the basin.

Pollution control and effective waste management are critical interventions that can significantly enhance water quality and protect aquatic biodiversity in the LVB. The rehabilitation and proper maintenance of waste treatment and disposal facilities in urban areas and industrial zones are essential to preventing untreated sewage, solid waste, and industrial effluents from entering rivers and eventually Lake Victoria itself (Odada et al., 2004). These pollutants contribute to eutrophication, deoxygenation, and the loss of sensitive aquatic species - disrupting food webs and reducing the ecological resilience of the lake. Furthermore, the promotion of cleaner production technologies in industries, accompanied by strong economic incentives and enforcement mechanisms, is essential. Cleaner production reduces the generation of harmful waste at the source, lowering the risks of pollution.

5.3 Habitat conservation and rehabilitation

Habitat conservation and rehabilitation are essential for protecting aquatic biodiversity in the LVB. Wetlands, riverbanks, and shoreline habitats serve as breeding and feeding grounds for numerous aquatic species, including endemic fish and migratory birds (Chapman et al., 2001; Owino and Ryan, 2007; Sayer et al., 2018). Conserving these habitats helps maintain ecological balance and water quality by filtering pollutants and reducing sedimentation. Rehabilitation efforts, such as reforestation, wetland restoration, and erosion control, can revive degraded areas, restore natural hydrological cycles, and provide critical habitats for threatened species (Okeyo-Owuor et al., 2012). Protecting riparian zones also reduces runoff of agrochemicals and waste into the lake, minimizing harmful algal blooms and oxygen depletion. Additionally, engaging local communities in conservation programs promotes sustainable resource use and strengthens environmental stewardship (Were et al. 2013). Ultimately, habitat conservation ensures long-term ecosystem resilience and supports fisheries, water security, and livelihoods dependent on the lake's biodiversity (LVBC, 2016; UNEP, 2012).

The spatio-temporal dynamics of ecological processes in rivers are linked to those of riparian species. Similarly, riverine ecosystems in the LVB rely on direct organic matter inputs in the form of litterfall from riparian vegetation (Masese and McClain, 2012; Masese et al., 2014a). Prioritizing the restoration and upkeep of native riparian forests is important since introduced plant species such as sugarcane, maize, and *Eucalyptus* spp. have replaced native vegetation in riparian areas. Maintaining buffer strips beside riverbanks can also aid in the management of sediments and nutrients that are washed off agricultural hillslopes (Jacobs et al., 2017; Kroese et al., 2020a, b; Patoway et al. 2025). Deforestation should be stopped at the catchment level, and the current rehabilitation initiatives should be enhanced and extended. This will be very helpful in stabilizing river flows and reducing soil erosion and nutrient loading during the wet season (Jacobs et al., 2017; Guzha et al., 2018; Kroese et al., 2020a, b).

5.4 Enhancing research, monitoring and data sharing

Enhancing research, monitoring, and data sharing is crucial for protecting aquatic biodiversity in the LVB (Achieng et al., 2023). Continuous scientific research helps identify trends in species populations, water quality, and ecosystem health, enabling timely conservation actions. Improved monitoring systems allow for early detection of environmental threats such as pollution, invasive species, and overfishing (Masese et al., 2023; Plisnier et al., 2023; Arimoro et al., 2024). Sharing data across EAC's member states fosters regional cooperation, harmonizes management strategies, and supports evidence-based policy-making. Collaborative platforms involving governments, researchers, and communities ensure that biodiversity protection efforts are informed, coordinated, and adaptive to the basin's dynamic environmental challenges (LVBC, 2016; Odada et al., 2004; Lawrence et al., 2023).

More research effort should focus on the assessment of threats facing aquatic biodiversity and the description of new species and their environmental requirements. Offshore rocky islands, rocky mainland shores, satellite lakes of the LVB, and some deep-water sites in Lake Victoria host diverse fish assemblages, mostly threatened and endangered haplochromine cichlids (Kishe-Machumu et al., 2018). The lower and upper reaches of major rivers host diverse groups of cyprinid species, some of which have not been described (Mugo and Tweddle, 1999; Kishe-Machumu et al., 2018; Masese et al. 2020b). Extensive sampling efforts should be directed to these habitats to collect and identify all fishes to the species level and be continuously monitored and protected from ongoing habitat degradation and water pollution. Also, efforts to map the critical biodiversity hotspots, spawning sites, and nursery areas for fish species in rivers, wetlands, Lake Victoria and its satellite lakes need to be enhanced (Sayer et al., 2018; Aura et al., 2018).

Description of new species should be done using morphology, meristics, and genetic biomarkers. Genetic biomarkers are particularly important because they allow for the processing of vast quantities of specimens and the costs have tremendously reduced over the years. The use of genetic biomarkers in taxonomic studies should also be extended to investigate instances of genetic introgression and hybridization among species (Kwikiriza et al., 2023). Studies have shown that the decline of indigenous tilapiine cichlids in Lake Victoria is caused by, among a wider range of other factors, hybridization with introduced tilapiines (Goudswaard et al., 2002; Angienda et al., 2011). Similar incidences of genetic introgression have been reported among the small-bodied cyprinids (Schmidt et al., 2017), and haplochromine cichlids (Seehausen et al., 1997). Development of simplified taxonomic keys should also be done, and existing identification schema updated. The use of photo identifications of species, especially among non-cichlids whose identities is not dependent on color, should be explored. Additional fish taxonomists should be trained in the identification, systematics, and biodiversity of these species. These taxonomists will also help to update limited knowledge on the distribution of most fishes in the LVB.

Further research should explore the development of biological tools for bioassessment of aquatic ecosystems in the LVB. While several studies have used biological communities such as diatoms, plankton, invertebrates and fish in biomonitoring of water quality and other human disturbances in streams, the major rivers, wetlands, small water bodies and Lake Victoria (Masese et al., 2009a, b; Ngodhe et al., 2014; Abong'o et al., 2015; Raburu and Masese, 2012; Kondowe et al., 2022; Masese et al., 2025b), standardized indices have not been developed at the basin scale. Within the same framework, several indices have been developed to assess the ecological integrity of various river systems (Raburu et al., 2009a, b; Raburu and Masese, 2012; Achieng' et al., 2014). These indices have captured changes in aquatic environments as a result of the increasing extent and intensity of human activities. To preserve water quality and aquatic biodiversity, the greatest challenge is to lessen the effects of the existing human threats and preserve the integrity of water resources (Masese et al., 2023; Masese et al., 2025b).

Going forward, the development of biomonitoring indices should be standardized for use at both the whole basin and regional scale so that findings are comparable among river basins. Studies are underway in Kenya to develop a macroinvertebrate-based rapid bioassessment protocol - the Kenya Invertebrate Scoring System - for streams and wadable rivers (FO Masese et al. unpublished data). In Tanzania, a biotic index was developed called the Tanzania River Scoring System (TARISS, Kaaya et al., 2015), which was modeled along the South African Scoring System version 5 (SASS5; Dickens and Graham, 2002). If used for regular monitoring of streams and rivers, these indices will help identify streams and rivers in need of restoration and to monitor trends in ecological status. Similarly, if the indices are broadened to include fish and other aquatic communities, such as diatoms, macrophytes and amphibians, they would be useful in monitoring changes in assemblage characteristics because of human disturbance.

The LVB ecosystem is very dynamic and there in a need for continued research and monitoring. Most of the research in the lake basin is donor driven. However, donor funding is often irregular and may not be aligned with the pressing concerns on the management of the lake and its basin. There is, therefore, a need to come up with home grown projects with local sources of funds. For example, plans are at an advanced stage to create a fish levy trust from sale of fish. The fund is to be ploughed back to improve the management of the lake and its resources. Scientific findings should be made available to local communities in a way they can understand. This will make communities aware of the significance of environmental management and conservation.

To support evidence-based decision-making for the management and conservation of freshwater resources in the African Great Lakes region, including the LVB, the African

Centre for Aquatic Research and Education (ACARE – https://www.agl-care.org) has developed the African Lakes Hub (https://www.africanlakeshub.org). This platform enables the sharing of information (empirical data, publications, reports) among a diverse range of stakeholders, including scientists, educators, policymakers, managers and local communities. Limited research, restricted access to and sharing of existing data and research outputs have been identified as key barriers to the sustainable management of the African Great Lakes (Lawrence et al., 2023; Plisnier et al., 2023). Similar initiatives should be supported and scaled up to help protect freshwater ecosystems, their biodiversity, and the essential goods and services they provide to communities for their livelihoods and well-being.

5.5 Improvement of policy, legal and institutional arrangements

A comprehensive approach involving improvements in policy, legal frameworks, and institutional arrangements is needed to safeguard water resources and biodiversity in the LVB. Some of the causes of degradation of water resources in the LVB include lack of monitoring and enforcement of regulations (LVFO, 2015, 2016; Plisnier et al., 2023; Nyamweya et al., 2023b). While laws and regulations on environmental protection exist in all EAC countries, their enforcement is poor (Nunan et al., 2018). For example, all industries are required by law to have functional wastewater treatment facilities. However, few industries have working treatment plants. Wastewater and solid waste are left to spread and contaminate streams and finally find its way to the lake. Moreover, during enforcement of existing regulations, different laws and penalties exist in the partner states for the same offense. In addition, environmental management and enforcement of regulations are implemented by different government ministries in riparian states which makes it difficult to formulate and implement environment protection policies. In order to have a consistent and smooth policy implementation for the management of the environment and water resources in the LVB, harmonization of policies, regulations and laws across the different riparian countries is vital.

Under the umbrella of the EAC, natural resource management regulations are being revised and harmonized to improve efficiency during implementation. All EAC member states have endorsed many international conventions such Ramsar Convention on Wetlands, Convention on International Trade on Endangered Species of World Fauna and Flora (CITES), the Convention on Biological Diversity (CBD), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). However, not all endorsed conventions or environmental multilateral agreements (MEAs) are implemented as desired. As a result, there is continued degradation of the environment and biodiversity is declining. However, it is hoped that the enactment of sound environmental policies in all of the EAC member states, and the strengthening of environmental protection agencies to enforce them will lead to sound management and protection of natural resources, including water resources and biodiversity. Proper awareness, resource mobilization, full commitment by all partners, and community participation can further improve enforcement.

There is a suite of environmental laws and regulations in all countries in the LVB that are meant to safeguard the environment and minimize deleterious effects of human activities. However, the threats to water resources and aquatic biodiversity remain because of laxity or lack of capacity in enforcement. For instance, although laws and regulations prohibit the use of beach seines, trawl nets, monofilament, mosquito nets of less than 10 mm mesh size, and gill nets of less than 127 mm mesh size in Kenya, fishermen continue to use them in the Lake Victoria and rivermouths of influent rivers (Etiegni et al., 2011; Waswala-Olewe et al., 2014; Nyamweya et al., 2023b). Similarly, regulations provide for a riparian buffer along rivers and wetlands, but in many cases human activities, including farming and construction of settlements, do not respect this provision (Lelo et al., 2005). In Kenya, for instance, the law on riparian zone protection is fragmented in numerous pieces of legislations, which presents a problem of overlapping mandates and lack of coordination in enforcement (Makindi and Mugatsia, 2024). Moreover, the width of a riparian buffer zone is not clearly specified in these Acts, and it ranges from 6 m for small streams to 30 m for larger rivers.

Some of the measures that have been proposed to reverse biodiversity loss in the LVB include revamping of environmental policies, regional cooperation, public awareness, and harnessing of local innovations (Sayer et al., 2018). To improve the effectiveness of existing management structures, regulations, and laws in controlling logging and deforestation, papyrus swamp destruction and illegal fishing practices and introduction of alien species, it is recommended that resource managers work in collaboration with state agencies, and that they receive training in the biodiversity conservation and ecological requirements of vulnerable and threatened species (Kishe-Machumu et al., 2018).

5.6 Community participation and awareness creation

Effective protection and sustainable governance of biodiversity and water resources in the LVB require the active involvement of local communities, who are both the primary users and custodians of these ecosystems. The high level of dependency on fisheries, wetlands, forests, and freshwater sources by surrounding communities means that any conservation effort that excludes them is likely to be ineffective or short-lived. Recognizing this, it is essential to engage communities not merely as beneficiaries, but as core stakeholders in the design, implementation, monitoring, and enforcement of environmental regulations and conservation programs.

Community-based approaches, such as the establishment of Water Resources User Associations (WRUAs) and Beach Management Units (BMUs) in riparian countries, have proven effective in bringing together various users to collectively manage and protect shared resources (Munyua and Mbugua, 2019; Richards, 2019). These structures not only promote transparency and shared decision-making, but they also cultivate a strong sense of ownership, encouraging responsible and sustainable resource use. When communities see direct benefits - such as improved access to clean water, sustainable fish stocks, or enhanced agricultural productivity - they are more likely to support and uphold conservation practices (Dawson et al., 2021).

Furthermore, raising awareness about the importance of biodiversity and the environmental consequences of destructive practices is key to changing behavior and building a conservation ethic (Nielsen et al., 2021; Vucetich et al., 2021). Awareness campaigns that use culturally relevant messaging and leverage indigenous and local knowledge can significantly improve community understanding of ecological interdependencies and the long-term value of ecosystem services (Brondízio et al., 2021). Education initiatives, particularly those targeting youth and women, play a transformative role in fostering environmental stewardship across generations. Participation of communities in conservation initiatives can also incorporate citizen science whereby community members are involved in data collection regarding the status of ecosystems, their contributions to people's wellbeing and the impacts of human activities (Kobori et al., 2016; Aura et al., 2021).

The shift towards integrating community participation into all conservation and development projects within the LVB reflects a broader regional paradigm that aligns ecological sustainability with social inclusion. Mandating community-based components in biodiversity and water resource management ensures that interventions are grounded in local realities and are therefore more adaptable and resilient. This approach not only improves project outcomes but also strengthens the social fabric of environmental governance, enabling communities to become proactive agents in biodiversity protection.

5.7 Sustainable use of natural resources

Sustainable use of natural resources is critical to protecting the biodiversity of the LVB, a region rich in ecological value but facing increasing environmental pressure due to human activity. Central to sustainability is the principle of meeting current needs without compromising the ability of future generations to meet theirs (Lindsey, 2011). In the LVB, this means adopting practices that balance economic development with ecological integrity.

Overfishing is a major threat to aquatic biodiversity in Lake Victoria, with declining fish stocks and loss of endemic species (Nyamweya et al., 2023a, b). By implementing sustainable fishing practices - such as regulated fishing seasons, gear restrictions, and enforcement of catch limits - fish populations can be allowed to regenerate, preserving the ecological balance and securing long-term livelihoods.

Reducing dependency on natural resources, such as through alternative income-generating activities (e.g., aquaculture, eco-tourism, or beekeeping), helps alleviate pressure on forests, wetlands, and fisheries. This diversification also enhances community resilience to environmental shocks. Similarly, limiting excessive water abstractions, particularly for irrigation and industry, is vital to maintaining healthy river and lake ecosystems. When water levels drop significantly, it disrupts habitats, breeding cycles, and water quality- threatening both aquatic and terrestrial biodiversity (Wantzen et al., 2008; Sabater and Tockner, 2009). In addition, curbing deforestation through reforestation, agroforestry, and sustainable land-use planning prevents habitat loss, soil erosion, and sedimentation in water bodies, all of which harm biodiversity.

Ultimately, sustainable resource use promotes a more harmonious relationship between people and nature in the LVB. It ensures that natural ecosystems remain productive and diverse, supporting both environmental health and socio-economic well-being in the long term.

5.8 Maintaining connectivity of ecosystems

Maintenance of terrestrial-aquatic ecosystem connectivity is crucial, as aquatic communities in lower reaches are heavily dependent on external energy sources from upstream and adjacent riparian areas (Masese and McClain, 2012). Fish migrations between Lake Victoria and its tributaries play a vital role in accessing spawning habitats and food resources needed for reproduction (Manyala et al., 2005). The adverse effects of fishing gears impeding upstream fish migration during breeding seasons, particularly in the lower reaches of many rivers, are well known (Whitehead, 1959; Cadwalladr, 1965). Such practices have been detrimental to migrating fish but have also potentially limited the input of organic matter and nutrients into the rivers, released through the defecation or death of migrating fish. Diking rivers and draining wetlands through channel construction have further restricted lateral connectivity and the transfer of organic matter and sediments between rivers and their floodplains (Masese and McClain, 2012).

To counteract issues of connectivity loss, and the associated impacts on nutrient and energy flows and ecosystem services, planning and construction of new dams and water storage facilities should consider the spatial configuration of dams and small-scale hydropower plants to minimize negative impacts (Nel et al., 2009; O'Brien et al., 2021). Special consideration should be given to off-channel storage of water to minimize blockage of waterways for migratory species (Masese and McClain, 2012). Further enhancement of connectivity should also emphasize the maintenance and protection of instream habitats and water quality, and meet the flow requirements of sensitive and migratory species (e.g., McClain et al., 2014). If flow and habitat conditions remain favorable, the important role played by LVB rivers as major breeding grounds for both lacustrine and riverine species will be maintained.

Enhancing ecosystem connectivity and the protection of aquatic biodiversity in the LVB will also entail the protection of environmental flows of streams and rivers. 'Environmental flows' refer to the water regime of a river, wetland or coastal zone necessary to maintain the biophysical components, ecological processes and health of aquatic ecosystems, and associated ecological goods and services (Arthington et al., 2006). Most countries of the LVB have laws that recognize and protect environmental flows in rivers in addition to maintaining minimum flows required to meet basic human needs (McClain et al., 2013). In the Kenya Water Act 2016, these protected flows are collectively referred to as the 'reserve', which is defined as "that quantity and quality of water required (a) to satisfy basic human needs for all people who are or may be supplied from the water resource; and (b) to protect aquatic ecosystems to secure ecologically sustainable development and use of the water resource". Similar laws and regulations are in place in all member states that share the LVB. Supported by these legal frameworks, water resource managers in the LVB should pay more attention to maintaining the natural flow regimes of rivers. Doing this will require a comprehensive and stakeholder-driven environmental flow assessment to determine the amount available on an annual basis for allocation while protecting the 'reserve' (McClain and Masese, 2024). Following the example of the Mara River (McClain et al., 2014), and the rising demand for water to meet needs of the increasing human population, assessment of environmental flows in other rivers will be important as a conservation strategy.

5.9 Management of exotic and invasive species

The management of exotic and invasive species is critical to safeguarding the aquatic ecosystem integrity and biodiversity of the LVB. Invasive species disrupt native ecosystems, often leading to the decline or extinction of indigenous flora and fauna. One of the most destructive invasive species in Lake Victoria is the water hyacinth (*Eichhornia crassipes*), which was introduced in the 1980s (Twongo, 1991). It rapidly colonized large areas of the lake, forming dense mats that blocked sunlight, reduced oxygen levels, and hindered the photosynthetic activity of aquatic plants, thereby altering aquatic habitats (LVEMP, 2011).

These mats also interfered with fishing, transport, hydropower generation, and water supply systems. The impact on biodiversity was severe, as many native fish species, particularly the endemic haplochromines, lost breeding and feeding grounds. To address this, biological control methods were introduced, notably the release of weevils (*Neochetina eichhorniae* and *Neochetina bruchi*), which feed on water hyacinth leaves and have significantly reduced its spread in some parts of the lake (Wilson et al., 2007). While not a complete solution, these weevils have proven effective in curbing water hyacinth proliferation when supported by mechanical and community-based manual removal programs.

Another invasive species of concern is the Nile perch (*Lates niloticus*), introduced in the 1950s to boost commercial fisheries (Marshall, 2018). While it created an economically valuable fishery, its introduction led to the extinction or drastic reduction of over 200 native fish species due to predation and competition (Ogutu-Ohwayo, 1990). The ecological imbalance caused by the Nile perch continues to threaten native biodiversity (Aloo et al., 2017). Current management efforts include promoting balanced fishing practices, protecting refugia for native species, and supporting the recovery of indigenous fish through restocking programs (Aura et al., 2023; Nyamweya et al., 2023b).

Controlling invasive species is not only a conservation priority but also an economic and social necessity. Effective management combines biological, mechanical, and policy-driven approaches, supported by scientific research and regional cooperation. Such integrated strategies are essential to restore ecological balance, support livelihoods, and preserve the unique biodiversity of Lake Victoria.

5.10 Climate change mitigation

The impacts of climate change on aquatic biodiversity in the LVB are increasingly evident through rising temperatures, changing rainfall patterns, more frequent extreme weather events, and fluctuating lake levels. These changes affect water quality, aquatic habitats, fish breeding cycles, and overall ecosystem health (Nyboer et al., 2022). Effective management and mitigation strategies are essential to reduce these impacts and protect biodiversity.

One key approach is ecosystem-based adaptation (EbA), which uses biodiversity and ecosystem services to help communities adapt to the adverse effects of climate change (Chong, 2014). For instance, restoring riparian buffers and wetlands helps regulate water flow, prevent erosion, and filter pollutants before they reach the lake. Wetlands also act as carbon sinks, contributing to climate mitigation while supporting biodiversity (UNEP, 2012).

Another important strategy is the promotion of climate-smart fisheries and agriculture. Practices such as regulating fishing seasons, protecting spawning grounds, and promoting alternative livelihoods like aquaculture, agriculture and engaging in businesses can help fish populations recover and adapt to changing conditions (LVBC, 2016; Nyboer et al., 2022). In Uganda, for example, fish breeding zones have been identified along the shores of Lake Victoria to support the regeneration of native fish species under increasing climatic stress (Nkalubo et al., 2018).

Improved data collection and climate modelling are also essential. Monitoring changes in water temperature, fish migration, and rainfall patterns can inform timely interventions and policy adjustments (Plisnier et al., 2023). Regional climate services coordinated by the Lake Victoria Basin Commission (LVBC) and the IGAD Climate Prediction and Applications Centre (ICPAC, https://www.icpac.net/) support early warning systems for droughts and floods, helping to protect both human communities and ecosystems.

6 Future research needs

A synthesis of available data and review of the literature has identified several knowledge gaps in understanding the structure and function of aquatic ecosystems, the influence of human activities and feedback to these influences (Table 4). Although not exhaustive, the list of research needs and knowledge gaps is aimed at stimulating discussion on information needed to better manage and protect aquatic ecosystems in the LVB.

TABLE 4 Research needs, gaps in knowledge and potential applicable tools in studies of aquatic ecosystems in the Lake Victoria basin. Both lists of potential tools and related studies are not exhaustive.

Research Needs	Knowledge gaps	Potential applicable tools	Examples of similar studies
Ecosystem structure and function	-Energy sources and nutrient flows in food webs -Changes in dietary quality of basal resources -Drivers of species distributions -Long term responses in fish community structure to land use and land cover change -Nutrient limitation and ecosystem productivity	-Trophic markers and stable isotopes -Stable isotopes, fatty acids, bioenergetic models -Population studies, ecological models -Population studies, ecological models -Nutrient additions experiments, nutrient diffusing substrates	-Masese et al., 2014a, 2018. -García et al., 2017; Jochum et al., 2017; Richoux et al., 2018. -Masese et al., 2014a; Fugère et al., 2018a, 2016. -Fugère et al., 2018b; Leitão et al., 2018. -Masese et al., 2017; Tank et al., 2017; Subalusky et al., 2018.
Ecosystems connectivity	-Status of fish migrations, status of riverine fisheries and the importance of migratory species -Longitudinal importance of different sources of carbon/ nutrients in rivers and effects of point sources, livestock and municipal and industrial discharges	-Acoustic telemetry, tagging studies, stable isotopes, otolith microchemistry, molecular biomarkers (genetics) -Trophic markers, ecological models, remote sensing	Parker Jr et al., 1990; Secor et al., 1995; O'Brien et al., 2013; Hart et al., 2015; Chemoiwa et al., 2013. -Ojwang et al., 2007; Hadwen et al., 2010; O'Brien et al., 2013; Cross et al., 2013
Effects of altered flow regimes	-Effects of reduced or altered flows on biodiversity and ecosystem functioning -Resilience and vulnerabilities of species and processes to altered or reduced flows -Determination of environmental flows for rivers -Effects of prolonged droughts and low flows on invertebrate and fish populations	-Ecological models, mesocosm experiments, physiological studies -Population surveys, ecological models -Population surveys, ecological models -Population surveys; mesocosm experiments; ecological models	-Bunn and Arthington, 2002; Arthington et al., 2010. -Miller et al., 2007; Rosenfeld et al., 2016; Wildhaber et al., 2017. -McClain et al., 2014; O'Brien et al., 2018 - Bogan et al., 2015; Leigh et al., 2016; Calapez et al., 2017.
Taxonomy and systematics of species	-Enhancement of species collections from neglected habitats and regions in the LVB -Preponderance of genetic introgression in different fish groups in rivers, e.g., cichlids and cyprinids -Description of new species, development of new species identification keys and/or updating existing keys and schema	-Surveys for specimen collections -Molecular/genetic biomarkers -Morphometry, meristics & molecular biomarkers (genetics)	- Mugo and Tweddle, 1999; Kishe-Machumu et al., 2018. - Goudswaard et al., 2002; Angienda et al., 2011; Schmidt et al., 2017. -SSchmidt, & Pezold, 2011; Schmidt et al., 2015; Duarte et al., 2017.
Effects of organic matter and nutrients loading	-Influence of nutrient loading by large wildlife and livestock on invertebrates and fish diversity and functional structure -Interaction between flow variation and nutrient loading on species diversity -Influence of carbon and nutrient loading on balance between autotrophy and allochthony	-Population studies, ecological modelling, experimental mesocosms -Population surveys, experimental mesocosms, ecological modelling -Nutrient additions, experimental mesocosms, ecological modelling	-Masese et al., 2015, 2018; Subalusky et al., 2018 -Dutton et al., 2018b; Masese et al., 2018; Dawson et al., 2016. -Riley and Dodds, 2012; Masese et al., 2017; Subalusky et al., 2018.
Determination of biotope requirements of species	-Establishment of environmental flow requirements of species -Effect of biotope availability on invertebrates and fish communities -Classification of species into environmental guilds	-Population surveys, ecological modeling - Population surveys, ecological models - Population surveys	-Muñoz-Mas et al., 2019a, b; Rosenfeld, 2003; Dallas, 2007; Leitão et al., 2018; Masese et al. 2021a - Welcomme et al., 2006.
Feeding habits, diet composition and trophic relationships	-Influence of water quality and habitat on diet composition of invertebrates and fishes -Influence of altered flows diet composition and condition of fishes -Niche overlaps and competition between exotic and indigenous species -Incidence and occurrences of parasites and diseases in riverine fishes and their influence on fish condition	-Stomach content analysis, trophic markers -Stomach content analysis, trophic markers -Stomach content analysis, trophic markers -Physiological studies, pathological studies	-Corbet, 1961; Olowo and Chapman, 1999; French et al., 2016; Masese et al., 2015. -Winemiller, 1990; Marsh et al., 2017. - Zengeya et al., 2015; Masese et al., 2018. -Susdorf et al., 2018.
Exotic introductions	-Mapping distribution of exotic species in streams and rivers -Population trends, ecology and impact of exotic species	-GIS tools (remote sensing), species distribution models -Individual and population surveys, community studies	-Jean-Nicolas et al., 2017; Aschonitis et al. (2018); Shechonge et al., 2018.

(Continued)

TABLE 4 Continued

Research Needs	Knowledge gaps	Potential applicable tools	Examples of similar studies
Biomonitoring and risk assessment of the fishery	-Assessment of ecological state of rivers -Ecological risk assessment of rivers and the riverine fishery	-Use of indices of biotic integrity utilizing invertebrates and fish -Ecological models	-Karr and Chu, 2000; Raburu et al., 2009a, b; Raburu and Masese, 2012; O'Brien and Wepener, 2012; O'Brien et al., 2018; Masese et al., 2021a; 2023; Arimoro et al., 2024.
Emerging contaminants	-Risks associated with the occurrence of emerging contaminants (e.g., pharmaceuticals and personal care products (PPCPs), polychlorinated biphenyls (PCBs), PFAS and persistent organic compounds (POPs) -Evaluation of harmful effects of these chemicals using persistence, bioaccumulation, and toxicity (PBT) criteria, including ecological effects	- Testing the persistence, bioaccumulation, and toxicity (PBT) criteria -Use of standardized protocols to quantify sub-lethal effects -Study the biological activity, exposure, and ecological effects of the chemicals	-Rosi-Marshall et al., 2015; Ebele et al., 2017; Richmond et al., 2017, 2018; Nantaba et al., 2020; Kandie et al., 2020

Given the dearth of information on ecosystem structure and functioning of Afromontane streams and savanna rivers (Masese et al., 2014a, 2018; Fugère et al., 2018a; Stears et al., 2018; Masese et al., 2022), additional research in LVB is needed to contribute to the development of new models on tropical freshwater ecosystems. However, the most urgent research needs are those involving the threats posed by human activities on water resources and ecosystem services (Masese and McClain, 2012). Research on streams and rivers should focus on organic matter processing and nutrient cycling and impacts of reduced or altered flow regimes on biodiversity and ecosystem function (Arthington et al., 2010). Similarly, research into the vulnerabilities of species and processes to altered habitats, flow regimes and nutrient dynamics in wetlands and lakes is needed. These studies should be tied to those investigating the role and influence of nutrient and organic matter loading from farmlands, wildlife, such as hippopotami, livestock and urban areas on aquatic communities and ecosystem processes (Dutton et al., 2018b; Masese et al., 2018; Stears et al., 2018).

The taxonomy of many invertebrates, fish groups and other taxa in the LVB is in a state of flux. Specifically for fishes, the taxonomy of the small-bodied cyprinids and clariids, and cichlids of the genus *Haplochromis* need particular attention. Studies in Lake Victoria have reported re-emergency of some *Haplochromis* spp. following the disappearance of many after the introduction of *Lates niloticus* into the lake (Kishe-Machumu et al., 2015). Studies are needed to identify the diversity and identity of these seemingly resilient species in Lake Victoria, satellite lakes, rivermouth wetlands and streams and rivers.

Understanding of habitat preferences and requirements of riverine invertebrates and fishes in streams and rivers, is also important (Muñoz-Mas et al., 2019a, b; Masese et al., 2021b). Habitat preferences and the availability of suitable habitats can influence behavior and metabolism of individual taxa as well as their geographical distribution (Dallas, 2007; Radinger and Wolter., 2015; Fugère et al., 2018b). Generating this information would go hand in hand with determination of environmental flow requirements that are needed to maintain ecosystem integrity, species well-being, and ecosystem services McClain and Masese, 2024. Equally important will be an understanding of adaptations of indigenous fishes to changes in ecological conditions, exotic introductions and preferred biotope availability.

Studies on the ecology, feeding habits, trophic and environmental guilds of riverine fishes in the LVB are also needed to augment understanding of biotope preferences and flow requirements of threatened and vulnerable species. The most comprehensive study on diet composition in riverine fishes in the LVB was done nearly 70 years ago (Corbet, 1961), and need to be updated in response to the changing environmental conditions in rivers (e.g., Olowo and Chapman, 1999). Studies in the Mara River have shown that insectivorous fishes are stenotopic and utilize a narrow range of food resources (Masese et al., 2015). This is informative for species management and conservation, considering that the upper reaches of LVB rivers mainly harbor insectivorous fishes, which constitute 70-100% of fish species and by far dominate the abundance and biomass in other river sections (Raburu and Masese, 2012; Masese et al., 2018). It has been suggested that all riverine fishes in the LVB incorporate insects to some extent in their diets (Corbet, 1961; Masese et al. 2020b; Nakangu et al., 2023), and this points to the role a healthy river system must play for invertebrate as well as fish communities. Thus, insectivorous fishes occupy an important position in the rivers as a highly viable option for bioindication and other ecological studies.

Hybridization has been identified as a threat to indigenous tilapiine and haplochromine cichlids in Lake Victoria (Goudswaard et al., 2002; Angienda et al., 2011; Wasonga et al., 2017). Thus, there is a need to study the preponderance and severity of genetic introgression in LVB fishes. Studies in rivers have noted genetic hybridization in species of genus *Enteromius* (Schmidt et al., 2017). The occurrence of these species in the LVB rivers is evidence that hybridization may also be occurring, which calls for further investigation. Similarly, a recent survey in the Mara River reported hybridized individuals of *Orechromis niloticus* and *Oreochromis variabilis* (O'Brien, 2016). There is an urgent need to understand the causes of these hybridizations, how common they are, and potential effects on indigenous species.

Comprehensive mapping of exotic species in all aquatic ecosystems in the LVB is also needed to determine their status and trends. These data should include population characteristics (abundance, reproduction) and distribution. For instance, the redswamp crayfish is widespread in wetlands, streams, and dams in Nzoia River basin. The risk exists that this aggressive invader is expanding its range to the lower reaches of the River Nzoia, wetlands surrounding Lake Victoria, the satellite lakes, and Lake Victoria itself. A second invasion of Lake Victoria by an aggressive macroconsumer will be detrimental to remnants of indigenous fish species that are recovering from unfortunate consequences of exotic introductions. Moreover, the role of rivermouth wetlands and satellite lakes as refugia for vulnerable fish species will be compromised. The distribution and populations of other introduced species in the headwaters of LVB rivers, such as trouts *Salmo trutta* Linnaeus, 1758 and *Oncorhynchus mykiss* Walbaum, 1792 in Mt Elgon and Cherangani streams (Seegers et al., 2003), should be assessed and their threats to indigenous species evaluated.

7 Conclusions

The LVB has witnessed significant changes to the structure and functioning of terrestrial and aquatic ecosystems. Consequently, water resources have been degraded and biodiversity threatened by a myriad of human activities and threats. Considering that the wellbeing of ecosystems and concerns about biodiversity conservation are intricately linked to nature's contributions to people's welfare, there is an increasing need for effective management measures to maintain the integrity of aquatic ecosystems and their ecosystem services. We have heighted the most pressing human impacts and threats facing aquatic resources and biodiversity conservation in the LVB, and have suggested management strategies necessary to halt the negative trends. We have also identified research needs and areas of research that will contribute to the sustainable management of aquatic ecosystems and better protect biodiversity in the LVB.

Although a number of research gaps have been identified in the LVB that need to be filled, the most pressing research needs are those investigating the threats posed by human activities on the structure and functioning of ecosystem and losses of ecosystem services. Research focusing on novel strategies that reduce human impacts while simultaneously supporting the sustainable use of aquatic resources should be prioritized. These approaches include understanding the habitat requirements of different species, studies on water accounting and allocation, payment for ecosystem/ watershed services, streamlining climate change into water resources management and participatory approaches for natural resources management such as co-management and citizen science. Further research is needed into the susceptibilities of species and ecological processes to modified flow regimes, along with the identification of environmental flow requirements that sustain a targeted degree of ecosystem functionality. Additionally, a key focus should be on exploring ecohydrological processes and nature-based solutions that align with resource management goals, encompassing the natural assimilation of nutrients and pollutants, mitigation of floods, and other mechanisms that augment the efficiency of engineered management systems.

Author contributions

FM: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. EW: Conceptualization, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. HN: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

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