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REVIEW ARTICLE

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Endemic Lake Baringo *Oreochromis niloticus* fishery on verge of collapse: Review of causes and strategies directed to its recovery, conservation and management for sustainable exploitation

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Abstract

Lake Baringo is a Ramsar-designated water body facing a myriad environmental challenges attributable to anthropogenic activities, thereby being an ecosystem under perturbation. At the same time, however, it is an important aquatic resource not only to the local community, but also to the international arena because of its rich biodiversity. It supports an artisanal fishery with four major fish of economic importance, including *Oreochromis niloticus*, *Protopterus aethiopicus*, *Clarias gariepinus* and *Barbus intermidus australis*. The once-vibrant *O. niloticus* fishery that flourished before the small town of Kampi ya Samaki was transformed into a beehive of activity on the shores of the lake is no longer sustainable. *O. niloticus* contributed over 80% of the landed total catch up to the year 2002, averaging >600 tons annually, but had declined to about 12 tons annually by the year 2006. The introduced *P. aethiopicus* is currently the major fishery, representing more than 75% of the total fish landings, with the *O. niloticus* landing being just 1%. Although *O. niloticus* is listed as 'endangered' in the IUCN Red List of Endangered Species, it is evident that its fishery is threatened with a total collapse if sound management strategies are not implemented. Accordingly, the present study reviewed past studies on the Lake Baringo *O. niloticus* and critically analysed the possible reasons for its decline, as well as possible strategies directed to its recovery, conservation and management for sustainable exploitation.

KEYWORDS

conservation and management, Lake Baringo, *Oreochromis niloticus* fishery, overexploitation, sustainable exploitation

1 | INTRODUCTION

Lake Baringo is a shallow tropical freshwater lake located in the Eastern Rift Valley of Kenya. As a result of its unique biodiversity, it was designated as a Ramsar site in 2002 (Ramsar, 2002). The lake has a significant role in the social, economic and political welfare of the riparian communities. It brings together three major pastoral ethnic communities (Tugen; Pokot; Icchamus), all of whom derive their livelihoods via fisheries, water resources and tourism. Located in a semi-arid region, agriculture is dependent on irrigation water from the lake (Hickley, Muchiri, Boar, et al., 2004). The lake is synonymous with ever-fluctuating water levels as a result of unpredictable rainfall patterns, and because of marked increases in agricultural activities in its catchments (Harper & Mavuti, 2004). Water turbidity in the lake is another challenge identified as a cause for the declining fishery, being attributed to anthropogenic activities associated with land and water use rights in the upper catchments in the basin. Since 2011, however, the lake has exhibited improved water quality in the form of decreased turbidity. This phenomenon is attributed to rising water levels and rehabilitation of the large, degraded Lake Baringo basin by the introduced *Prosopis julifora* (commonly referred to as 'Mathenge'), which has reduced the soil erosion rate in the basin.

Research efforts conducted by Cambridge explorations between 1930 and 1931 to East African Lakes, *Oreochromis niloticus baringoensis* (Linnaeus, 1852; now known as *Oreochromis niloticus*), *Barbus gregorii* (Boulenger, 1902), *Barbus Lineomaculatus* (Boulenger, 1903), *Aplocheilichthys* species, *Clarias mossambicus* (Peters, 1852) and *Labeo cylindricus* (Peters, 1852), have been identified as the main fish species in Lake Baringo (Ssentongo & Mann, 2008). *O. niloticus* was the main fish of economic importance (De Vos et al., 1998), with saw Kampi ya Samaki developing into an urban centre wherein a filleting factory for fish processing was installed, mainly targeting the export market. This situation improved the socioeconomic status of the population living around Lake Baringo by way of improved incomes, ready employment and a cheap protein source. According to Aloo (2002), *O. niloticus* comprised 80% of the total catch from the lake up to the year 2002, contributing an average of >600 tons annually, which subsequently declined to about 12 tons in 2006 (Britton & Harper, 2005, 2008; Britton et al., 2009). However, serious declining fish trends were noted as early as the year 2003 onwards, with *P. aethiopicus* taking the lead at 51%, followed by *Clarias gariepinus* at 25% and *O. niloticus* being third with just 17% of the total catch (Britton & Harper, 2008).

The exploitation of fisheries resources must be balanced against maintenance of a sustainable fish population in order to the resource to optimally provide its goods and services. This objective has not been achieved in Lake Baringo because large fluctuations in catch returns have been reported on many occasions (Hickley & Harper, 2002; Hickley, Muchiri, Boar, et al., 2004). This situation necessitated the introduction of closed fishing seasons to facilitate the recovery of the lake's fisheries resource. Nevertheless, the continuing decline in the *O. niloticus* fishery is becoming increasingly worrisome. The drastic changes in fish catches could be related to high turbidity and lowest water depth (i.e. mean of 2.5-m; Britton et al., 2009) ever experienced in the lake that year (2003). Lakes exhibiting low water depths are characterized by complete mixing. Being a water body affected by siltation and sedimentation, the turbidity in Lake Baringo could have been catalysed by wave-induced lake bottom disturbance, thereby inhibiting primary productivity. This might have reduced food availability (i.e., algae) for *O. niloticus*, which is mainly an herbivore, thereby possibly contributing to its decline. Furthermore, poor primary productivity would have resulted in decreased levels of dissolved oxygen, thereby also possibly contributing to the decline. Unlike *P. aethiopicus* and *C. gariepinus*, *O. niloticus* cannot survive in dissolved oxygen concentrations below 4 mg/l (Mohsen et al., 2015). Overfishing might also have played a major role in the *O. niloticus* decline. This is because the local pastoral community, who were taught fishing of the then-plentiful *O. niloticus* in the 1930s by the Luo fishermen from the shores of Lake Victoria, knew it to be the only edible fish, unlike the 'snake-like' *C. gariepinus* and the introduced *P. aethiopicus*. The taste of *O. niloticus* was also preferred over that of *P. aethiopicus* and *C. gariepinus*, fuelling its eventual overexploitation. The situation has been further exacerbated to an extent that the *O. niloticus* fishery in Lake Baringo is heading to extinction. Current studies by the Kenya Marine and Fisheries Research Institute (KMFRI) Baringo have reported disturbing trends, whereby *O. niloticus* is contributing just 1% of the total fish catches being landed. Furthermore, the fishes caught exhibit stunted growth, exhibiting a mean total length of only 8 cm at maturity (Tsuma et al., 2017). Similar findings have been reported by Britton and Harper (2008) who reported 13-cm TL *O. niloticus* as being mature.

Many reasons have been advanced for the *O. niloticus* decline, including environmental perturbations, overfishing and lack of food in the lake (i.e., low nutrients; Omondi et al., 2013), as well as the effects of climate change. Some, if not all, of these mentioned factors might have contributed to the decimation and possible collapse of the *O. niloticus* fishery. However, many questions remain unanswered, mainly because environmental degradation in the years between 1960 and 2002 in the Lake Baringo catchment is thought to have taken a severe toll on the fishery. Soil erosion, siltation and sedimentation were common occurrences in the lake, reducing its depth from an average of 5 m to 2.5 m deep (Britton et al., 2009). Thus, turbidity was a major result, which might have reduced the rate of photosynthesis in the lake. Food for *O. niloticus* also was definitely reduced by such factors. This situation ironically did not affect the landings or quality of *O. niloticus* in terms of growth rates because the fish landed were over 20 cm total length (Britton & Harper, 2005). Furthermore, this fishery sustained a fish factory that processed *O. niloticus* for export (Britton et al., 2009). Fortunately, the lake environment is currently better, compared to its past condition, exhibiting a restored catchment with thriving *P. fujiflora* and grass that has since minimized the soil erosion, siltation, sedimentation and turbidity. The lake depth has improved dramatically from an average of 2.5 m in 2003 to a current 10.5 m deep. This has improved the lake water clarity, thereby facilitating an increased rate of primary productivity. Such improvements in the lake environment should have improved the *O. niloticus* fishery. However, the situation continues to worsen, not only in regard to dwindling fish stocks, but also a generally poor body condition of *O. niloticus*, noting they grow only to an average total length of 8 cm at maturity. Thus, there is a need to better understand the reasons for the current state of affairs of *O. niloticus* in Lake Baringo. Accordingly, the current study examines in detail the reasons that might have impacted the serious decline (and eminent collapse) of the *O. niloticus* fishery. Several strategies to assist in its conservation and management are also explored and recommendations provided for sustainable exploitation of the fishery.

2 | METHODOLOGY

2.1 | Study area

The study area is Lake Baringo (Figure 1), which lies at 0°36′N, 36°04′E, approximately 60 km north of the Equator at an altitude of 975 m above sea level (Kallqvist, 1987; Owen et al., 2004). Its depth has been varying from an average of 9.55 m in September 2012 (Omondi et al., 2013) to 11.22 m by June 2017 (Nyakeya et al., 2018), currently being 15.8 m (KMFRI unpublished data). This increase has been attributed to the heavy rainfall witnessed in the country since 2011, with the same situation being documented for all the Great Rift Valley lakes of East Africa. It is noted, however, the lake has initially been characterized as a very shallow water body with an average depth of 2.5 m (Britton et al., 2009) until approximately the year 2010, when the depth changes commenced. The lake's estimated surface area is approximately 130 km^2, draining a catchment of 6820 km^2. The surface area is likely to have increased to more than 250 km^2, subsequent to the lake flooding (personal observation). Lake Baringo area is generally characterized by dry and wet seasons with unpredictable timing, exhibiting a mean annual rainfall of 635 mm (Kassilly, 2002). Seven islands are located in the lake, the largest being the volcanic Kokwa Island, from which a number of hot springs discharge into the lake (Cl'ement et al., 2003). The Molo and Perkerra rivers are perennial, being the main rivers draining into Lake Baringo at its southern arm, whereas the Endao, Mukutani and Or Arabel rivers are seasonal rivers draining to the lake (Ramsar, 2002). In the recent past, however, the Molo River has displayed seasonal characteristics, drying up towards the lake during the dry spell of each year. River impoundment, sand harvesting and irrigation for flower farms

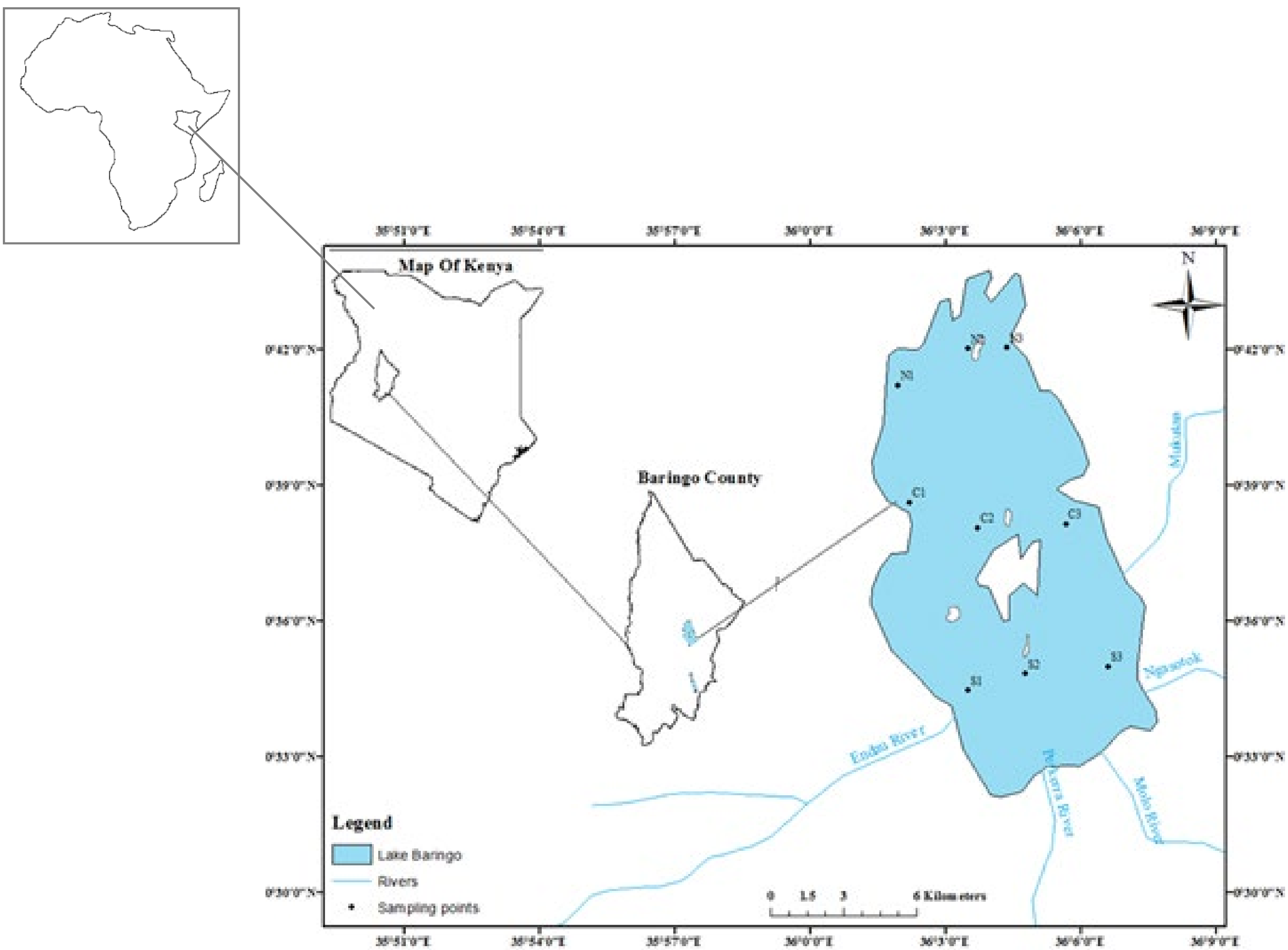

FIGURE 1 Map of Lake Baringo showing some modified geo-referenced sampling sites previously used for different studies

and personal farms, as well as unpredictable rainfall patterns, have contributed to its current state.

The lake exhibits a rich biodiversity, with some fish species being endemic. Other aquatic organisms of economic importance include the Nile Crocodile (*Crocodylus niloticus*), hippos, snakes and different bird species that attract a large number of tourists. The lake is a source of water and provides livelihoods (mainly fishing) for the Icchamus, Tugen, Pokot and Turkana communities, among others. The lake has no known outlet; however, it loses some water via underground seepage through the fractured lake floor (Odouor et al., 2003; Onyando et al., 2005). Lake Baringo experiences very high annual evaporation rates ranging between 1650 and 2300 mm (Odada et al., 2006), with its survival dependent on the river inflows. The vegetation in the area is bushy, being characterized by indigenous species such as *Acacia* spp., *Acalypha fruticosa*, *Maerua edulis*, and the exotic species *Lantana camara* and *Prosopis fujiflora* (Mathenge) (Odada et al., 2006).

Most of the limnological and fishery studies conducted on the lake do consider its three ecological zones, namely the southern (S1, S2 and S3), central (C1, C2 and C3) and northern (N1, N2 and N3) parts. These three areas exhibit distinctive features; hence, they are geo-referenced (Figure 1). The southern part is the shallowest, being characterized by in-coming rivers and some pockets of macrophytes (Nyakeya, Kipkorir, Nyamora, Odoli, et al., 2018). The central part contains the major islands and the pelagic zone of the lake, deficient of any form of macrophytes, while the northern part is mainly characterized by rocky shores and a fractured underground structure through which the lake loses water. It is also regarded as the deepest part of the lake (15.8-m). The northern part also contains some small pockets of macrophytes, attributed mainly to two islands found within its vicinity (Nyakeya, Kipkorir, Nyamora, Odoli, et al., 2018).

2.2 | Data sourcing and analysis

Data sourcing included reviewing published manuscripts from peer-reviewed journals accessed via different databases (e.g. Web of Science; Directorate of Open Access Journals; Google Scholar; KMFRI Institutional Repository; African Journals Online). Scientific reports and unpublished institutional data from the State Department of Fisheries, Aquaculture and Blue Economy—Baringo County Fisheries Office and personal observations were also accessed. All the reviewed data for the present study were based on research conducted in Lake Baringo and its catchments. Other data sources not necessarily referring to Lake Baringo, but which exhibited some relevancy to the thematic area of the present study were also used to enrich this manuscript, and also to help shape professional opinion towards the sustainable utilization, conservation and management of the Lake Baringo *O. niloticus*. It is on this basis that management strategies, logical conclusions and recommendation were developed.

3 | RESULTS

3.1 | Possible reasons for the decline and potential collapse of the Lake Baringo *O. niloticus* fishery

3.1.1 | Invasive species

The introduction of invasive species in many aquatic systems produced negative impacts in many cases on the native endemic species. They contribute to a larger extent to the endangerment and extinction of species in freshwater systems, ranked second to species extinction globally only to habitat destruction (Callaway & Ridenour, 2004). Alien fish species and their subsequent establishment has been a feature of Lake Baringo. The marbled lungfish, *P. aethiopicus* (Heckel, 1851), was introduced into the lake in 1975 without any ecological assessment of its potential impacts. After the Nakuru Agricultural Society of Kenya (ASK) show, unidentified fisheries officers took the three *P. aethiopicus* on exhibition and stocked the waters of Lake Baringo to ecologically exploit the lake's murky waters. The intentional introduction comprised two females and one male.

Protopterus aethiopicus is native to Africa and survives largely in many East and Central Africa wetlands (Mlewa & Green, 2004). The species was first witnessed in Lake Baringo landing beaches in 1984 (De Vos et al., 1998). Since that time, the *P. aethiopicus* fishery has comprised the long line fishery of the lake, alongside the native catfish *C. gariepinus* (Burchell, 1822), and is now the dominant species in the fish catches.

Although there are no conclusive studies indicating this fish is invasive, it is a predator fish and data highlight that that it preyed on *O. niloticus* on many occasions (Nyakeya, Kipkorir, Nyamora, Odoli, et al., 2018). With the decline in macrophytes in Lake Baringo (Ondiba et al., 2018), the chances are great that *O. niloticus* had no refugia areas in which to hide from the predator, this being a possible reason for its decline. However, as much as it can be argued that it contributed to the decimation of *O. niloticus*, its presence made the lake fisheries commercially viable, sustaining a growing number of fishermen and fish mongers each day. It currently constitutes about 90% of the total fish landing at the beaches (Baringo County fisheries data), whereas *O. niloticus* comprises only about 1% (unpublished KMFRI data). This situation, however, might not last for long because *P. aethiopicus* cannot withstand the high exploitation it is currently experiencing. The fecundity of individual females in Lake Baringo has been documented to be too low, wherein females of 77.0 to 125.0-cm are confirmed to lay eggs numbering between 4179 and 16,528 (Mlewa & Green, 2004). Thus, the population generation time is relatively too long, thereby increasing vulnerability to the adverse impacts of high exploitation. Furthermore, despite their paternal care and nest building characteristics that enhance the survival of the young, the decline in macrophytes (Ondiba et al., 2018), especially emergent Hippo grass (*Vossia cuspidata*) in the lake, is likely to jeopardize nesting capabilities.

Another invasive species in Lake Baringo worth noting is the water hyacinth (*Eichhornia crassipes*), which was first noticed in the year 2014. Although it has not been determined how it ended up into the lake, there are assumptions it might have found its way into the lake from the washing of sand ferrying lorries from the Lake Victoria basin in one of its inflowing rivers. Although known for its invasive characteristics, the alien *E. crassipes* has not yet established itself in lake Baringo to levels likely to have detrimental ecological impacts, mainly because the lake is nutrient poor, with a pH ranges between 8 and 8.5, which makes the waters of the lake alkaline (Nyakeya, Kipkorir, Nyamora, Odoli, et al., 2018). Under these environmental conditions, *E. crassipes* withers within the first one week whenever its drifting branches are first seen in the open parts of the lake. The roots of *E. crassipes* are characteristically long, indicating a low nutrient level. Although known to cause anoxic conditions in freshwater bodies, such a scenario has not yet occurred in Lake Baringo. In spite of its obnoxious nature, therefore, this water hyacinth has not had any negative impacts on *O. niloticus*.

The other phenomenon thought to have contributed to decimation of *O. niloticus* in the lake is the major invasion of greater cormorants and the unique sightings of other bird life. Up until early 2014, the greater cormorants were a rare bird on and around Lake Baringo, with the long-tailed cormorant being the primary cormorant on the lake (anecdotal observations for a period of more than 12 years documenting bird life on the lake). The arrival and nesting of thousands of greater cormorants was cited in February 2014 at the mouth of the Molo River on the southern border of the lake (unpublished data). However, to the best of our knowledge no one has quantified the numbers of this event. The birds had spread around the lake in 2015, with a new habitat of dead trees left from the flooded lake being a foraging site. While this cormorant invasion is new to Lake Baringo, this bird species is known to cause problems to various fisheries around the world (Madula & Jones, 2016). Recent observations, however, suggest a majority of the greater cormorants are exiting from Lake Baringo, possibly attributable to fishery that is less attractive as a foraging site. The assumption in the present study is that, upon near collapse of the *O. niloticus* fishery, the birds had to move elsewhere, mainly because *P. aethiopicus* and *C. gariepinus*, which currently constitute a higher proportion of fish landings, are too large for the birds to swallow. This suggestion corroborates well with the observations by Madula and Jones (2016) who reported in their study on invasive species sustaining double-crested cormorants in southern Lake Michigan that small-bodied invasive fish species such as round goby (*Neogobius melanostomus*), white perch (*Morone Americana*) and alewife (*Alosa pseudoharengus*) constituted over 80% and 90% of the diet of cormorants by biomass and number, respectively. Thus, because of the stunted growth of *O. niloticus* in Lake Baringo, the cormorants might have found an easy target for food, contributing to their dwindling stocks.

3.1.2 | Lack of sufficient food

Primary productivity is a key process in all aquatic bodies, forming the base of the food chain. It occurs in small, microscopic plants

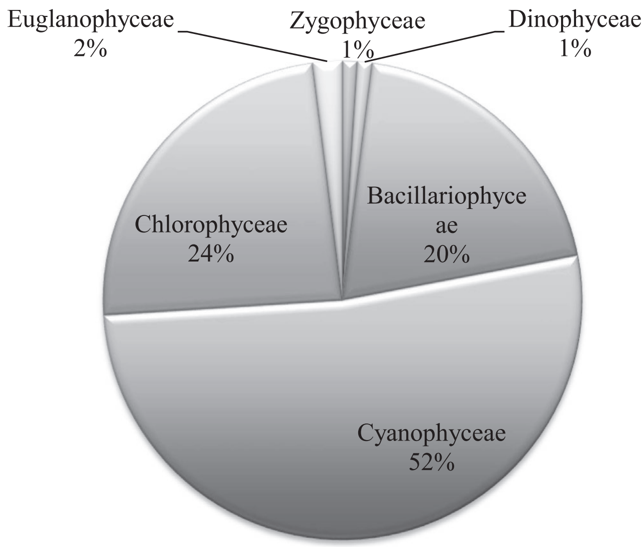

FIGURE 2 Percentage (%) composition of phytoplankton taxa in Lake Baringo during a low water depth, especially in the years 2010 and earlier (KMFRI unpublished data)

(phytoplankton) in water that manufacture their own food via photosynthesis, meaning sunlight is crucial. In a lake, sunlight can only penetrate to depths if the water is clear, thereby facilitating the photosynthesis process, and without which aquatic life would be compromised. Lake Baringo has been characterized as exhibiting high turbidity levels, with primary productivity therefore being an issue of concern (Beadle, 1932; Kallqvist, 1980). As a result of this reality, it is thought that the lake is insufficient in regard to food (Omondi et al., 2013), a condition that has been associated with stunted growth in *O. niloticus*. Earlier studies documented cyanobacteria (e.g. *Microcystis*) as the leading phytoplankton in terms of numbers (Figure 2; Beadle, 1932; Kallqvist, 1980; Wilson, 1989), compared with other forms of algae. Other authors (e.g. Omondi et al., 2013) have suggested this as a reason for a lack of sufficient food to support the population, thereby contributing to the decimation and slowed growth of *O. niloticus*. Based on a critical analysis of documented data, this assertion might not be true. One reason is that *Microcystis* used to be the main type of algae thriving in Lake Baringo as earlier as the 1960s (Wilson, 1989) when the turbidity was very high, but when *O. niloticus* could still grow greater than 25 cm in total length. Thus, *O. niloticus* apparently derived sufficient energy mainly from *Microcystis* species, given that it is associated with a polluted environment. The findings of the present study agree with those of Semyalo et al. (2010) who reported that 80% of the ingested phytoplankton in the diet of *O. niloticus* in a eutrophic water body producing cyanobacteria was a *Microcystis* species. At the same time, however, physiological studies also confirm that *O. niloticus* relying on *Microcystis* species as their main diet displayed stunted growth characteristics. According to Zikova et al. (2010), high supplementation of a *Microcystis* diet to *O. niloticus* is likely to inhibit growth because the fish loses a lot of energy to counter stress while detoxifying the associated hepatic metabolites. Although this might explain the reason for the stunted growth of *O. niloticus* in Lake Baringo, it is not possible to credibly argue this possibility because of lack of any documented literature on the lake to support it.

All the Great Rift Valley lakes in East Africa experienced sudden increased water levels in 2011 associated with heavy rains. The high increased water levels in Lake Baringo resulted in the lake flooding its banks and displacing many people. The water clarity improved 10-fold, being accompanied by changes in the ecology of the lake. For the first time, diatoms were observed in the lake, even becoming dominant (Figure 3), unlike in past years. The primary productivity improved likely because of increase in light penetration into the water column, thereby enhancing photosynthesis.

Based on these factors, food availability in the lake might not be the reason for the decline in the *O. niloticus* fishery, particularly because of the improved phytoplankton diversity and abundance (Figure 3). What is most disturbing is the continuing dwindling of *O. niloticus* stocks, and those being found in the lake in small numbers also appear to be stunted. Another pertinent question defying an answer to the present time relates to the ability of *O. niloticus* to grow to a total length exceeding 26 cm during the years when phytoplankton productivity was dominated by cyanobacteria, as well as exhibiting a limited number in terms of taxa due mainly to low water levels and high turbidity. There is a clear manifestation that food availability might have contributed to the state of *O. niloticus* fishery in the lake, although there is no conclusive evidence to support this assertion.

It is no question that higher trophic-level aquatic organisms depend either directly or indirectly on primary producers for their energy supply. The photosynthesis process provides organic matter that forms the base of the aquatic food chain, thereby resulting in the natural fish population exploited by humans. Nevertheless, there are insufficient trend data on the productivity of Lake Baringo, and how it affects the ecology of *O. niloticus*, to properly guide management decisions. Addressing this data deficiency requires continuous

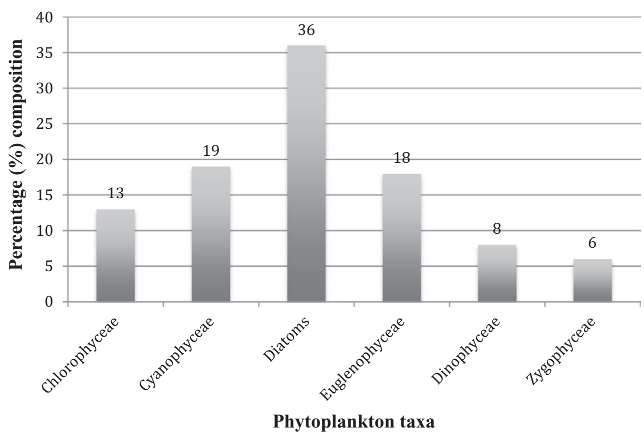

FIGURE 3 Percentage (%) composition (mm^3/L) of phytoplankton families observed at different geo-referenced sites of Lake Baringo in association with increased water levels, improved water transparency and low turbidity since 2011 to the present time

monitoring in regard to lake productivity and the characterization of critical habitats and aquatic biodiversity in the lake as a means of facilitating the sustainable exploitation of the lake fishery.

3.1.3 | Fluctuating water levels

Lake Baringo is geographically situated in a semi-arid region, with one of its main challenges being increased water evaporation and unpredictable rainfall patterns, both resulting in water-level fluctuations. Decreased water depth increases the possibility of increased turbidity, influencing primary productivity because of the decreased light penetration into the water column. Water turbidity becomes even more pronounced during mixing periods because lakes of shallow depth allow uniform mixing from the bottom sediments to the water surface. The latter occurs on a daily basis, being observed from 14:00 h when the wind is blowing (Wilson, 1989) from the northeastern parts, which generates strong waves that inhibits fishing activities (personal communication by fishermen). This situation compromises the photosynthesis rate because of its interference with light penetration into the water column. Being an herbivore, the feeding habits of *O. niloticus* are affected because of an insufficient availability of phytoplankton. The fish also rely on visual sight to locate food, which is inhibited because of increased turbidity. This factor could be a major reason for the continuing decline, and now a likelihood of collapse of the *O. niloticus* fishery. To this end, Hickley, Muchiri, Boar, et al. (2004) reported increased catches with increased water levels and decreased turbidity.

The above factors might not be completely responsible for the serious decline and eminent collapse of the Lake Baringo *O. niloticus* fishery. Heavy rainfall that has been experienced in the area since 2011 (Omondi et al., 2013), for example, results in an increased lake depth, which currently stands at about 15.8 m. Rehabilitation of the degraded Baringo basin has also reduced the rates of soil erosion, sedimentation and siltation into the lake (Figure 4), enhancing water clarity with Secchi disc reading being slightly greater than 1 m compared with former years (Figure 5). The rate of primary productivity therefore is likely to have improved, resulting in sufficient food being present in the lake. The rate at which the catch of *O. niloticus* is declining, however, remains worrying. In addition, caught fish (in rare occasions) are stunted, with mature fish rarely exceeding a total length of 8 cm. On rare occasions, especially during heavy lake flooding, *O. niloticus* of about a total length of 16 cm can be caught, but the fish often are emaciated, exhibiting big heads and tiny bodies with no flesh (personal observation and communication from fishermen). This scenario raises serious yet-unexplained questions. Between the years 1960 and 1990, for example, *O. niloticus* could be caught in high numbers in the lake, with an average total length of 30 cm and a large body mass. At the same time, however, the lake depth averaged 3 m, therefore being too turbid. Furthermore, the *O. niloticus* fishery was a steady source of raw material for a filleting factory in the area (Britton et al., 2009) that created job opportunities

FIGURE 4 Rehabilitation of Lake Baringo basin (LBB) (left side: degraded environmental state leading to soil erosion and resulting sedimentation and siltation of lake, resulting in increased turbidity and reduced depth from 2005 backwards; right side: rehabilitated environmental state resulting from reduced soil erosion, sedimentation and siltation leading to improved water clarity with increased water levels from 2011 to present time)

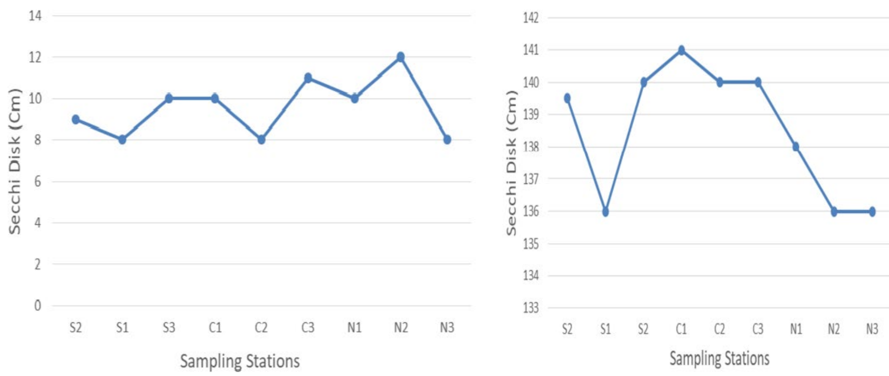

FIGURE 5 Secchi disc measurements during 2002 to 2003 (left) and current state from 2011 to 2019 in Lake Baringo (transformations above were experienced because of water-level changes; left side: low water clarity due to increased turbidity and probable low water depth; right side: improved water clarity attributed to increased rainfall and reduced turbidity)

for the local inhabitants, improving their economic status. The confusing question therefore is what contributed to its abundant catches (and normal growth rates) under such a degraded environmental state unlike that existing now with the lake exhibiting improved water levels and clarity? This contradiction suggests there are additional reasons regarding why the *O. niloticus* is declining, experiencing stunted growths and a likely collapsing fishery. It is clear a combined holistic study is required to answer this difficult question.

3.1.4 | Overexploitation of fishery

An ever-increasing human population continues to exert more pressures on natural resources. Overexploitation poses a serious threat to biodiversity, occurring when the harvest rate of any given population exceeds its natural replacement rate, and regarded as the third-most important threat for freshwater fish extinctions, after habitat loss and introduced species (Allan & Flecker, 1993; Pimental et al., 1997; Postel et al., 1996; Vitousek et al., 1997). As a consequence, the world's fisheries resources are being overexploited and could collapse at some point in the future.

The number of fishermen in Lake Baringo has increased over time, resulting in an upsurge in fish catches and potential fish exploitation over time. Hickley, Muchiri, Boar, et al. (2004) pointed out that overexploitation resulted into the decline in *O. niloticus*, prompting fisheries managers to close the fishery, and subsequently leading to improved fish catches between 1999 and 2000. This situation did not last long, however, because there was an increased fishing effort, resulting in any gain in terms of high catch rate to be unsustainable. Unreported unregulated illegal fishing is also common. As a result of weak co-management and inadequate enforcement of existing regulations by the county fisheries office, many fishermen are not licensed, facilitating illegal fishing in terms of the use of wrong gear and/or fishing in protected areas, thereby causing the declining *O. niloticus* fishery. In a community-based fishery resource, many fishermen do not adhere to accepted fishing norms and instead use all means to reap the highest fish-related benefits with little regard to their sustainability. Overfishing is a 'Tragedy of the Commons' situation wherein fishermen share a common fishing ground from which they are each entitled to fish. In this case, each fisherman pays additional attention on the fishing ground, resulting in its carrying capacity to be exceeded. Accordingly, it is temporarily or permanently damaged for all fishermen. Since all fishermen reach the same rational decision, overexploitation in the form of overfishing often occurs, with the fish stocks potentially be depleted to the point it can no longer provide a sustainable fishery. Therefore, the *O. niloticus* fishery of Lake Baringo can be considered as an example of the Tragedy of the Commons phenomenon since it was the main target species. Ogello et al. (2013) also confirmed that the 'Freedom of the Commoners' advanced by Hardin is responsible for overexploitation of Lake Victoria fisheries resources.

3.1.5 | Environmental degradation

Habitat destruction, modification and fragmentation are widely recognized as serious threats to biological diversity and a primary cause of recent fish extinctions. Lake Baringo is an ecosystem currently being stressed as a result of increased anthropogenic activities, being highly influenced directly from its catchments (Nyakeya, Kipkorir, Nyamora, & Kerich, 2018). River damming, for example, is pronounced in almost all the rivers discharging into the lake. A noteworthy example is the Endau River, whose down flow was seriously affected by upstream construction of the Kiriandich Dam. Furthermore, the Molo River, currently considered a permanent river, has become seasonal with more than three impoundments located upstream to supply irrigation water to agricultural and flower farms. During the dry spell, the river waters no longer reach the lake, with the reduced water inflows resulting in low lake water levels that have been associated with the declining *O. niloticus* fishery (Britton et al., 2009). Other human-induced activities interfering with the lake ecosystem include pesticide and fertilizer run-off from irrigated farms, overgrazing, charcoal burning, deforestation, sand mining, water abstractions, soil erosion, sedimentation and urbanization. To this end, environmental degradation has been identified as a main reason for the decline in the fishery. Hickley, Muchiri, Boar, et al. (2004) suggested a disturbed lake environment might hinder the ability of fish stocks to regenerate to former levels because of increased turbidity and loss of macrophytes (Hickley & Harper, 2002). According to Helfman (2007), fish lose their habitats when water bodies dry up or flood at inappropriate times, fill with sediment, become choked with vegetation or debris, are contaminated by toxicants, become unlivable because of hyper-eutrophication or de-oxygenation, or are destroyed or homogenized through structural damage or removal.

Habitat degradation might not clearly be identified as a major causative factor impeding the *O. niloticus* stock recovery now that *P. aethiopicus* is flourishing. It is worth noting that *P. aethiopicus* exhibited wide environmental tolerances (Mlewa & Green, 2004), compared with *O. niloticus*, and can survive under poor conditions (e.g. periods of low dissolved oxygen concentrations), and the fact that its feeding does not depend on visual cues (Goudswaard et al., 2002; Greenwood, 1986). Thus, Lake Baringo's degraded ecosystem is unlikely to adversely impact the *P. aethiopicus* population. As a result of its facultative nature of breathing, for example, *P. aethiopicus* can survive in murky waters, unlike *O. niloticus* that depends only on its gills.

Such activities as river damming in the Molo, Endau and Perkerra rivers reduce the quantity of water reaching the lake during the dry seasons (Nyakeya, Kipkorir, Nyamora, & Kerich, 2018), thereby reducing the lake depth, and as a result, the *O. niloticus* breeding areas along the shores shrink, leading to possible decline. However, rapidly moving raging waters once released from overflowing dams along the rivers during sporadic heavy rain events cause soil erosion, siltation and sedimentation in the lake. Sedimentation might contribute to filling up the fractured substratum in the northern part of Lake Baringo, thereby blocking the underground seepage through which the lake loses its waters. The underground seepage helps the lake maintain its freshwater status (Nyakeya, Kipkorir, Nyamora, Odoli, et al., 2018), meaning that blocking it might change it into a saline water body, thereby affecting the *O. niloticus* fishery. It has also led to filling the lake through continuous piling, thereby causing the lake to flood unnecessarily and possibly destroying the breeding areas by destroying the submerged and emergent macrophytes (Ondiba et al., 2018) that typically shelter *O. niloticus* fries and fingerlings from predators.

Fish in degraded environments tend to adapt to the prevailing situation for survival and develop life history strategies that comprise the lifetime patterns of an organism's growth, development and reproduction (Carlos et al., 2020). Some life history theories attempt to explain the evolution of organismal traits as being adaptations to environmental variations and stresses (Winemiller & Rose, 1992). According to MacArthur (1972), species inhabiting different environments exhibit different life history patterns. Fish in disturbed environments will display r-selected reproduction strategies for their survival (i.e. short-lived, small-bodied individuals with high fecundity and low per capita investment per offspring; high mortality rates). However, fish in stable environment adopt the K-selected strategies, including being long-lived, large-bodied individuals with low fecundity and high per capita investment per offspring, as well as low mortality rates (MacArthur, 1972; Pianka, 1974). Thus, with Lake Baringo being a disturbed ecosystem, *O. niloticus* have developed r-strategy reproduction patterns, as exemplified by their small body size at maturity (total length of 8-m) and high fecundity. Altered growth patterns (delayed growth; stunting) can occur in extreme wild conditions (Winemiller & Rose, 1992).

3.1.6 | Macrophytes

Like other shallow water bodies, Lake Baringo contained a diverse group of macrophytes (Ondiba et al., 2018). This situation has changed, however, because of sudden increases in lake levels since 2011 in which the lake reclaimed riparian lands and all terrestrial plants, as well as emergent macrophytes drying and disappearing. The macrophytes that previously covered almost 20 acres of lake water, especially in the eastern part of the lake, are currently only seen now in small pockets. Some of the previously dominant emergent macrophytes that commonly dominated Lake Baringo include Hippo grass (*Vossia. cuspidata* (Roxb.) Griff.), Common papyrus (*Cyperus papyrus* L.), Narrow-leafed cattail and *Typha domingensis*. Macrophytes provide a fertile ground for breeding and refugia, acting as a fish nursery area, which has been reported by Barilwa (1995) who suggested that the marginal edges of lakes with dominant growths of emergent macrophytes constitute good feeding grounds, spawning and nursery habitats for fish. According to Gichuki et al. (2001), most fish found in macrophyte-infested areas of a water body are mainly prey fish species that seek refugia from predators, with about 7% being *O. niloticus*. Thus, diminishing refugia space in the lake occasioned by condensed macrophytes coverage might have exposed *O. niloticus* to unprecedented predation, as well as exploitation with fishing gear.

3.1.7 | Conflicts over decision-making associated with resource management

Conflicts can occur when a community is not involved in managing a natural resource in their area of jurisdiction. Community-based management is a process that empowers local communities to manage their resources by letting individuals contribute to decisions affecting the local resources. One of the major benefits of community-based management is developing strategies compatible with the unique environment, its specific resources, and the cultural and historical context of the local areas. Community-based management can also aid in resolving conflicts over limited fishery resources among multiple stakeholders (Capitini et al., 2004), including involvement of the indigenous community in management, including an integrated approach to natural resource management and developing new institutional programmes.

The Beach Management Units (BMU) and the old men who originally formed the defunct Lake Baringo Fisheries Sacco Society do not agree on the management of Lake Baringo fishery, resulting in a 'don't care' attitude regarding the manner in which fishers conducted their trade in the lake. This situation is thought due primarily to lack of continuous creation of awareness amid the changing fishery dynamics. Since *O. niloticus* was the main target species in the lake, it suffered from overexploitation, consequently leading to the decline and collapse of the fishery. Thus, there is need of promoting co-management of the fishery, as well as enforcement of laws and regulations to guarantee ecosystem sustainability. This situation can only happen and succeed, however, in an area from where all the stakeholders speak from one script.

3.1.8 | Conflicts over water resource use

Good water quality and quantity is key for any successful fishery. Reduced water levels have been cited as one of the major reasons for the declining *O. niloticus* fishery in Lake Baringo (Britton et al., 2009; Hickley, Muchiri, Boar, et al., 2004). The lake is prone to harsh climatic conditions with high temperatures, noting that the temperature can exceed 32°C in some cases, thereby causing reduced water levels through evaporation. This stressed state is further aggravated by unregulated water abstractions by different players, including domestic users, hoteliers, farmers and geothermal prospecting companies. The Geothermal Development Company (GDC), for example, installed a water abstraction plant at one of the *O. niloticus* breeding and conservation grounds at the northern part of the lake. The riparian community was (and still is) against the GDC water abstraction because of its detrimental effects to the ecology of the entire lake fishery. However, GDC argued that the abstracted water was of no consequence and that power generation is of greater economic benefit to the community than the fisheries. However, the KMFRI mandate is to conduct aquatic ecosystem research in the country for the sustainable exploitation, management and conservation for the purposes of enhanced food security and job creation. Thus, it is not in agreement with the notion of major water abstractions from the already-stressed Lake Baringo ecosystem. This perspective is based on the fact that because of the earmarked Nakubem tilapia BCA, chances are that eggs and larvae are likely to be pumped out of the lake, in addition to its reduced water levels and shrinking sheltered breeding areas. Furthermore, whereas WARMA is responsible for licensing water users, most users have installed either portable pumps and/or generators at many designated points, which are operated without any licence from the regulators, based on the argument that water is a natural resource to be exploited by the riparian community. These types of conflicts place the management and conservation efforts for *O. niloticus* at a perilous crossroads.

3.1.9 | Conflicts involving fishers and county governments

Conflicts between fishery resource users and managers are not new in Kenya. Before the promulgation of the new Kenyan constitution in 2010, fishermen could be reported for defying orders to pay for fishing licences from the then State Department of Fisheries (Obura et al., 2005). The same scenario is being witnessed in Lake Baringo under the new constitution wherein regulation and management of fisheries resources is a devolved function. Out of an estimated 150 fishermen operating in the lake, only 15% are licensed (Unpublished Baringo County Fisheries data). On many occasions, fishers have argued that the fisheries resource is God-given and, just like any other global common property, should be open and free to exploit. They further argue that in any desert there is an oasis and that this is the case for the Lake Baringo people who live in a semi-arid area with unpredictable rainfall patterns. Accordingly, Lake Baringo provides a ready fishery resource as 'vegetables' for their daily meals and therefore should be left for them to sustain their lives without any government agency interferences. These could negate the precautionary principle approach needed to halt further increased fishing efforts, especially in regard to *O. niloticus*, which represents the main target species.

3.1.10 | Inadequate enforcement

The management of fisheries resources is a devolved unit under Kenya's newly promulgated constitution, with respective county governments overseeing enforcement of relevant laws and regulations governing fisheries within their jurisdiction. The required mesh size for catching *O. niloticus* in Lake Baringo is four inches. Many fishermen, however, deploy nets with smaller mesh sizes, while some also use mosquito nets, resulting in the catching of immature fish. Rampant use of bar soaps as fishing bait is also common in Lake Baringo, contributing to fish kills. Over 75% of the fishermen operating in Lake Baringo are also unlicensed (KMFRI unpublished data). These factors have collectively caused detrimental effects due to insecurity, especially towards the northern, northeastern, eastern and parts of the lake that are prone to ethnic conflicts. Accordingly, fishing in the demarcated fish breeding and protection sites is inevitable.

The above activities thrive amidst weak enforcement of existing laws. The Baringo county government charged with Lake Baringo fishery management is situated 57 km from the lake. Although an office exists a few yards from the lake, its staff comprises only three fish scouts and an intern, resulting in unregulated fishing becoming inevitable. The officers are also poorly financed, with their boat lacking fuel for months; therefore, regular patrols do not occur. Furthermore, the BMUs, also charged with responsibility for fishery management, are no longer active. Although such an organization could be in a better position to ensure demarcated areas are no-go zones since they belong to particular communities, this is not the case. Thus, lack of enforcement is a key reason as to why the *O. niloticus* fishery is declining and facing eminent collapse.

3.1.11 | Fishing in demarcated fish breeding and conservation areas

Reports on the *O. niloticus* fishery decline were documented as early as the 1990s (Aloo, 2002; Britton & Harper, 2008; Odada et al., 2006). KMFRI embarked on studies earmarked for conservation efforts. In 2010, AKMFRI research expedition dubbed 'Lake Baringo Research Expedition' (LABRE) undertook studies on mapping breeding and conservation areas (BCAs). A total of eight (8) areas were mapped and identified as possible BCAs (Figure 6). To date, however, only three of the identified and mapped BCAs have been demarcated. The remaining six BCAs remain as unrestricted fishing grounds by fishermen, another factor that has likely contributed to the dwindling and likely collapse of the *O. niloticus* fishery. Furthermore, invasion of the three demarcated BCAs by fishermen is also of serious concern.

Despite stakeholder sensitization meetings held before the demarcation of the three BCAs, fishermen fish freely in these sites. They are mainly designated at littoral parts of the lake largely rich in fish food and nutrients, compared with pelagic and profundal regions. Thus, fishermen can justify their stressing activities by arguing they are following fish species (predators) other than *O. niloticus* to the three demarcated BCAs. The littoral areas are characterized as containing many macrophyte species, with prey fish species such as *O. niloticus* seeking refuge here and therefore attracting predators (*C. gariepinus*; *P. aethiopicus*), resulting in these sites exhibiting rich biodiversity, an observation also supported by Gichuki et al. (2001), who reported that in wetlands with plentiful macrophytes, fish of almost all feeding guilds assemble, including prey species seeking refuge, spawning and nursery grounds and therefore also attracting predators. As much as such actions might be justified, they wind up depleting the earmarked fish for conservation, namely *O. niloticus*. Another dilemma in ensuring that the demarcated BCAs are restricted fishing areas is the lack of gazettement of the three sites to make them binding by law, such that anyone found fishing inside the BCAs could be prosecuted in a court of law.

3.1.12 | Institutional policy and legal framework

Governance is key towards the effective and sustainable management of natural resources. Poorly instituted and uncoordinated institutional policies and legal framework result in chaos and anarchy. According to Ogello et al. (2013), poorly coordinated laws on management of aquatic resources in Kenya are responsible for the unwarranted decline in fisheries resources. Under the new constitutional dispensation, the fisheries sector is a devolved unit in Kenya. The management of all natural resources in Kenya, however, falls under the jurisdiction of the national government, an arrangement

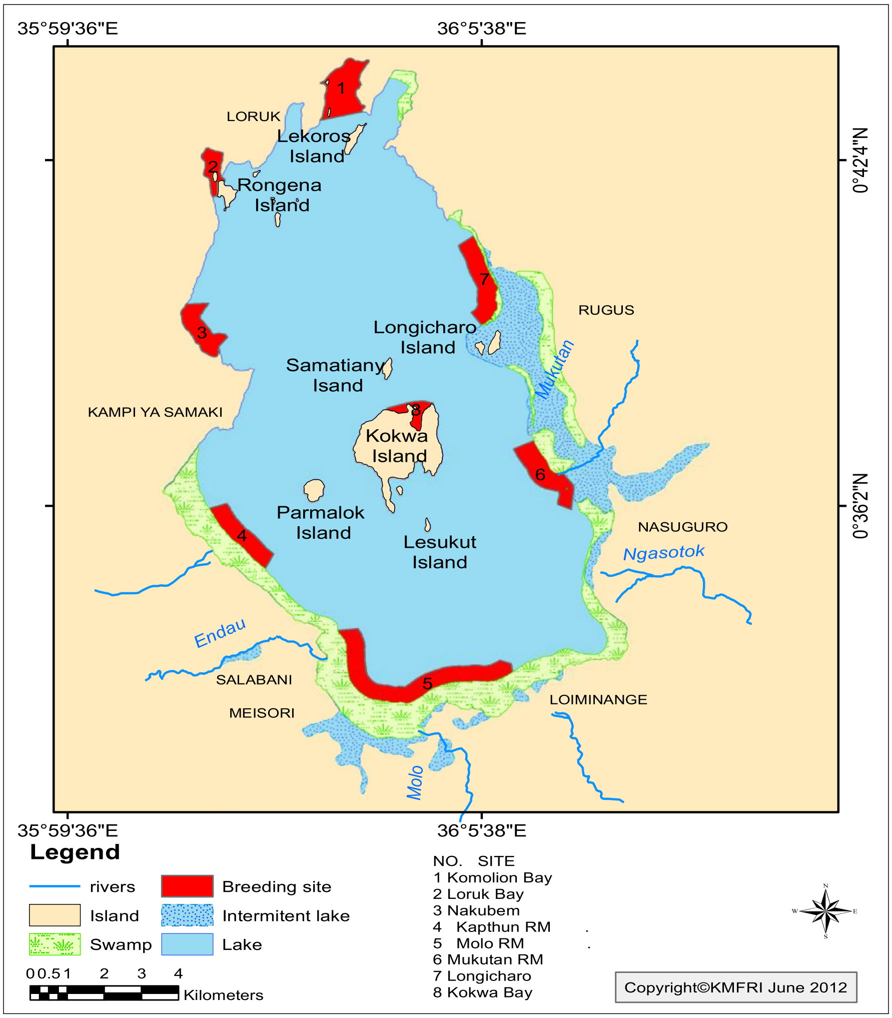

FIGURE 6 Map showing *O. niloticus* fish breeding and conservation areas (1 = Komolion; 3 = Nakubem; 5 = Molo River mouth; source: KMFRI unpublished data)

that breeds confusion between the national and county governments in regard to prudent fisheries management. The county government, for example, is responsible for all fishing activities in a given water body by enforcing relevant laws and regulations and licensing the fishermen. As there is no explicit explanation on how the national government plays its role in this regard, this situation has resulted in conflicts between Lake Baringo fishermen and the Baringo county government fisheries officers, primarily because the fishermen feel fisheries as a resource is a national government property that should be exploited for free. Consequently, almost all the fishermen utilizing the lake are unlicensed (personal observation of the author). Thus, there is a need either to devolve the fisheries sector completely, or to leave it entirely with the jurisdiction of the national government in order to facilitate its sustainable management.

Different institutions were created by relevant Acts of parliament to manage aquatic resources in Kenya, including the Kenyan Marine and Fisheries Research Institute (KMFRI), Water Regulatory Management Authority (WARMA), National Environment Management Authority (NEMA), Kenya Wildlife Service (KWS), Kenya Forest Research Institute (KFRI), Kenya Water Towers and the National Museums of Kenya. Universities also play a role in the conservation and management of aquatic resources. With such a large number of institutions managing aquatic resources in the country to varying degrees and levels, duplication of duties and mandates is evident such that conflicts of interest exist in some instances, interfering with prudent management of these resources. Studies conducted by different institutions also might produce differing results, thus raising questions as to which ones to be accurate and relied upon to inform its management. Thus, there is a need to streamline the mandates of all these mentioned institutions as a means of eliminating unwanted and confusing duplication in authority and actions.

Lake Baringo contains a number of wildlife animals, including the Nile crocodile (*C. niloticus*). KWS, which is mandated with the management and conservation of wildlife, both on land and in water, has never documented the number of *C. niloticus* living in the lake. From the perspective of local communities, *C. niloticus* have multiplied in the lake to an extent they are observed along the shores predating on fish, implying they have contributed to the dwindling *O. niloticus* stocks in the lake (fishermen observations). Despite *C. niloticus* being an aquatic resource, there is a contradiction in that it is also considered a wildlife animal. It is not clear whether or not KMFRI should conduct studies on its role in the ecosystem. Furthermore, even if KMFRI recommends its control in regard to its numbers, the KWS might have a different opinion.

KWS, KMFRI, National Museums of Kenya and Kenya Towers are also charged with managing wetlands. However, KWS and the National Museums of Kenya are the only institutions listed as Kenyan focal points for Ramsar Small Grants Funds for Wetland Conservation and Wise Use (SGF). Thus, a KMFRI scientist cannot apply directly for SGF grants to undertake research in Lake Baringo. Such an application would need the prior approval from either of the institutions (KWS or National Museums of Kenya). With different institutional priorities, a KMFRI scientist might not get approval of the two institutions, thereby hindering the effective mismanagement of such an international wetland, another institutional conflict that might have contributed to the declining Lake Baringo *O. niloticus* fishery.

3.1.13 | Co-management

Despite the national government committing financial, human and material resources to address various threats to the Lake Baringo fishery (e.g. low recruitment; overfishing; illegal fishing), the lake's fish production has remained low. This was the case when fisheries resources were managed with a top-down strategy wherein the government relied on biological parameters to draw relevant policies to govern the Kenyan fisheries sector. Thus, the fisheries resources were regarded as being state-owned. The stakeholders, especially riparian communities, were not involved in the decision-making process related to the management of any given lake fishery, resulting in ineffective, expensive and unsuitable management. To achieve sustainable management of fisheries resources in the country, the government adopted co-management or community-based natural resource management through Beach Management Units (BMUs), which is mainly a fisher-led action type of governance. It is a bottom-up approach wherein fishing communities for a given water body are charged with the responsibility of regulating and monitoring the resource. The government recognizes this form of fisheries governance, with BMUs being formed at each gazetted fish landing beach. This co-management approach was aimed at providing a platform for collaborative and cooperative partnership.

There are nine main Lake Baringo landing beaches, with six officially gazetted. As BMU members are not paid by the government; however, almost all the BMUs are dysfunctional, except for the BMU at Kampi ya Samaki, which is still operational with an active chairman and secretary. The remaining members rarely take part in the organization's activities. On some occasions, the use of mosquito nets and bar soaps is widespread, resulting into massive seining of *O. niloticus* fries, and fish deaths attributable to poisoning (personal observation), thereby also contributing to the possible decline in the *O. niloticus* fishery. With the limited government resources for enforcing some of fisheries regulations, BMUs are at a better position to do so. As a result of their non-functioning nature, however, Lake Baringo fisheries management remains problematic at best. Fishing is usually done in the demarcated areas meriting protection by the BMUs. As the units are no longer functional, however, overexploitation is rampant in the protection and conservation areas, further facilitating the decimation of the *O. niloticus* fishery.

4 | DISCUSSION

4.1 | Strategies towards resuscitation, sustainable exploitation, conservation and management of *O. niloticus*

4.1.1 | Resolving environmental conflicts

When introducing conservation and management measures to be adopted by natural resource users, care and caution must be exercised to ensure environmental conflicts do not arise from any stakeholder quarters. The introduction of demarcated BCAs in Lake Baringo offers a classical example of the common environmental conflicts that can arise in community-level management of natural resources. In the case of Lake Baringo, the environmental conflicts at play are complex because of biological uncertainties, a myriad of stakeholders and issues, multiple and unique values, and a mismatch between scientific and traditional knowledge (Daniels & Walker, 2001). One effective strategy to resolve the invasion of demarcated BCAs by Lake Baringo fishermen could be the complete involvement of all stakeholders, starting at the community level and including public–private partnerships (PPP), county governments and the national government. According to Holling (1978) and Michaelidou et al. (2002), effective conservation and natural resource management dictates continuous involvement of different sectors, including biology, ecology, social, economic and political economy, should be followed to create an integrated management approach.

4.1.2 | Introduction of closed seasons

It is now nearly two decades ago that the last closed season was introduced for Lake Baringo. Its ban at the end of the year 2000 was accompanied by an increased catch of 465 t/y. A continuing decline, however, was subsequently witnessed such that by the year 2004, only 58 t/y was declared. By 1990, the *O. niloticus* catch led the commercial catches, constituting 86% of the total catch (Britton et al., 2005). By the year 2004, however, it comprised only about 4% of the total catch, with *P. aethiopicus* leading by 62%, followed by *C. gariepinus* at 33%.

It is evident closed seasons are one of the surest strategies to resuscitate the collapsing *O. niloticus* fishery. When introduced for Lake Baringo in the 1990s and early 2000s, there was an increased fish production and, conversely, a serious decline and eminent collapse to date since lifting the season ban in the year 2000. Closed seasons to ensure *O. niloticus* recovery were recommended by Britton et al. (2009). In Lake Naivasha, for example, this strategy has worked very well and is still applicable to the present time.

4.1.3 | Regulating fishing efforts

Fishery closures might not be effective in enabling stock recovery if exploitation levels during the open season have not also been adequately controlled. The fishery management effort should recognize the slow, long-term nature of the recovery process and work to regulate the long-term effort at appropriate levels. The regulatory agencies, both national and county governments, should license a reasonable number of fishermen with a minimum number of fishing gear. This is because allowing an agreed number of fishermen into the lake without also regulating the size and number of nets that each fisherman can deploy into the lake will not facilitate achievement of the recovery process.

4.1.4 | Fish cage culture

Another key strategy for the conservation and management of *O. niloticus* in the Lake Baringo Basin is through cage culture. Successful cage farming has been reported in Lake Victoria (Kenyan portion), despite its eutrophic status. Unlike Lake Victoria, Lake Baringo is oligotrophic (i.e. nutrient deficient), the reason its primary productivity is low. Thus, if cage culture should be considered, it will offer both a permanent solution to enhanced and reliable *O. niloticus* fish production in the cages, and easing fishing pressure on *O. niloticus* in the wild. And because of the associated increase in nutrients from the cages via fish waste, and spillover of unfed feeds, the waters of Lake Baringo will have sufficient nutrients to trigger an increased rate of primary productivity, thereby enhancing food availability for the fish in the wild. Thus, it calls for cost-effective interventions to address the situation and improve the livelihoods of the Lake Baringo fishing community and, to some extent, reduce the fishing pressure in the lake. Other small water bodies within the larger Baringo County should also be considered for cage culture of *O. niloticus* since the vast Baringo County is endowed with about 35 dams/satellite lakes (both natural and manmade), thereby easing over-reliance on fish bred in the wild. Thus, there is a need to make use of these potential fishery resources for conserving and managing *O. niloticus*.

4.1.5 | Complete demarcation of the eight mapped spawning, nursery and conservation areas

Establishing fish breeding and conservation areas in Lake Baringo is faced with multiple management challenges, such as a few fisher folks not complying to non-fishing inside the breeding areas, this being a possible reason for the small mean sizes and negative allometric growth of *O. niloticus* noted in the present study. It might be too early, however, to make firm conclusions on this matter since the demarcation of these areas occurred less than five years ago. While the exact impacts of the existing three protected breeding areas might not be appreciated at the moment, it is expected that a higher fish production will be achieved. Beneficiaries of the spillover effect and development of a more comprehensive protected area could improve the probability that tilapia stocks will show replenishment within the nearby future. While a multitude of factors could influence tilapia life history characteristics both inside and outside of these areas, a longer evaluation period is needed to better understand the status of this population. Better monitoring, control and surveillance (MCS) measures might well realize favourable fishery production results. This goal, however, is not only challenging but will be limited by governmental capacity through county governments to provide more financial and human resources to manage the demarcated areas. To continue effectively managing these areas, the programme must be more inclusive, have strengthened political representation and also strengthen the role communities are playing in the sustainable development of their fishery. More sensitization of the fisher folk also will be needed for the benefits of protected areas to be realized.

4.1.6 | Regular stakeholder sensitization

The KMFRI Baringo station conducts research in the lake on different thematic areas on an annual basis geared towards providing information and data for informed management of the Lake Baringo fishery. As witnessed for other water body fisheries, the findings of such research efforts are often disseminated in the form of so-called 'grey literature'. To maximize the benefit of such findings to stakeholders, there is need to hold biannual stakeholder meetings in which the community is sensitized through dissemination and discussion of findings focusing on how to sustainably exploit the fishery, thereby facilitating its conservation and management.

4.1.7 | Regulation of water abstraction from the lake

To ensure sufficient water reaches the lake from its catchments via inflowing rivers, sound water management schemes such as regulated abstraction and agricultural irrigation, as well as increased rainwater recycling, must be enforced (Britton & Harper, 2005; Odada et al., 2006). This will ensure reasonable lake levels are maintained, especially during the dry seasons of low rainfall. Implementation of this strategy will facilitate achievement of ecological benefits for *O. niloticus*, thereby enhancing its conservation. This goal could be reinforced by the Water Resource Management Authority (WARMA), which is mandated with the regulation and management of water resources in the country.

4.1.8 | Revision of institutional frameworks

With many institutions charged with a mandate involving the management and conservation of aquatic resources, there is need to revise such mandates to ensure an overlap is avoided. Furthermore, where an overlap is inevitable, there is a need to provide a clear definition as to which institution does what, why and to what extent. This action will facilitate the prudent management and conservation of aquatic resources.

5 | CONCLUSIONS

An overall conclusion is that the Lake Baringo *O. niloticus* fishery is in eminent danger of collapse and extinction. Almost all the discussed reasons for its decline in Lake Baringo have been cited in other studies as the causes of extinctions of major world fisheries (Allan et al., 2005; Helfman, 2007). As previously discussed, some reasons for its decimation include overexploitation or overfishing, environmental perturbations, poor legal and institutional policy frameworks, invasive species, fluctuating water levels and lack of enforcement. Although a lack of food in the lake is thought to have contributed to the decline in the *O. niloticus* fishery, the results of the present study do not provide credible evidence to support this assertion. Eliminating this possibility as a contributing factor to the declining *O. niloticus* in Lake Baringo, however, will require additional study of their food sources and feeding mechanisms in order to better inform fishery management policy. Co-management of Lake Baringo has totally failed. Accordingly, there is need for the County Director of Fisheries to exercise his authority as provided in the BMU regulation to disband all the five dysfunctional BMUs. This will provide a good opportunity for the fishermen to re-examine their role in the fishery management and to form a fresh BMU directed to the sustainable management of the Lake Baringo fishery. There is increased pressure on the *O. niloticus* fishery attributable to an ever-increasing number of fishermen and fishing boats. The fishery is totally unregulated because many of the fishing boats are unlicensed, providing considerable opportunities for the use of unlawful gears and fishing methods. Accordingly, the County Director of Fisheries should ensure all fishing boats are licensed and, if possible, also regulate and license the number of fishing gear in each boat. Mapping and demarcating BCAs will be futile without implementing laws to deter fishermen from fishing inside the BCAs, an action that will conserve *O. niloticus* and other fish species in Lake Baringo.

The presence of cormorants in Lake Baringo is a possible precursor to the drastic decline of the *O. niloticus* fishery. Accordingly, it is also recommended that this issue deserves urgent study and continuous monitoring of these birds as a means of examining their role in the demise of the overall Lake Baringo fishery.

Environmental degradation in the Lake Baringo drainage basin also contributes to the possible collapse of the *O. niloticus* fishery. Clearing of riparian land enhances soil erosion that is subsequently washed downstream into the lake, causing siltation and sedimentation that ultimately decreases the quality of the lake for aquatic life. It is recommended therefore that the relevant government agencies facilitate the reforestation and protection of the lake's riparian zones and ensure that Acts such as Environmental Management and Coordination Act (EMCA) of 1999 are implemented and enforced.

Other recommended strategies for the recovery of the Lake Baringo fishery include resolving of environmental conflicts, the introduction of cage culture, closed seasons, regulation of fishing efforts, enforcement of existing regulations, complete demarcation of mapped breeding and conservation areas, community sensitization and regularization of water abstraction by WARMA. It is also noted that *P. aethiopicus* has become of great economic value in supporting the Lake Baringo fishery at the present time, despite the fact that it predates on *O. niloticus*. Thus, it also is recommended that, in addition to demarcated and conservation areas for *O. niloticus*, the southern part of the lake that contains multiple pockets of macrophytes be protected from fishing as a means of enhancing recruitment of *P. aethiopicus*. Other similar sites also should be mapped and designated as breeding and conservation sites for this fish.

Researchers, funders and practitioners working to save the Lake Baringo *O. niloticus* fishery through action-oriented research partnerships must also address a series of other issues. These include determining what are the key environmental stressors requiring continuous monitoring to generate critical socioeconomic and ecological indicators for sustainability of Lake Baringo fisheries in general? Another relevant issue is determining how existing policies and regulations can be harnessed to improve resource/fisheries management and governance? Furthermore, what are the opportunities for research that will most constructively contribute to achieving positive environmental outcomes and sustainability?

This review provides a series of principles for designing research efforts to engage in policy and institutional change focusing on improving resource management and governance of Lake Baringo. These principles include the following: (a) nurturing multi-stakeholder coalitions for change at different points in the Lake Baringo governance structure and management framework; (b) engaging alternative forms of power and spaces of engagement; (c) embedding ongoing research communications to support dialogue among stakeholders involved in managing Lake Baringo fisheries, and (d) employing evaluation in a cycle of action and learning to strengthen research engagement.

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