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Research

Impacts of algal blooms and microcystins in fish on small-scale fishers in Winam Gulf, Lake Victoria: implications for health and livelihood

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ABSTRACT. Lake Victoria, bordered by Kenya, Tanzania, and Uganda, provides one of the largest freshwater fisheries in the world and supports millions in small-scale fishing communities. Historical environmental change, including population growth, nutrient loading, introduced invasive species, and rising temperatures, has resulted in eutrophication and persistent cyanobacterial harmful algae blooms (cyanoHABs) over recent decades, particularly in the shallower gulfs, bays, and inlets. CyanoHABs impact fisheries and food web dynamics and compromise food and water security for nearshore fisher populations. In this study, we examine the social-ecological impact of freshwater blooms on fisher health in one of these eutrophic regions, Winam Gulf in Lake Victoria. CyanoHABs persist for months and produce microcystins and hepatotoxins at levels unsafe for human health. We assessed potential risk and contribution of microcystin exposure through fish consumption, in addition to exposure through water source, and conducted 400 fisher and 400 household surveys. Average microcystin concentrations exceeded the World Health Organization (WHO) guideline for drinking water consistently during the long dry season, and cyanobacterial cell counts surpassed WHO standards for recreational risk in 84% of samples. Hazard quotients for fish consumed by young children were 5 to 10 times higher than permissible levels. In addition, fishers chronicled profound ecosystem changes with direct impact on livelihood, fisheries, and water quality with 77.4% reporting a decline in profit or catch, 83.1% reporting adverse impacts of cyanoHABs on fish in the lake, and 98.2% reporting indicators of declining water quality in the lake overall. Through the application of a social-ecological lens to a public health model, we identified spheres of influence that modify how fishers experience HABs related stressors and risks to provide a starting point at which to identify sustainable strategies to improve food and water security and livelihood for the millions in nearshore communities.

Key Words: *algal blooms; cyanoHABs; ecosystem services; fishers; Lake Victoria; livelihood; microcystins; Winam Gulf*

INTRODUCTION

Freshwater cyanobacterial harmful algal blooms (cyanoHABs) are an emerging public health threat globally, exacerbated by climate change (Gobler 2020, Griffith and Gobler 2020, Lad et al. 2022). CyanoHABs produce toxins of concern for human and animal populations and threaten food and water security. Many researchers have called for a social-ecological perspective to address cyanoHABs in aquatic ecosystems, recognizing the dual role of human and natural systems in lake eutrophication (Liu et al. 2007, Carpenter et al. 2009, Cobourn et al. 2018). However, most interventions promoted by public health agencies have been reductive (Golden and Wendel 2020) based on individual actions to be taken or avoided, e.g., recreational advisories such as "when in doubt, get out" or fisheries advisories (Chorus and Bartram 1999, Ibelings and Chorus 2007, Codd et al. 2020). Conversely, ecosystem-based management has focused almost exclusively on defining the ecological perturbation, remediation, and, in some cases, restoring ecological resilience (Merel et al. 2013, Paerl and Otten 2013, Rastogi et al. 2015, Paerl et al. 2016). These approaches have assumed that social resilience and adaptation of impacted social groups would follow equally (Woods et al. 2021).

Reductionist approaches to cyanoHABs have overlooked upstream nutrient contributions and ignored the intrinsic social-ecological nature (Paerl et al. 2016, Cobourn et al. 2018, Foulon et al. 2019). In the global north, cyanoHABs tend to only be of concern in the warmer seasons, and populations tend to have more alternatives to the ecosystem services that lakes provide, such that short term avoidance can temporarily abate the issue while ignoring underlying causes and long-term consequences. These short-sighted management strategies and policies also ignore disparate impacts on marginalized communities (Moore et al. 2020). In contrast, freshwater cyanoHABs persist for longer periods of time in the global south (Mowe et al. 2015), and greater portions of the population rely more directly on those freshwater resources for drinking water, food, and livelihood (Roegner et al. 2014, 2020, Olokotum et al. 2020, Abdallah et al. 2021, Gianelli et al. 2021). CyanoHABs provide an opportunity for global communities to share sustainable intervention strategies embedded within a social-ecological framework.

There has been little to no scrutiny of potential public health impacts of cyanoHABs on already vulnerable communities, such as those facing endemic diseases, poverty, and other climate-related pressures. By applying a social-ecological lens to the manifold health impacts of blooms in a highly resource dependent setting, we posit a sustainable approach to boosting ecological and human social resilience. Through direct community and organizational engagement, we focused on the interaction between highly impacted cyanoHAB waters in Winam Gulf, Lake Victoria, Kenya and vulnerable fisher populations to broadly delineate the public health impact on a demographic already facing endemic diseases and poverty. We employed a mixed-methods approach by (1) seeking to further define the extent of

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social-ecological risk from recreational and drinking water, as well as from toxin ingestion via fish (Sitoki et al. 2012, Simiyu et al. 2018, Roegner et al. 2020), through more intensive sampling; and (2) interviewing fishers and female heads of households to capture perceptions and impacts of cyanoHABs on water quality, fisheries, and livelihood. Although not an exhaustive study, the approach can provide a roadmap for addressing the multifactorial risks from freshwater cyanoHABs, a global health threat embedded directly in ecosystem health and intimately tied to climate change.

Impacts of cyanoHABs on human and ecosystem health

Cyanobacterial harmful algal blooms (cyanoHABs) are the proliferation and visible accumulation of photosynthetic microorganisms. Although anthropogenic phosphorus and nitrogen loading trigger blooms, climactic factors, such as light intensity, rainfall, wind, and water temperature, play a mediating role (Paerl and Otten 2013, Rastogi et al. 2015, Paerl et al. 2016, Coffey et al. 2018, Kimambo et al. 2019). Cyanobacteria produce a variety of secondary metabolites, including ones that are incidentally toxic to humans and wildlife. Cyanotoxins target manifold systems including the hepatobiliary, integument, nervous, renal, cardiovascular, and immune systems (Merel et al. 2013, Bouaicha et al. 2019, Du et al. 2019, Codd et al. 2020, Metcalf et al. 2021). The primary routes of exposure are ingestion of drinking water, contaminated shellfish and seafood, crops irrigated with bloom-laden water, and water during recreational activities. Other routes of exposure may include dermal contact and inhalation of aerosols containing toxins during recreational activities (Mulvenna et al. 2012, Backer et al. 2015, Massey et al. 2018, Codd et al. 2020, Abdallah et al. 2021, Plaas and Paerl 2021).

The most commonly identified group of cyanotoxins in freshwater are microcystins (MCs), which acutely target the liver, resulting in oxidative stress as well as multi-system effects (Merel et al. 2013, Valário et al. 2016, McLellan and Manderville 2017, Massey et al. 2018, Bouaicha et al. 2019). With 200 MC variants identified, the most commonly identified variant, Microcystin-LR (MC-LR) has been used to develop the World Health Organization's (WHO) drinking water provisional guideline of 1 $\mu g/L^{-1}$ based on daily tolerable intake (TDI) for lifetime exposure of MC, based on rodent studies (Valerio et al. 2016, Massey et al. 2018, Arman and Clarke 2021). Chronic MC exposures are linked to liver and colon cancer and multisystem effects, as well to impaired neurodevelopment, immune suppression, impaired reproduction, and kidney and cardiovascular diseases, with marked discrepancies in congener effects in rodent models (Valerio et al. 2016, McLellan and Manderville 2017, Massey et al. 2018, Bouaicha et al. 2019, Metcalf et al. 2021).

CyanoHABs and cyanotoxins also impact aquatic species and ecosystem services (Malbrouck and Kestemont 2006, Huisman et al. 2018, Simiyu et al. 2018, Olokotum et al. 2020). CyanoHABs result in low oxygen saturation levels in the water column, which can cause fish die offs; cyanobacteria outcompete other photosynthesizers and cause toxicity to grazers and food web alterations with more hypoxia tolerant species predominating (Malbrouck and Kestemont 2006, Huisman et al. 2018, Banerjee et al. 2021). Humans reliant on fisheries for income or sustenance directly suffer the consequences when survival and abundance of individual species are impacted or when potent cyanotoxins accumulate in shellfish or seafood that they ingest (Ibelings and Chorus 2007, Poste et al. 2011, Olokotum et al. 2020, Abdallah et al. 2021).

Lake Victoria and environmental change

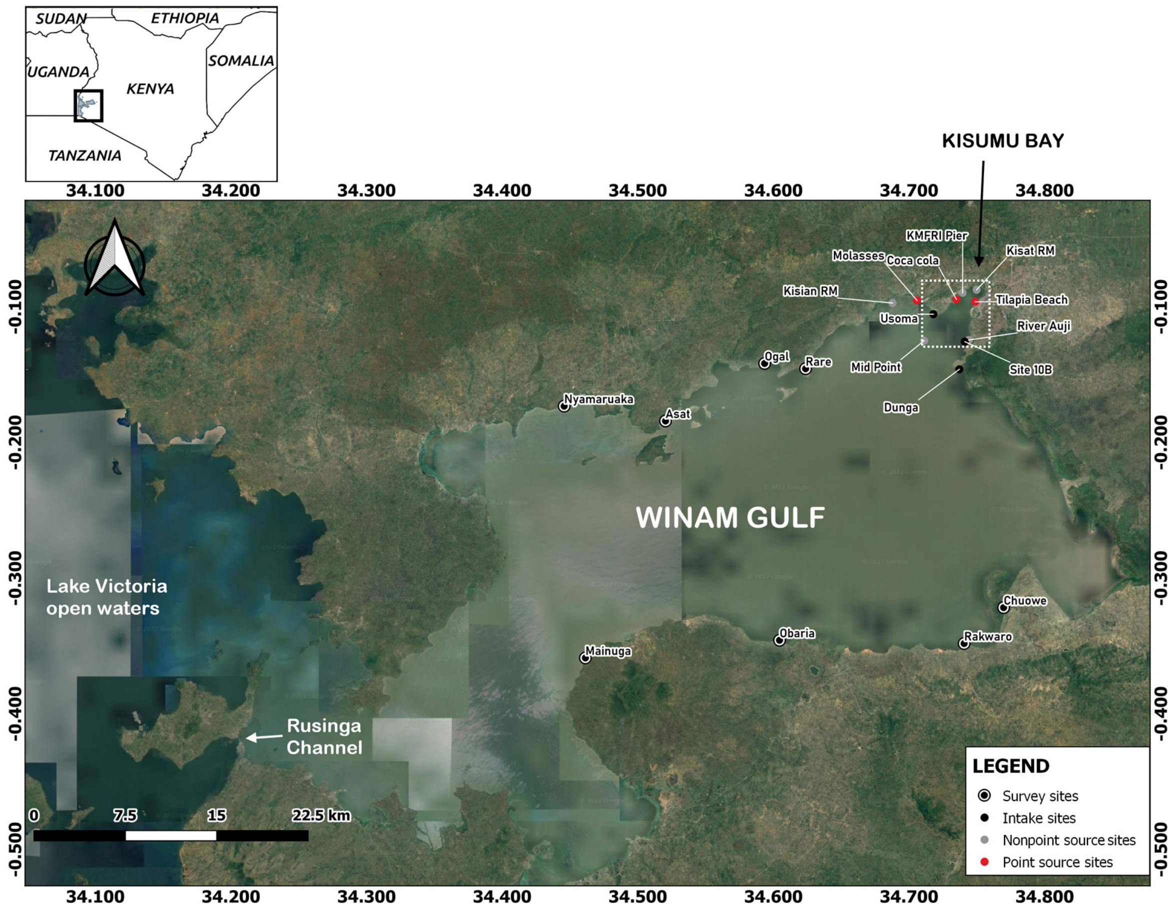
Lake Victoria covers a surface area of 68,800 km^3, has a maximum depth of 84 m, a mean depth of 40 km, and a shoreline of 3440 km (Sitoki et al. 2012, Sterner et al. 2020). Bounded to the north by Uganda (43% surface area), to the south by Tanzania (51%), with a northeastern sector bounded by Kenya (6%), Lake Victoria services a watershed area of 194,200 km^2, including Burundi and Rwanda tributaries. The largest freshwater fishery in the world with approximately 1.0 million tonnes of fish landed annually, it supports export markets to the European Union, Israel, and East Asia. The fishery relies on three main species, silver cyprinid dagaa (*Rastrineobola argentea*), Nile perch (*Lates niloticus*), and Nile tilapia (*Oreochromis niloticus*; Odongkara et al. 2005, Sitoki et al. 2010, Nyamweya et al. 2020, Olokotum et al. 2020), is largely artisanal, and provides basic resources, services, and livelihoods for millions of people at the lake's shores (Nyamweya et al. 2020, Olokotum et al. 2020, Sterner et al. 2020, Oyango et al. 2021).

CyanoHABs and vulnerability of small-scale fishers at Lake Victoria

Lake Victoria supports more than 42 million people in its basin by providing drinking water and food. Small-scale fisher communities, concentrated in the bays, gulfs, and scattered around urban population centers, feel the burden of change in health and livelihood most directly (Simiyu et al. 2018, Olokotum et al. 2020, Oyango et al. 2021). CyanoHABs predominate in bays and inlets around the lake, notably impacting drinking water in the region and reducing catch and fish availability (Sitoki et al. 2012, Simiyu et al. 2018, Mchau et al. 2019, Olokotum et al. 2020, Roegner et al. 2020). Microcystins exceeding WHO provisional guidelines have been detected in raw source waters for these communities (Sitoki et al. 2012, Mchau et al. 2019, Roegner et al. 2020). The fisherfolk rely heavily on fish as a protein, including ingestion of *R. argentea* snacks by small children, particularly vulnerable to chronic MC exposures through water and food sources (Kabahenda et al. 2011, Poste et al. 2011, Simiyu et al. 2018, de Bruyn et al. 2021, Oyango et al. 2021). These small cyprinid species may deliver significant levels of toxins, especially if consumed whole (Poste et al. 2011, Simiyu et al. 2018). Fish obtained near these population centers have an increased risk for MC content, given bloom persistence in shallower waters.

Given high reliance of fisher communities on impacted waters in Winam Gulf, Kenya for food, water, and livelihoods, the main objectives of our study were: (1) to capture demographics of fishers impacted by CyanoHABs; (2) to assess fisher perceptions of changes in the lake and fish catch in the recent past; (3) to determine MC concentrations in species of fish consumed by small scale fishers with concurrent spatial and temporal water quality monitoring; and (4) to evaluate contribution of fish consumption to total daily intake (TDI) of MCs by fishers. We hypothesized that lake water would exceed WHO provisional guidelines for MCs across a number of sites and months; that muscle of consumed fish species would have levels of MCs resulting in high-risk hazard quotients; and that fishers witness

Fig. 1. The majority of the portion of Lake Victoria in Kenyan waters is depicted. The 11 Kisumu Bay sites sampled monthly from October 2015 to May 2016 are visible in the northeast corner of Winam Gulf. Site 10b represents the drinking water intake, River Auji comprises tertiary treatment of wastewater discharge, Kisian and Kisat are river mouths, Dunga and Usoma are fisher villages, and Molasses, Coca-Cola®, and Tilapia are point sources. In the greater Winam Gulf, the fisher villages where surveys took place are depicted in the Kisumu (Nyamaruaka, Asat, Ogal, Rare) and Homa Bay (Mainuga, Obaria, Rakwaro, Chuowe) regions. Fish were purchased from beach landing sites within Kisumu Bay.



direct impact of cyanoHABs on their livelihood. Our findings have implications for Lake Victoria and for worldwide small-scale fishers reliant on surface waters impacted by cyanoHABs.

METHODS

Study area

Sitting at an inlet bay (Kisumu Bay) at the northeastern edge of Lake Victoria in Winam Gulf, Kisumu (Fig. 1) is the third most populous city in Kenya, with a population of approximately ½ million people living in the metro and surrounding areas. Despite high dependence on the lake for municipal drinking water (Fig. 1, Site 10B), fisheries, and recreation, wastewater sewage discharges directly into the lake, although some of it is diverted through historical wetlands (Fig. 1, River Auji). The northwestern side of Kisumu Bay is flanked by industry including a molasses and Coca-Cola® factory (Fig. 1), and several river mouths that discharge nonpoint source industrial runoff. Tourist sites (Tilapia Beach and Dunga) serve as sites of fish purchase and consumption for urban residents and visitors. Residents of the fisher village at Dunga profit from both the fish trade and tourism, while residents of the fisher village at Usoma frequently interact with nonprofit endeavors because of their close proximity to the city center. A summary of all sampling sites can be found in Table 1.

Beyond industrial and municipal discharge, nonpoint source agricultural runoff exists through much of the gulf. Small-scale fisher villages are scattered in smaller bays and inlets throughout Winam Gulf (Fig. 1; representative fisher villages of Nyamaruaka, Asat, Ogal, and Rare along the north of the Gulf and Mainuga, Obaria, Rakwaro,and Chuowe along the south), with fishers often traveling long distances and staying overnight to fish and sell catch. Winam Gulf is connected to the open, deep waters of Lake Victoria through a narrow inlet (Rusinga Channel), and although water within the gulf is well mixed, there is only periodic mixing between the gulf and the open waters. Thus, much of the water along Winam Gulf is impacted by blooms, particularly during the second dry season that extends approximately from December to March or April. Typically, a long rainy season then follows until August, though climate change has rendered weather patterns and associated crop cycles much less predictable. A short dry season from August to September then follows, with short rains in October or November. Blooms have historically appeared during the long dry season from December through March, when light intensity and temperature are most favorable for cyanobacterial proliferation, but changes in climate have meant that blooms can now appear throughout the course of the year.

Table 1. The 11 lake-water sampling sites within Kisumu Bay were traveled to by the Kenya Marine and Fisheries Research Institute (KMFRI) boat, whereas the 8 community survey sites were traveled to by land vehicle to cover a greater span of the gulf.

Name	Sampling Site Description	Data Collected
Kisian River mouth	nonpoint source	water quality
Molasses	point source	water quality
Usoma	fisher village, high NGO presence	water quality
Coca Cola	point source	water quality
KMFRI pier	KMFRI home station	water quality
Kisat River mouth	nonpoint source	water quality
Tilapia Beach	nonpoint source, tourist location	water quality
River Auji wetlands	tertiary wastewater outflow	water quality
Site 10B city intake	city drinking water intake	water quality
Dunga Beach	fisher village, tourist site	water quality
Midpoint	center point of well-mixed bay	water quality
Nyamaruaka	fisher village, Kisumu Bay	surveys
Asat	fisher village, Kisumu Bay	surveys
Ogal	fisher village, Kisumu Bay	surveys
Rare	fisher village, Kisumu Bay	surveys
Mainuga	fisher village, Homa Bay	surveys
Obaria	fisher village, Homa Bay	surveys
Rakwaro	fisher village, Homa Bay	surveys
Chuowe	fisher village, Homa Bay	surveys

For the purposes of identifying communities and households for engagement around the blooms, we worked with community health mobilizers already doing outreach for HIV prevention and treatment across Winam Gulf. Mobilizers were asked to identify communities in which blooms had already emerged as a health concern during community clinics or ongoing focus group discussions. The study design also sought to generate geographic spread across Winam Gulf (Fig. 1) to capture potential regional heterogeneity.

Collection of water samples

Monthly sampling from September 2015 to May 2016 occurred by boat in Kisumu Bay at 11 designated sites, including nonpoint and point sources, riverine outflows, near municipal drinking water facility intake, nearshore to fisher villages, and a central midpoint to serve as a baseline for this well-mixed bay (Fig. 1, Table 1). Surface (top 0.5 meter) and depth integrated samples were collected in 250 ml amber glass vials and kept on ice in a cooler for transport. The integrated sample was collected by a KC 11.200 3 Liter Van Dorn (CANIMPEX Enterprises LTD., Halifax, Nova Scotia, Canada) and mixed in a five-gallon bucket. Secchi depth, dissolved oxygen, water temperature, pH, and conductivity were measured in the field. Lugol's solution was used to preserve phytoplankton samples for cyanobacterial identification and cell counts, as previously described in Sitoki et al. 2012 and Roegner et al. 2020. For water, 50 mL were filtered through Whatman ™ GF/C glass fiber filters (0.7 µm nominal pore size, Sigma-Aldrich, St. Louis, Missouri) in duplicate. These filters were then immediately dried in an oven at 40 °C for 48 hours. For extremely eutrophic samples, the amount filtered was reduced to 20 mL. One set of dried filters were immediately frozen at -20 °C wrapped in aluminum foil until further extraction and analysis of intracellular toxins, while the duplicate set was used to determine chlorophyll-a, using previously published methods (Sitoki et al. 2012, Roegner et al. 2020).

Collection of fish samples and dissection

In cooperation with Kenya Medical Research Institute (KEMRI) and Family AIDS Care and Education Services (FACES), we sampled lake water from the littoral zone of bloom-impacted fisher communities across four seasons (Roegner et al. 2020). When encountering fishers at landing sites, team members purchased fresh-caught fish intended for local consumption. Fish variety was encouraged, so species do not represent typical catch distribution. Fish were kept on ice for transport and later frozen whole at -20 °C.

Fish dissection, by KMFRI research biologists and student interns, included ID by biologists, photographs by students with measurement of weight (to the nearest 0.1 grams), and total and standard length (to the nearest 0.1 cm). The stage of sexual maturity and stomach contents of each fish was noted. Epaxial muscle was dissected from the left side of the fish with the skin removed. After wet weight was recorded, the sample was placed in a seven oz Whirl-Pak® (Madison, Wisconsin). One species, *Rastrineobola argentea*, is consumed whole and was maintained as such for analysis. All samples were frozen at -20 °C until transported to the U.S. for extraction and MC analysis.

Microcystin (MC) extraction from fish and water samples

Microcystins were extracted from filters as previously described and analyzed using liquid chromatography tandem mass spectrometry (LC-MS/MS; Roegner et al. 2020). Fish muscle samples were lyophilized with a Labconco® Freezone freeze dryer (Kansas City, Missouri) with approximately 0.5 g of fish tissue. Replicate samples were spiked with a known amount of all MC congeners targeted by LC-MS/MS prior to lyophilization to determine percent recoveries. Samples were lyophilized for at least 48 hours. Lyophilized samples were then weighed and hand homogenized with a rounded pestle wand. Ten mL of extraction solvent (5 mM EDTA, 10 mM acetic acid in 80% methanol) was added while rinsing the pestle wand for a quantitative transfer. The extract was then homogenized for 1-2 minutes using a Cole-Parmer® LabGEN electric homogenizer (Vernon Hills, Illinois). The tip was then rinsed with deionized water, bringing the extract volume to 50 mL and solvent strength to 16% methanol. Cellular debris was pelted by centrifugation at 10,000 x g for 20 minutes, and the supernatant loaded onto an Elute Bond C18 solid phase extraction cartridge at < 5 psi vacuum. Microcystins were eluted with 100% methanol, dried at 37 °C under nitrogen gas and resuspended in 1 mL of 50% methanol. The final extract was cleared of particulates by centrifugation and spiked with 5 µL of $^{13}C_6$-Phenylalanine to quantify matrix effects. Representative chromatogram runs and product ion spectra have been published elsewhere (Miller et al. 2020).

For both fish and water samples, MC-LR, -YR, -RR, -LA, [Dha^7] MC-LR (dmLR), and nodularin were quantified by LC-MS/MS based on a linear regression of peak area compared to the known concentration of eight calibration standards. Reference standards were purchased from Enzo Life Sciences or from the National Research Council of Canada's (NRC) Metrology Research Centre (Miller et al. 2020). Microcystins are named for the common amino acids that occupy the two variable positions in the seven amino acid ring. For example, MC-LR indicates leucine and arginine at positions two and four, respectively, whereas MC-YR is tyrosine and arginine at those positions.

Fisher and household interviews

Quantitative surveys were carried out at local beach management units (BMUS) at four communities in Kisumu Bay (Asat, Nyamaruaka, Ogal, and Rare) and four communities in Homa Bay (Chuowe, Mainuga, Obaria, and Rakwaro) between July 2016 through March 2017 (Fig. 1). These surveys were conducted under the KEMRI/Scientific and Ethics Review Unit (SERU) protocol no. KEMRI/SERU/CMR/P00033/3248 and UC Davis IRB 826854. Beach management units, locally elected councils of officers from within the fisher communities were approached to generate a list of all eligible community members. Kenya Medical Research Institute and KMFRI personnel then worked in collaboration with FACES community mobilizers to take this list and randomly select potential participants. Potential participants were then contacted with an offer of participation and verification of eligibility requirements. Inclusion criteria included active fishing activities as part of household income, over the age 18 and able to consent, and willingness to be a participant in the study. Children, teenagers less than 18, incarcerated, and mentally unstable individuals were excluded from the list. This formal approach through community representatives may have had limitations in avoidance by fishers not wanting to engage with the BMUs, potentially those engaged in illegal fishing activities. However, direct surveying at the beaches could have skewed demographics along geographic access, socioeconomic status, and fisher type.

Fifty fishers were recruited from each of the 8 towns (Fig. 1) to answer survey questions regarding state of the fisheries and impacts of water quality on fisheries, and 50 household heads (all female) were recruited from the same towns to answer questions about lake water and fisheries usage. Fisher and household survey questionnaires took less than 15 minutes and were conducted with each individual in private by a trained interviewer fluent in both dhoLuo and Swahili with an assistant recorder (Appendix 1). Surveys were anonymized, other than gender and approximate age of participant. Respondents in surveys were also given the opportunity make additional comments or address additional concerns in open-ended responses.

Data analysis and risk assessment

Descriptive statistics, including sample skew and one-sided (1-α) upper 95% confidence limit of the geometric mean, were used to summarize cyanobacterial cell counts and MC concentrations in water across sites and seasons, and employed to characterize fisher and household survey responses across towns, bays, and as a whole. One-way analysis of variance (ANOVA) was used to probe potential differences between towns and bays in survey responses. Statistical tests were determined significant when $P < 0.05$. Open-ended survey responses to fisher and household surveys were summarized in word clouds displayed on a logarithmic scale based on frequency, with common conjunctions and articles eliminated first.

Microcystins congener concentration in fish was divided by the wet weight analyzed (~0.5 g) to yield µg/kg wet weight (w.w.) The 'sumMC' content was calculated by summing of all MC congeners detected:

[sumMC]/kg fish ={[MCLR]+[MCYR]+[MCRR]+[MCLA]+[Dha7-MCLR]}/wet weight

The World Health Organization (WHO) lifetime tolerable daily intake (TDI) guideline of 0.04 µg per kg body weight per day over a lifetime is based upon the no observable adverse effect level (NOAEL) from rodent studies with an extrapolation factor of 100 and, uncertainty factor of 10 (Chorus and Bartram 1999). Herein, guideline values for MCs from food were determined for a 13 kg child and 60 kg average Kenyan adult (Walpole et al. 2012). Given that previous work in the region has also indicated a potential substantial contribution through drinking water to daily intake, we calculated guidelines for MCs in fish for adults and children in two scenarios (Ibelings and Chorus 2007). Scenario 1 assumes all MC intake comes from food with an allocation factor of 1, whereas Scenario 2 assumes 80% of the dose is coming through the water sources, following assumptions made during derivation of the WHO drinking water provisional guideline of 1 µg/L, with 80% of MC intake coming through drinking water and an allocation of factor of 0.2 for dietary sources. Each scenario's guidance values were calculated as follows for the 10 kg child and 60 kg adult, assuming 100 grams daily fish intake on health recommendations in the region for adequate protein intake (de Bruyn et al. 2021). However, daily intakes of particular species such as *O. niloticus* and *L. niloticus* have been reported to be much higher in market place surveys, at 0.27 and 0.35 kg per day, respectively (Esilaba et al. 2020).

GV_{food} = TDI *bw_{ave} *AF/C,

where GV= guidance value, bw_{ave} = average body weight for Kenya, AF = allocation factor, and C = amount of food ingested.

Scenario 1 (AF = 1, assumes all intake through fish):
GV_{child} = 0.04 µg/kg *10 kg *1/0.1 kg = 4 µg/kg fish
GV_{adult} = 0.04 µg/kg *60 kg *1/0.1 kg = 24 µg/kg fish

Scenario 2 (AF = 0.2, assumes 20% through dietary fish intake):
GV_{child} = 0.04 µg/kg *10 kg *0.2/0.1 kg = 0.8 µg/kg fish = 0.8 µgs/kg fish
GV_{adult} = 0.04 µg/kg *60 kg *0.2/0.1 kg = µg/kg fish = 4.8 µgs/kg fish

A hazard quotient (HQ) was then calculated for each species and overall daily fish consumption using the average measured sumMCs. An HQ greater than 1 is considered high risk.

HQ_{child} = sumMC µgs/kg fish/ GV_{child}

HQ_{adult} = sumMC µgs/kg fish/ GV_{adult}

RESULTS

Water quality in Kisumu Bay, Lake Victoria

Figure 1 illustrates the locations of monthly lake sampling sites, during seasonal water quality sampling. As described in the study site description in the methods section, these included industrial point and nonpoint sources, wastewater discharge through wetlands, municipal drinking water intake, fisher beaches, and tourism sites. Surface (n = 92) and integrated water (n = 86) samples were taken over eight months.

Microcystis spp. and *Dolichospermum* spp. consistently exceeded WHO actionable cell counts across the bay (Chorus and Bartram 1999, Codd et al. 2020). Table 2 shows the geometric mean, standard deviation, sample skew, upper 95% confidence limit, maximum, and minimum for monthly total cyanobacterial, *Microcystis*, *Dolichospermum* cell counts, as well as the corresponding MC concentrations measured. For surface samples, 83.7% exceeded 20,000 total cyanobacterial cell counts/mL, for short-term health risk from recreational contact; 68.5% exceeded 100,000 for long-term health risk from recreational contact (WHO recreation criteria 1999). Similar trends were found with integrated samples: 79.3% for short-term risk and 69.6% for long-term health risk.

Microcystins were detected in surface waters every month with average levels exceeding the WHO provisional guideline for drinking water during the long dry season. The mean sumMC detected in surface and integrated waters for the 11 sites in October 2015 to May 2016 was 1.6 ± 3.8 µg/L (1-á = 3.72) and 1.6 ± 2.7 µg/L (1-á = 3.42), respectively. The highest surface MCs detected was 23.3 µg/L outside the Coca-Cola® facility in February 2016, while the highest integrated was 13.7 µg/L near Dunga Beach in February 2016. The second highest integrated MCs was 10.8 µg/L near the Coca-Cola® bottling facility in 2021. Only particulate MC, contained within the cyanobacterial cells themselves, were captured, and total MCs, including both particulate and dissolved, were likely even higher, depending upon the growth phase of the cyanobacterial cells.

All MC variants were detected. The most commonly detected congeners, overall, as well as for surface and integrated samples were MC-LR (55.6% of samples), MC-YR (53.3% of samples), MC-LA (46.63% of samples), followed by [Dha^7]MC-LR and MCRR (37.1% and 30.1% of samples, respectively. Both frequency and concentrations of MCs were higher in the surface water samples, on average, compared with the integrated water sample. Correlation between surface and integrated samples for total microcystins (0.64) was better than correlation between surface and integrated samples of total and cyanobacterial cell counts (0.35 for all species, 0.29 for *Microcystis* spp., 0.06 for *Dolichospermum* spp.).

Physical characteristics and microcystins (MC) detections in consumed fish

A total of 82 fish samples were analyzed. Table 3 provides descriptive statistics of physical characteristics and seasonal representation. Figure 2A gives the distribution of the number of individual fish that had detectable levels of MCs (detects) across species of fish purchased and analyzed. The majority of fish were collected in the dry period from December to March (n = 41) and at the start of the long rain period in April (n = 31), both targeted for peak bloom season as described by local fisheries biologists. Over half of the samples had empty stomach contents (n = 44), with bottom-dwelling catfish eating detritus, shellfish, and insects. Other species had mixtures of zooplankton and phytoplankton contents. Many of the fish were immature (n = 30), while the remainder of fish were split between M2 to M4 stage males (n = 18) and F2 to F6 stage females (n = 14). *R. argentea* were not evaluated for sex characteristics. Juvenile or undersized *Lates niloticus* and *Oreochromis niloticus* and were designated as those under 150 grams in accordance with local fisheries guidelines.

Eleven MC positive detects (13.4%) were found. The congener microcystin MC-YR (named for tyrosine and arginine at the variable positions) had eight detects, followed by MC-LR (leucine and arginine, n = 7), MC-LA (leucine and alanine, n = 5), MC-RR (arginine and arginine, n = 4), and MC-LY (leucine and tyrosine, n = 3). Table 4 details the physical characteristics of individual fish, seasons in which caught, and sumMCs detected, while Figure 2B depicts the individual congener distribution for each of the individual fish with detects. The following species had no detects: *Barbus altianalis* (n = 3), *Clarias gariepinus* (n = 8), and *Synodontis victoriae* (n = 15).

Human health risk assessment from daily consumption of fish during bloom season

Hazards quotients for adult and child daily consumption are presented in Table 5. Based on previously published data on water sources (Roegner et al. 2020), we assumed drinking water would also be a major source of MC intake for fishers. The HQ for adults and children overall were 0.5 and 3.0, respectively, assuming equal distribution of consumption across all fish employed in this study, with notable variability in risk across species. The highest hazard quotient (50.7 and 8.5 for children and adults, respectively) was from a single *Brycinus sadleri*. The HQ_{child} for *Haplochromis* spp. (10.3) and *Rastrineobola argentea* (5.8) represent a concern for children snacking on these smaller fish. Figure 2B illustrates the mean and standard deviation of toxin detects in µg per kg tissue for each species as typically consumed, muscle or whole fish, with number of replicates obtained and analyzed during this study denoted atop the bar graph. The purple and red dashed lines denote permissible intake, for a 60 kg adult and 10 kg child, respectively, for sustained, lifetime exposures (Ibelings and Chorus 2007).

Fisher and boat demographics

Respondents to fisher surveys were male. Boat owners comprised 24.0 % of survey respondents, but the majority of respondents, 73.1%, were crew. The remainder were involved with boat repair, nets, fish trading, fish sales, fishing gear, fishing by foot, and fungi harvesting, with each category comprising less than 1%. The average number of crew members per boat (n = 385) was 3.52 ± 1.7, with a median of 4, ranging from 1 to 14. There was significant variation in size of crew between beaches ($p < 2e-16$, F-value = 14.46), but not between the distinct bays; however, the overwhelming majority (93.9%) of crew sizes were 4 members or less. The boat crews were overwhelmingly male (> 99.9%). Two respondents reported women fishers included in the boat crew: two in a Rakwaro crew and four in an Obaria crew. Twelve children total were indicated as members of a boat crew. Figure 3A shows distribution of crew size across beaches.

Table 2. Monthly cyanobacterial cell counts and microcystin concentrations in surface waters across Kisumu Bay from 2015-2016. The table captures the mean (X), standard deviation (s), maximum, and minimum monthly, along with sample skew and *one-sided (1-α) upper confidence limit of the geometric mean. Total cyanobacterial, *Microcystis* spp., *Dolichospermum* spp. cell counts, and corresponding MC concentrations for surface and integrated data are also shown. Data represent average values across 11 near-shore sites that include nonpoint and point sources, as well as drinking water intakes.

Month	Depth	Statistic	Cyanobacterial cells per mL	*Microcystis* cells per mL	*Dolichospermum* cells per mL	sumMC µg/L	MCLR µg/L	MCYR µg/L	MCLA µg/L	MCRR µg/L	dmLR µg/L
October	Surface (n = 10)	mean (X)	199250	224758	58138	0.07	0.03	0.03	0.02	0.02	ND[‡]
		max	921524	753059	428862	0.11	0.04	0.04	0.03	0.03	
		min	100	33	1133	0.03	0.02	0.01	0.01	0.01	
		stdev (s)	272922	247223	124997	0.04	0.01	0.02	0.02	0.01	
		β (Skewness)	0.56	-0.33	2.57	-0.11	-1.39	-1.73		-0.44	
		(1-α)[†]	234715	339586	86445	1.72	1.67	1.68		1.67	
		detects	1.00	0.50	0.80	0.40	0.40	0.30	0.10	0.30	
	Integrated (n = 10)	mean (X)	212824	193752	60494	0.11	0.05	0.05	0.01	0.02	ND[‡]
		max	442329	391829	155998	0.24	0.08	0.11	0.01	0.03	
		min	2333	400	1567	0.02	0.02	0.02	0.01	0.01	
		stdev (s)	171673	143216	70745	0.11	0.04	0.05	n/a	0.01	
		β (Skewness)	0.01	-0.31	0.73	1.44		1.64			
		(1-α)[†]	212857	192609	61843	1.76		1.70			
		%detects	1.00	0.80	0.60	0.30	0.20	0.20	0.10	0.20	
November	Surface (n = 11)	mean (X)	181101	158121	24866	0.03	0.02	0.01	0.01	ND[‡]	ND[‡]
		max	921524	753059	156965	0.03	0.02	0.01	0.01		
		min	5767	33	1133	0.03	0.02	0.01	0.01		
		stdev (s)	266644	235714	58274						
		β (Skewness)	2.20	2.11	2.44						
		(1-α)[†]	218938	195870	32524						
		%detects	1.00	0.73	0.64	0.09	0.09	0.09	0.09		
	Integrated (n = 11)	mean (X)	390889	261397	60494	0.11	0.05	ND[‡]	ND[‡]	ND[‡]	ND[‡]
		max	1140089	390889	155998	0.24	0.08				
		min	7300	1140089	1567	0.02	0.02				
		stdev (s)	384105	138929	254170						
		β (Skewness)	1.38	0.79	1.73						
		(1-α)[†]	404671	244570	162953						
		%detects	0.82	0.64	0.27	0.09	0.09				
December	Surface (n = 11)	mean (X)	520398	322209	93080	0.02	0.01	0.01	ND[‡]	ND[‡]	ND[‡]
		max	1592751	503328	256664	0.02	0.01	0.01			
		min	24466	267	3400	0.02	0.01	0.01			
		stdev (s)	527038	197425	84909						
		β (Skewness)	1.06	-0.89	1.22						
		(1-α)[†]	534953	317667	95764						
		%detects	1.00	0.73	0.64	0.09	0.09	0.09			
	Integrated (n = 11)	Mean (X)	355633	368807	151751	ND[‡]	ND[‡]	ND[‡]	ND[‡]	ND[‡]	ND[‡]
		max	1140089	491662	444996						
		min	7300	78999	3400						
		stdev (s)	384105	138929	254170						
		β (Skewness)	0.92	0.12	1.40						
		(1-α)	365642	369927	158894						
		%detects	0.91	0.55	0.64						
January	Surface (n = 11)	mean (X)	451688	328376	75752	3.04	1.40	1.22	0.27	0.07	0.09
		max	1580151	782126	129999	11.65	5.50	5.26	0.90	0.39	0.31
		min	25780	22600	20833	0.16	0.09	0.03	0.02	0.01	0.01
		stdev (s)	463558	270470	48770	4.50	2.00	1.99	0.32	0.13	0.12
		β (Skewness)	1.71	0.63	0.05	1.73	1.74	1.77	1.64	2.69	1.53
		(1-α)[†]	472249	332817	75818	4.88	3.13	2.96	1.93	1.73	1.74
		%detects	1.00	0.82	0.64	0.91	0.91	0.91	0.91	0.73	0.82
	Integrated (n = 11)	mean (X)	219377	227219	40722	1.85	0.87	0.70	0.18	0.06	0.08
		max	517828	510262	141332	6.41	2.98	2.64	0.56	0.21	0.21
		min	3133	3400	7567	0.16	0.10	0.03	0.02	0.01	0.01
		stdev (s)	170154	173191	45254	2.28	1.04	0.92	0.19	0.07	0.08
		β (Skewness)	0.35	0.36	1.65	1.64	1.67	1.64	1.52	0.92	1.35
		(1-α)[†]	220936	228862	42665	3.60	2.56	2.38	1.83	1.73	1.71
		%detects	1.00	0.73	0.82	0.09	0.09	1.00	1.00	0.73	0.73
February	Surface (n = 10)	mean (X)	485168	328376	75752	3.73	1.88	1.39	0.33	0.04	0.19
		max	1828815	782126	129999	23.31	11.26	9.48	1.60	0.13	0.85
		min	18100	22600	20833	0.09	0.04	0.02	0.01	0.01	0.02
		stdev (s)	629499	270470	48770	7.93	3.81	3.27	0.56	0.05	0.32
		β (Skewness)	1.51	0.63	0.05	1.73	1.74	1.77	1.64	2.69	1.53
		(1-α)[†]	509890	332817	75818	4.88	3.13	2.96	1.93	1.73	1.74

(con'd)

		%detects	1.00	0.70	0.50	0.80	0.80	0.80	0.70	0.50	0.60
	Integrated (n = 11)	mean (X)	616261	227219	40722	1.85	0.87	0.70	0.18	0.06	0.08
		max	517828	510262	141332	6.41	2.98	2.64	0.56	0.21	0.21
		min	3133	3400	7567	0.16	0.10	0.03	0.02	0.01	0.01
		stdev (s)	170154	173191	45254	2.28	1.04	0.92	0.19	0.07	0.08
		β (Skewness)	0.94	0.86	0.15	1.32	1.38	1.25	1.63	1.32	0.37
		(1-α)[†]	630733	290227	42843	5.71	3.78	2.89	2.04	1.80	1.88
		%detects	1.00	0.82	0.73	0.64	0.64	0.64	0.64	0.36	0.73
March	Surface (n = 11)	mean (X)	504362	397596	121036	0.92	0.63	0.22	0.05	0.02	0.05
		max	1476952	940657	498328	3.05	1.88	0.84	0.14	0.05	0.15
		min	66166	49333	1633	0.05	0.04	0.01	0.01	0.01	0.01
		stdev (s)	522670	335390	198387	1.02	0.65	0.30	0.05	0.02	0.05
		β (Skewness)	1.28	0.75	1.62	1.40	1.13	1.64	0.93	1.84	1.86
		(1-α)[†]	521697	404132	129376	2.60	2.29	1.87	1.70	1.66	1.69
		%detects	1.00	0.91	0.82	0.82	0.82	0.73	0.82	0.45	0.64
	Integrated (n = 10)	mean (X)	642942	629979	79449	1.18	0.81	0.27	0.11	0.03	0.07
		max	1863715	1699983	268831	3.18	2.20	0.77	0.30	0.04	0.18
		min	86599	99332	833	0.01	0.01	0.01	0.01	0.01	0.01
		stdev (s)	520742	492917	86384	1.29	0.86	0.31	0.10	0.02	0.06
		β (Skewness)	1.18	1.25	1.71	0.81	0.80	0.90	1.21	0.88	-1.47
		(1-α)[†]	658878	646053	83288	2.86	2.48	1.92	1.76	1.72	1.67
		%detects	1.00	0.82	0.73	0.91	0.91	0.73	0.73	0.27	0.73
April	Surface (n = 11)	mean (X)	262540	241004	43129	1.05	0.58	0.28	0.11	0.04	0.08
		max	911758	705493	202998	3.40	1.76	1.09	0.35	0.14	0.18
		min	7633	1800	5600	0.19	0.12	0.02	0.02	0.01	0.03
		stdev (s)	248335	195357	65198	1.27	0.64	0.42	0.12	0.05	0.06
		β (Skewness)	1.41	1.16	1.39	1.53	1.35	1.67	1.58	1.87	0.88
		(1-α)[†]	360382	427200	35350	2.75	2.25	1.95	1.76	1.68	1.73
		%detects	1.00	0.91	0.73	0.91	0.91	0.91	0.91	0.64	0.55
	Integrated (n = 11)	mean (X)	368375	331787	20808	1.41	0.73	0.49	0.12	0.05	0.07
		max	892324	780825	61499	5.47	2.74	1.99	0.46	0.09	0.23
		min	66366	49333	4833	0.09	0.06	0.01	0.01	0.02	0.01
		stdev (s)	347400	295561	18938	1.81	0.90	0.67	0.15	0.03	0.08
		β (Skewness)	0.71	0.66	1.74	1.55	1.54	1.55	1.56	1.47	0.73
		(1-α)[†]	374759	336859	21669	3.13	2.41	2.16	1.77	1.72	1.70
		%detects	1.00	0.91	0.73	1.00	1.00	1.00	1.00	0.36	0.82
May	Surface (n = 11)	mean (X)	360269	396378	24985	0.46	0.21	0.18	0.12	0.02	0.03
		max	1130655	1009657	93332	1.70	0.84	0.52	0.27	0.03	0.07
		min	767	600	1933	0.02	0.01	0.01	0.03	0.01	0.01
		stdev (s)	430399	420813	33262	0.62	0.29	0.21	0.13	0.01	0.03
		β (Skewness)	1.13	0.79	1.86	1.52	1.76	1.13	1.55	-0.90	1.40
		(1-α)[†]	372928	405019	26593	2.13	1.87	1.83	1.77	1.67	1.68
		%detects	1.00	0.82	0.64	0.73	0.73	0.73	0.27	0.27	0.36
	Integrated (n = 11)	mean (X)	262540	241004	43129	0.24	0.13	0.13	0.03	0.02	0.02
		max	911758	705493	202998	1.23	0.57	0.56	0.05	0.02	0.03
		min	7633	1800	5600	0.01	0.01	0.01	0.01	0.02	0.01
		stdev (s)	248335	195357	65198	0.49	0.25	0.24	0.03		0.02
		β (Skewness)	1.91	1.52	2.73	2.42	2.22	2.22			
		(1-α)[†]	274844	248721	47749	1.92	1.79	1.79			
		%detects	1.00	0.91	0.73	0.55	0.45	0.45	0.18	0.09	0.18

[†] one-sided (1-α) upper confidence limit on the mean.
[‡] ND = non detect.

The mean fisher age for interviewees (n = 391) was 34.6 ± 12.7 years, with a median of 32, and age range from 16 to 76 (Fig. 3B). The average for years spent in fisheries (n = 390) was 13.3 ± 10.4, with a median of 10 and ranged from 1 month to 70 years. Regionally, by bay, there was a significant variation in years spent in fisheries ($p = 0.0356$, F-value = 4.446) with slightly more years spent in Kisumu (14.4 ± 11.9 years) compared to Homa (12.2 ± 11.9 years). In terms of days per month spent on the lake, the fishers averaged 18.6 ± 8.1, ranging from 2 days to 30 days. There was no significant variation in age or years between individual beaches; however, there was a significant variation between time spent on lake between beaches ($p < 2e-16$, F-value=16.07) (Fig. 3C). Interestingly, primary income streams reported in accompanying household surveys, were not limited to fisheries (72%), varied across beach communities, included vendors (11.3%), business (5.5%), farming (3.5%), professional (1.5%), and other or not specified (5.3%; Fig. 3D), although all households listed fisheries as either a primary, secondary, or tertiary source of income.

Site selection and fisheries change

Fishers primarily select their fishing site based upon proximity (46.3%) and fishing quality and availability (40.2%). Strikingly, 36% of fishers from Rakwaro reported selecting fishing sites based on absence of water hyacinth (5.1% respondents overall), which can entangle fishing boats and gear. Very few selected sites based on water quality (3.6%). Less than 1% mentioned absence of cyanobacteria, access for fishing, avoiding breeding areas, away from shore due to regulations, selecting deeper water for larger fish, less competition, good fish business in the region, type of catch or gear, and wind direction. An overwhelming number (96.7%) reported a change in catch since first starting in the trade, with 95.3% reporting a decrease in catch, 0.8% reporting an increase, 2.6% reporting no change, and 1.3% noting seasonality or fluctuations in catch. The vast majority, 94.3%, reported a decrease in quantity of fish, while 80.2% reported a decline in types of fish available. For the remainder, 10.9% reported no change in variety of fish, while 8.3% reported an increase in types of fish available.

Table 3. Consumed species collected and physical characteristics. The descriptive statistics of physical characteristics of species of fish collected from fishers in this study, as well as distribution of sexual maturity and seasonal representation. Fish were collected from fishing landing sites within communities fresh off the boat, and represented fish that would not be sold at market, but rather consumed at home by fishing households. IMM = immature, F(x) = female (reproductive stage), M(x) = male (reproductive stage).

Season	Species	Local Name	Total length (cm)	Standard length (cm)	Weight (g)	Sexual maturity	Stomach	Contents	sumMC (μ g/kg)
Dry 2	*Brycinus cydlera*	Ndera	5.3	NA	1.2	IMM	empty	none	40.6
Dry 2	*Haplochromis* spp.	Fulu	11.6	10.1	17.9	M4	empty	none	14
Dry 2	*Haplochromis* spp.	Fulu	10.2	9.4	8.4	F4	empty	none	12.3
Dry 1	*Haplochromis* spp.	Fulu	4.3	NA	0.9	IMM	empty	none	64.8
Long rain	*Lates niloticus*	Apengo, undersized Nile Perch	21	16.9	108.3	F2	empty	none	0.7
Dry 2	*Oreochromis niloticus*	Tede, undersized Nile Tilapia	9.7	7.9	13.8	IMM	empty	none	0.8
Long rain	*Oreochromis niloticus*	Nege, Nile Tilapia	19.9	15.8	155.3	M3	1/2 full	algae	0.6
Long rain	*Oreochromis niloticus*	Nege, Nile Tilapia	16.1	20.6	155.6	M3	1/2 full	algae	2.8
Long rain	*Oreochromis niloticus*	Tede, undersized Nile Tilapia	18.9	15	139.6	F2	1/2 full	algae	15
Short rain	*Protopterus aethiopicus*	Kamongo	13	NA	307.3	M3	empty	none	2.6
Dry 2	*Rastrineobola argentea*	Dagaa, Omena	5.1	NA	0.7	not assessed	full	algae	23.4
Dry 2	*Schilbe mystus*	Sire	25	22	109.9	F6	empty	none	22

When asked about contributing factors to the changes in catch, participants identified illegal or unregulated gear (46.1%), overfishing or increase in fisher population (15.7%), pollution (11.1%), water quality (9.3%), odor in water (8.8%), water hyacinth (7.7%), and climate change (3.6%). Odor in water was notable among participants at Asat, Rare, and Rakwaro, whereas pollution was more readily identified by participants at Mainuga and Obaria. Other causes mentioned by a handful of participants included algal blooms, fish migration, breeding ground impacts, environmental change, the Mbita causeway, reduction in water level, seasonal, improved water quality, uncertain of change, or unknown.

Fisher observations of eutrophication and impacts of cyanoHABs on fisheries

The majority (92.6%) of fishers noted a decrease in water clarity. The majority (85.2%) noted an overall increase in water smell, with 6.6 % noting a seasonal increase in water smell. 70.3% noted a decrease in fish abundance overall, with a contrasting 25.3% noting an increased in fish abundance in numbers, potentially explained by years in fishing. 81.1% reported a decline in fish species. In terms of variety of plants present in water, 87.0% of fishers noticed an increase in species and 90.7% in abundance.

Figure 4A illustrates a histogram of distribution of first recalled algal bloom across beaches as well as age distribution of participants. We broadly asked participants about the impacts of cyanoHABs on the lake water, fisheries, and their livelihood (Fig. 4B-4D). The participants identified the blooms as causing poor water quality (60.6%), contamination (17.9%), odor change (15.1%), and color change (4.6%; Fig. 4B). As for impact of blooms on their livelihood, 52.7% reported a decrease in profit, 24.7% reported a decrease in catch, while 10.0% reported an increase in profit to an increased demand driven by supply shortage (Fig. 4C). The remainder either reported business was not impacted by the blooms (7.7%) or reported uncertainty or variability. When asked how blooms have impacted fish in the lake (Fig. 4C) respondents reported impact on fish mortality through suffocation (36.3%), reduced quantity or disappearance (24.3%), interference with breeding zones and movement or avoidance (13.8%), and negatively impacting fish health (8.7%). Others reported that blooms provide food for fish (6.4%) and improve fish health (3.8%). As for impact of blooms on their livelihood, 52.7% reported a decrease in profit, 24.7% reported a decrease in catch, while 10.0% reported an increase in profit to an increased demand driven by supply shortage (Fig. 4D).A small portion were not sure (1.3%) or reported no effect (5.9%).

More than half of respondents did not think that future generations would be able to fish in Lake Victoria (66.9%). There was no significant trend in this response across beaches, bays, or ages of fishers in this outlook.

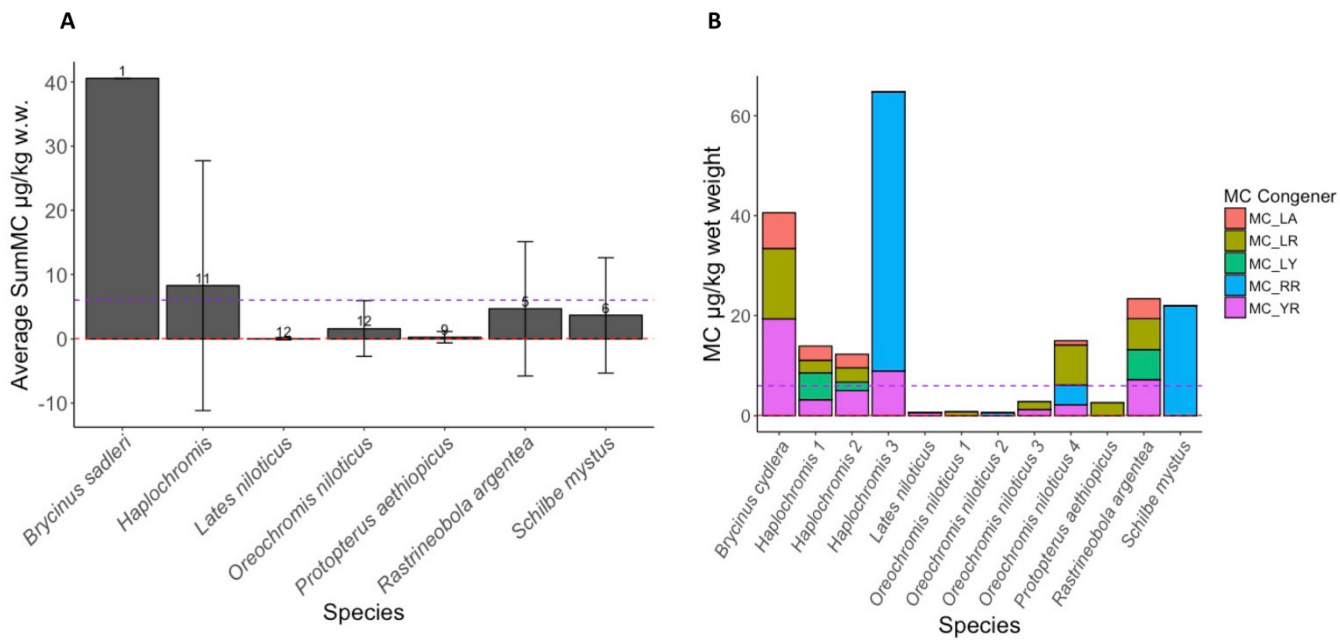
Household characterization of catch

Figure 5 illustrates the most frequent and valuable reported catch by the women heads of households with adult *Lates niloticus* occupying the top of both categories at 56.1% and 58%, respectively. The next in frequency of catch was adult *Oreochromis niloticus* (20.1%), likely because of their presence closer to shore in shallower waters, whereas schooling *Rastrineobola argentea* (dagaa, 14.1%) require more effort. Inversely, a greater portion of households identified *R. argentea* as more valuable (19.3%) compared to *Oreochromis niloticus* (7.9%). The catfish, *Clarias gariepinus* was both more regionally available and valuable in Homa Bay relative to Kisumu. Fewer households in Homa Bay indicated availability and value of juvenile *Late niloticus* perhaps reflecting regional variation in breeding ground locations or willingness to disclose that undersized fish are sought and of value.

Open-ended perspectives and concerns

Although the constraints of this particular study did not allow for in-depth interviewing, open-ended questions were included to capture outstanding or additional concerns not covered within the survey guides. Appendix 2 depicts the 250 most common

Fig. 2. Microcystins across locally consumed fish species from Winam Gulf, Lake Victoria, Kenya. Microcystins were detected using Liquid chromatography–mass spectrometry (HPLC-MS/MS) from extracted muscle for all species, except for *R. argentea*, which is consumed whole, and reported per wet weight (w. w.) of kgs of fish tissue extracted. Figure 2A depicts the individual congener distribution for each of the individual fishes with MC detects, while Figure 2B depicts the averaged sumMC across all fish extracted in the study with standard deviation to depict mean risk from replicate species. The following species had no MC detects: *Barbus altianalis* (n = 3), *Clarias gariepinus* (n = 8), *Synodontis victoriae* (n = 15), and thus are not depicted in the graphs. The dashed purple line represents the calculated daily tolerable intake (TDI) of amount of microcystins per kg gram of fish for a 60 kg adult, based on WHO guidelines and an allocation factor of 0.2, assuming 80% of intake is through drinking water. The dashed red line is the equivalent for a 10 kg child. Note: "MC congener" refers to the structural variations of microcystins (MCs) with the appropriate amino acid abbreviation indicating the substitutions made at positions 2 and 4 of the cyclic ring, respectively. In this case, LA denotes Leucine and Alanine, LR denotes Leucine and Arginine, LY denotes Leucine and Tyrosine, RR denotes Arginine and Arginine, and YR denotes Tyrosine and Arginine.



employed words, outside of common conjunctions or articles, within fisher and household surveys. Frequently cited concerns among the fishers included use of illegal gear, declining water quality attributable to a number of factors, declining fish availability and numbers, water hyacinth as a nuisance, and indicators of poor water quality related to fish health and access. Many wondered whether the planned opening of the Mbita causeway near Mfangano Island within Rusinga Channel (Fig. 1) would allow for additional mixing and improve water quality as planned. Frequently cited household concerns included declining water quality as related to disease, lack of access to safe and clean drinking water, distance to travel to obtain water for use, uncertainty as to if it will improve, and requests for community-level treatment or government intervention like piping water from other locations. A common potential alternate source mentioned was a borehole with the mention that it dries up for long periods of time, provides salty tasty water, or is contaminated itself. Rain water was also a possibility, but not during most of the duration of bloom seasons.

DISCUSSION

Water quality in Kisumu Bay, Lake Victoria

Water quality data illustrated persistent cyanoHABs and human health risk for drinking water taken from the lake. The predominance of MC-LR and MC-YR corresponds with previously published data in the region (Sitoki et al. 2012, Miles et al. 2013, Simiyu et al. 2018, Onyango et al. 2020), alongside MC-RR. MC-LA and dmLR have been less commonly reported (Miles et al. 2013, Onyango et al. 2020), although there has not been routine monitoring. The temporal and spatial variability noted in this study (Table 2) is of concern for monitoring and risk assessment. Furthermore, methods rely on availability of standards for congener verification and limitations are set by resources and access to standards for quantification. Of particular concern for drinking water intake is the Coca-Cola® bottling facility with the highest MC concentration detected, near the city intake (Sitoki et al. 2012), and for communities drawing water directly in the nearshore environment (Roegner et al. 2020). We examined particulate MCs, i.e., those dissolved in the water column. Dissolved MCs occur when cyanobacterial cell populations begin to lyse or die given either physical, chemical,

Table 4. Physical characteristics of microcystins (MC) positive fish and sumMC content in wet weight of fish tissue. The table details the physical characteristics of individual fish, seasons in which caught, and MCs detected.

Season	Species	Local name	Total length (cm)	Standard length (cm)	Weight (g)	Sexual maturity	Stomach	Contents	sumMC (µ g/kg)
Dry 2	*Brycinus cydlera*	Ndera	5.3	NA†	1.2	IMM	empty	none	40.6
Dry 2	*Haplochromis* spp.	Fulu	11.6	10.1	17.9	M4	empty	none	14
Dry 2	*Haplochromis* spp.	Fulu	10.2	9.4	8.4	F4	empty	none	12.3
Dry 1	*Haplochromis* spp.	Fulu	4.3	NA†	0.9	IMM	empty	none	64.8
Long rain	*Lates niloticus*	Apengo, undersized Nile Perch	21	16.9	108.3	F2	empty	none	0.7
Dry 2	*Oreochromis niloticus*	Tede, undersized Nile Tilapia	9.7	7.9	13.8	immature	empty	none	0.8
Long rain	*Oreochromis niloticus*	Nege, Nile Tilapia	19.9	15.8	155.3	M3	1/2 full	algae	0.6
Long rain	*Oreochromis niloticus*	Nege, Nile Tilapia	16.1	20.6	155.6	M3	1/2 full	algae	2.8
Long rain	*Oreochromis niloticus*	Tede, undersized Nile Tilapia	18.9	15	139.6	F2	1/2 full	algae	15
Short rain	*Protopterus aethiopicus*	Kamongo	13	NA†	307.3	M3	empty	none	2.6
Dry 2	*Rastrineobola argentea*	Dagaa, Omena	5.1	NA†	0.7	NA†	full	algae	23.4
Dry 2	*Schilbe mystus*	Sire	25	22	109.9	F6	empty	none	22

† NA = not applicable.

or biological perturbations (Chorus and Bartram 1999, Codd et al. 2020). Thus, risk from water consumption may be underestimated with this data.

Physical characteristics and MC detections in consumed fish

Very few other studies have reported values of MCs in fish tissues from Lake Victoria, with three publications detailing levels in fish from Ugandan waters (Poste et al. 2011, Miles et al. 2013) and one focusing on *R. argentea* in Kenyan waters from both inside and outside the gulf (Simiyu et al. 2018). To our knowledge, this is the first study to look at MCs in fish tissues across a variety of species from the Kenyan side of Lake Victoria within the eutrophic Winam Gulf, and the only one to employ LC-MS/MS in the same setting across a wide variety of species. The distribution in detects among congeners across MC positive fish tissues approximately followed the congener distribution in detects in surface waters.

The detection frequency and concentrations of MCs were much higher in Poste et al. 2011 across food web fish species from the Ugandan portion of Lake Victoria. These authors noted extremely high levels in whole *R. argentea* (36.2-41.2 µg kg^{-1} w. w. in Murchison Bay, and from 39.0-129 µg kg^{-1} w. w. in Napoleon Gulf) in eutrophic gulfs in Uganda, easily exceeding the WHO TDI (24 µg kg^{-1} w. w. for a consumer weighing 60 kg and consuming 100 g of fish daily). However, this study employed the Abraxis anti-ADDA ELISA kit for indirect competitive antibody detection, which accounts for both bound and unbound tissue portions of microcystins, as did similar studies from Murchison Bay in the early 2000s (Nyakairu et al. 2010, Semyalo et al. 2010). These competitive ELISAs developed for surface water detection may cross-react with other ADDA-containing compounds or metabolized by-products and have not been validated for use in tissues (Abraxis, *personal communication*). A more recent study examined small fish (predominantly *R. argentea* and *Haplochromis* spp.) collected from fishermen early in the morning from Kisumu Bay and from open waters near Rusinga channel in 2011 and 2012 (Simiyu et al. 2018). Whole fish were dried, in the oven or sundried as per the local custom, and MC content was determined by the anti-ADDA Abraxis ELISA. Although the same concerns of cross reactivity and lack of validation remain with the detection method, of note, the fish collected from the open waters and purchased near Rusinga channel had significantly lower MC levels compared with those from Kisumu Bay, consistent with an observed gradient of water quality.

We note a number of undersized samples (Table 4) were collected, indicating that the juvenile *Lates niloticus* and *Oreochromis niloticus* may represent a higher portion of fish more frequently caught and locally consumed or traded, but not reported because households do not want disclose potential illegal catch. A similar undercount in beach land site fisheries reporting may contribute to an underestimate of the local economy and livelihood provided for small-scale fishers (Olokotum et al. 2020, Onyango et al. 2020) as well as threaten the sustainability of the fisheries. Additionally, younger fish do not have fully formed stomachs yet, and thus tend to eat a more herbivorous diet, including algae. This increases the risk for toxin ingestion, particularly if internal organs are consumed, or if fish are eaten whole. Although we did not survey the dietary patterns of fishers or households in this study, allocation of different types of fish or organs consumed may differ between and within households, and thus alter risk.

Notably, dissected stomach contents did not have any fish therein (Table 4), with only some of the bottom-dwelling species having shellfish species and insects. Greater than 50% of the fish dissected had empty stomachs, unusual given empty gut contents are typically associated with higher trophic levels (Arrington et al. 2002), and the typically piscivorous *Late niloticus* were undersized juveniles, unlikely to have fully transitioned to an adult diet from feeding on phytoplankton. Of note, algae was only found in five stomachs, all *O. niloticus*. As discussed, the presence of algae in the gut contents has implications for fish consumed whole; the non-detect *R. argentea* had empty stomachs, whereas the one MC detect (23.4 µg kg^{-1} w. w.; Table 5, Fig. 2B) had algal contents.

Though not a food web analysis of the distribution of MCs across species, our study detects did mirror a recent global analysis that found microcystins to typically be the highest in omnivorous

Table 5. Mean sumMC concentrations across fish species and hazards quotients (HQ). Descriptive data for sumMCs detected by species are presented, including the skewness and the upper limit of the 95% confidence interval of the geometric mean. Hazard quotients were calculated from the mean sumMC of each species and across all species divided by the GVchild (0.8 µgs/kg fish) and GVadult(4.8 µgs/kg fish), based on 100 grams of fish being consumed daily for a 10 kg child and 60 kg adult. Hazards quotients greater than 1 are considered high risk.

Species	Replicates	Mean sumMC (µg/kg)	Standard deviation	β (Skewness)	(1-α)[†]	HQ_{child}	HQ_{adult}
Brycinus sadleri	1	40.6	n/a	n/a	n/a	50.7	8.5
Haplochromis spp.	11	8.3	19.45	2.92	11.40	10.3	1.7
Lates niloticus	12	0.1	0.19	3.61	11.75	0.1	0.0
Oreochromis niloticus	12	1.6	4.31	3.26	3.62	2.2	0.4
Protopterus aethiopicus	9	0.3	0.88	3.00	2.01	0.4	0.1
Rastrineobola argentea	5	4.7	10.44	2.24	6.92	5.8	1.0
Schilbe mystus	6	3.7	8.96	2.45	5.87	4.6	0.8
Total fish	83	2.4	9.26	5.03	5.29	3.0	0.5

[†] One-sided (1-α) upper confidence limit on the mean.

species (Flores et al. 2018) and did not indicate biomagnification to top predators (Onyango et al. 2020). *O. niloticus* is predominantly a herbivore, feeding on phytoplankton and algae, but also has omnivorous tendencies, particularly when juvenile. *B. sadleri* is ominivorous, feeding on aquatic plants, insects, and sometimes small fish. *Schilbe mystus*, African butter catfish, feed on a wide variety of foods, including fish, insects, shrimps, snails, plant seeds, and fruits. *P. aethiopicus*, marbled lungfish, are typically carnivorous, even cannibalistic, but will also feed opportunistically on aquatic plants and detritus, particularly in the near-shore environment. *Haplochromis* species, the all-encompassing genus for ray-finned cichlids from the east African Rift, many of which became extinct after the introduction of *Lates niloticus* and later *O. niloticus*, are notorious omnivores with tremendous species variability in diet. A recent study in *R. argentea* at Lake Victoria, Kenya, suggests these omnivores may actually feed mostly on zooplankton as juveniles, while adults prefer insects. Finally, although *L. niloticus* are known top predators as adults, juveniles again may have an altered dietary intake, making them more susceptible to toxin accumulation. Given the known effects of microcystins on a variety of fish organs and development, food web dynamics can be substantially altered, directly affecting what types and kinds of fish that might be available for harvest, sale, and consumption.

Human health risk assessment from daily consumption of fish during bloom season

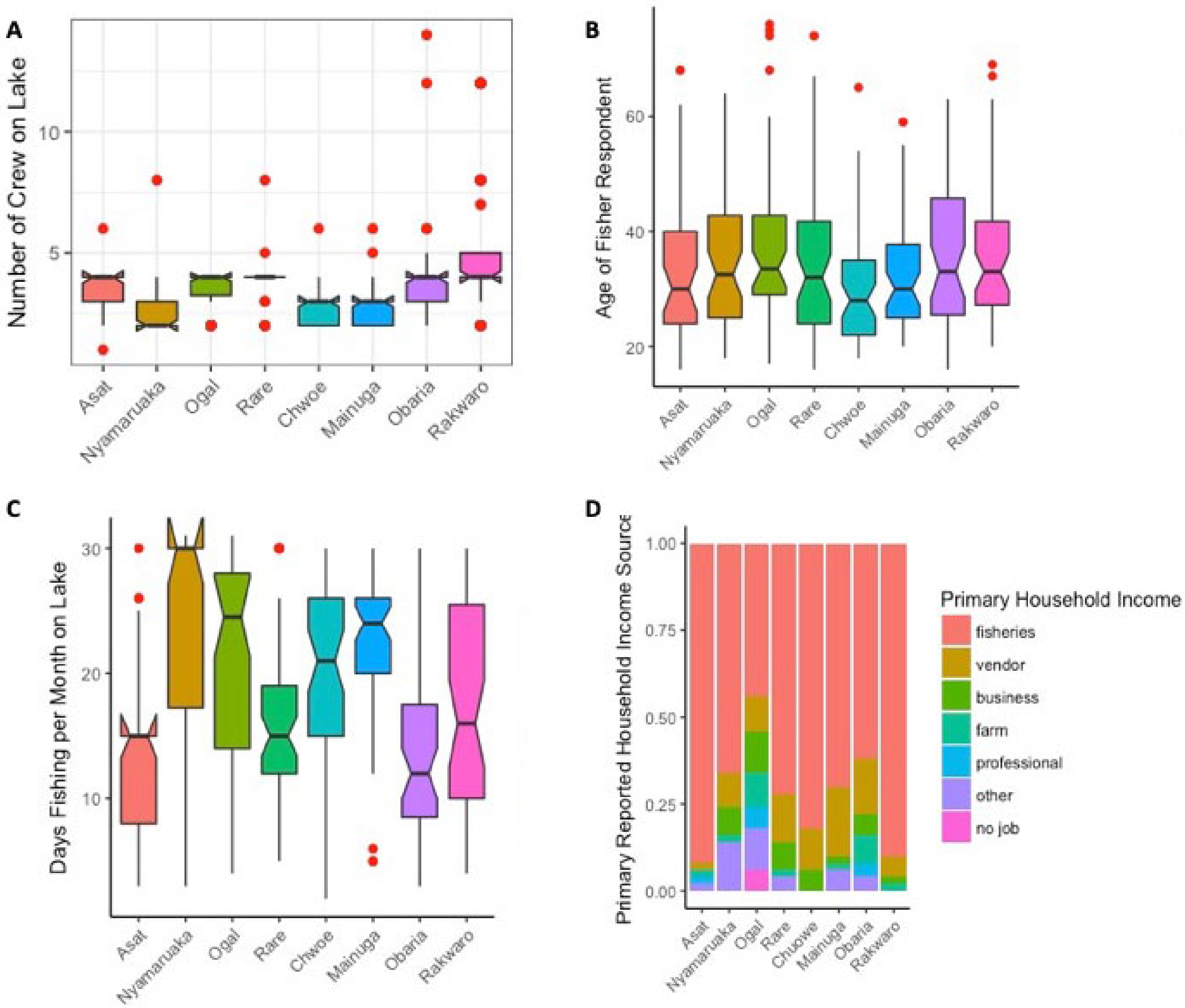
Our HQ assessment demonstrates that fisher communities, and, in particular, vulnerable groups such as children or immunocompromised individuals, along the Lake Victoria Basin face a significant MC health risk from seafood consumption. Previous work in the region has confirmed and even encouraged high reliance on fish for dietary protein intake for children (Kabahenda et al. 2011, Poste et al. 2011, Simiyu et al. 2018, Esilaba et al. 2020, Onyango et al. 2020, de Bruyn et al. 2021), particularly among species with higher HQs in this study. Average daily intakes from these *R. argentea* and other small species may be 5 to 10 times the permissible limit as dictated by the lifetime TDI. We did not calculate HQs for contribution to daily intake from drinking water for this study, and the model excludes other potential routes of MC exposure, such as agricultural products irrigated with lake water (Codd et al. 2020, Abdallah et al. 2021) and livestock at the lake's edge. Increased developmental risk for children is well documented (Weirich and Miller 2014, Roegner et al. 2019), and work in the Three Gorges Reservoir Region China has linked MC in aquatic food and water sources to liver damage in children (Li et al. 2011). In addition, health risks for adult fishers, such as endemic HIV, concurrent high risk behaviors without adequate intervention access (Kwena et al. 2020) and environmental parasites such as schistosomiasis (Odiere et al. 2012), and malaria (Minakawa et al. 2012), compromise immune and liver organ function and position adults at heightened risk from toxins impacting the liver and immune function. We did not robustly examine seasonal effect, region of fish harvest, and variability among fish species or stage in life cycle relative to risk for humans, so more work is needed to make any health or management recommendations. To note, perception of human health risk from consumption of fish, either in toxicant form or illness, did not emerge from any of the fisher or household surveys, whereas water as widespread concern for human health did emerge with respect to disease and toxicity.

Income heterogeneity in fisher household and demographic shifts

The smaller sized, mostly male crews captured reaffirm the small-scale nature of these artisanal fisher communities and is corroborated by recent evaluation of the economic and financial value of small-scale fisheries at Lake Victoria (Oyango et al. 2021) and coping strategies in the face of fishery decline (Magego et al. 2021). Our study did find discrepancy in trends in boat size and days spent on lake among fisher households, which points to the heterogeneity of these communities.

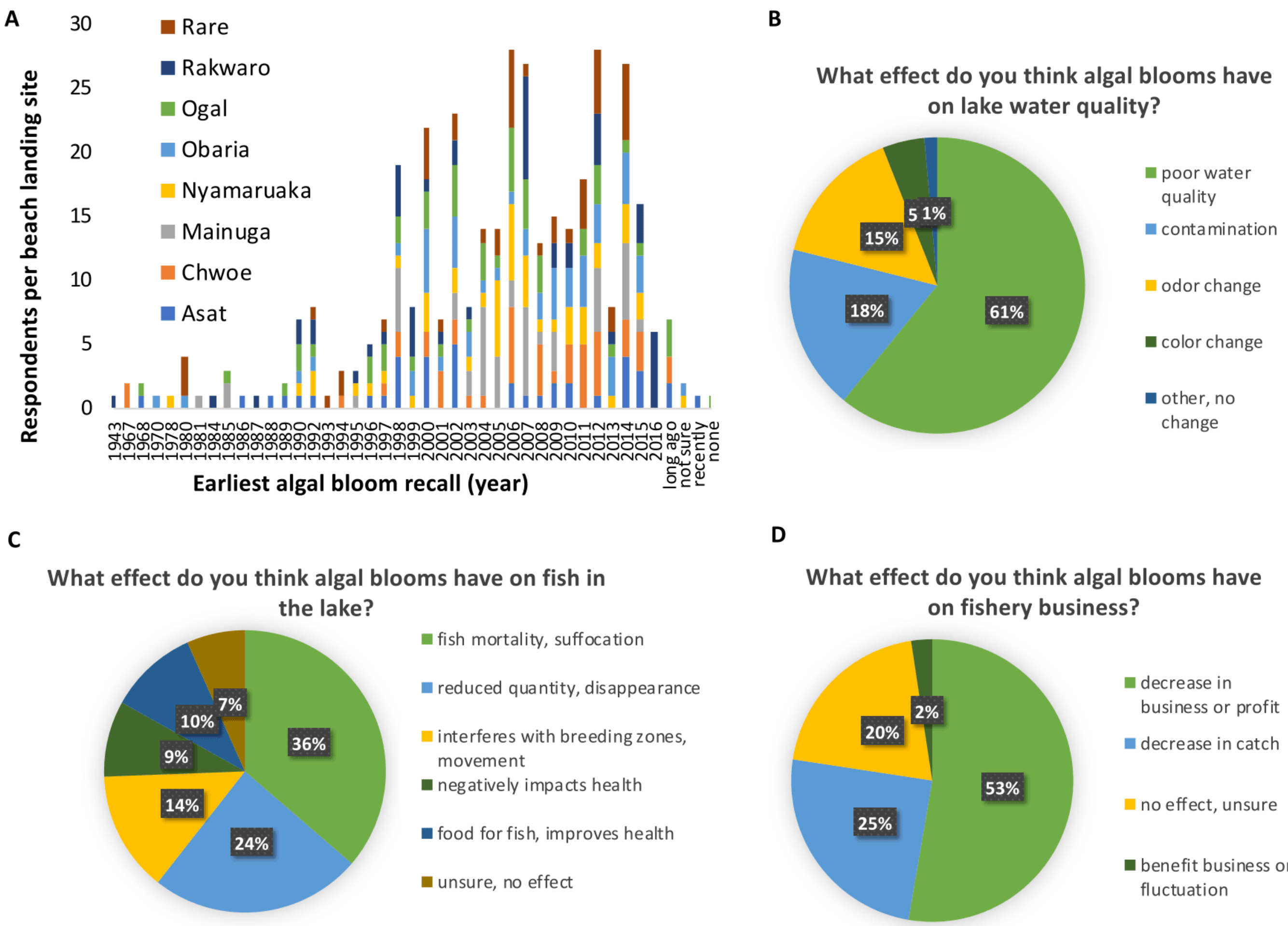
We also found lower average days spent on lake. Lake Victoria Fisheries Organization (LVFO) has typically reported five days per week with single-day trips and two days of rest (Abila et al. 2009, Nunan 2021). We may have captured a distinct portion of the fisher population that complements fishing income with other supplemental income (Fig. 3D). A decline in catch and availability may also be driving these households to look for alternate sources of primary income (Magego et al. 2021). In an earlier survey, LVFO (Abila et al. 2009) found 11% households in these fisher communities with a primary income outside fisheries, while we found over 20%. Average years spent in fisheries were increased in our study, so the population shift may capture those who have found a way to survive in the face of decline, i.e., whether through altered techniques, gear, approaches, or other streams of income.

Fig. 3. Fisher demographics across Kisumu Bay and Homa Bay fish landing sites. Approximately 50 fishers at Asat, Nyamaruaka, Ogal, and Rare (Kisumu Bay) and Chwoe, Mainuga, Obaria, and Rakwaro (Homa Bay) were interviewed regarding their fisheries involvement, changes observed over time in catch, and the health of the lake. Distribution of boat crew sizes (3A), fisher age demographics (3B), number of days per month spent on lake (3C), and primary income streams across beaches (3D). There was significant variation in crew size between beaches ($p < 2e-16$, F-value = 14.46). There was also significant variation between the two bays in years spent in fisheries ($p = 0.0356$, F-value = 4.446), but no significant patterns across age or income distributions.



The heterogeneity results from co-management of the fisheries, as well as from the variability in both population and permanency of landing sites. Fisheries co-management at Lake Victoria, East Africa, was introduced in the late 1990s. It was encouraged and facilitated by various donor-sponsored projects in near-shore smaller scale fisher communities to set a quota for minimal inclusion of women in community-based BMUs (Njiru et al. 2014, 2018, Nunan and Cepić 2019, Nunan 2021). The co-management of fisheries both facilitates and hinders women's involvement and livelihood in aspects of the fisheries supply chain (Nunan and Cepić 2019). The Lake Victoria Fisheries Organization reports less than 1% female fishers in boat crew, with few owners (LVFO 2015). Women in fishing typically participate in post-harvest categories such as processors or traders. Trading can include transactional sexual relationships, linked with migration of male fishers and leading to increased risk of HIV and other STDs (Kwena et al. 2019, 2020). Although these dynamics are problematic for gender equity, power dynamics, and community health, the local BMU management model does enable the ability to pivot in the face of economic hardship. In addition, the role of women may be an entry point for introducing newer sustainable practices, as well as ways to mitigate health risks from CyanoHABs for fishers and the public.

Fig. 4. Fisher recall and impression of effects of algal blooms. In Kisumu and Homa Bay, 398 fishers were interviewed, approximately 50 recruited from each town, regarding their recall of algal blooms and perceived changes over the last 5 years. Figure 4A illustrates a histogram of distribution of first recalled algal bloom, across beaches, as well as age distribution of participants. We broadly asked participants about the impacts of harmful algal blooms (HABs) on the lake water, their livelihood, and the fisheries, and have summarized the most common responses (Figs 4B-4D).

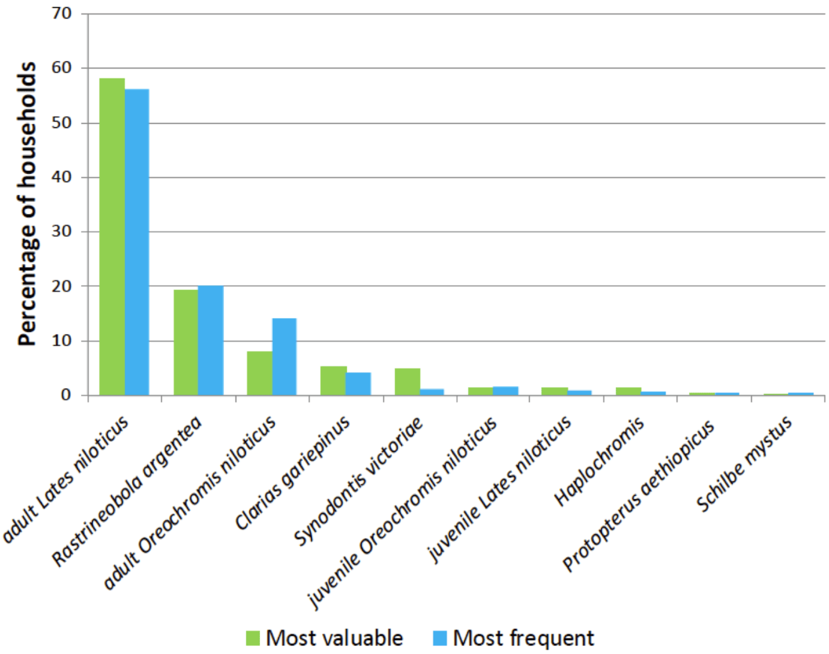


Site selection and fisheries change

Observations about decline in catch and in variety of species are corroborated by catch data and hydroacoustic estimates for *L. niloticus* and *R. argentea*. Although Lake Victoria as a whole has had increasing catch trends since 1965 (Oyango et al. 2021), with the largest increase coming from the robust harvest of *R. argentea* primarily for export, there generally has been a decline in total fish catch from Kenya's sector of the lake since 1995, which has been attributed variably to use of illegal fishing gears, proliferation of water hyacinth, declining water quality, and underestimated catch (Oyango et al. 2021). Site selection, primarily based on availability of catch and proximity, is consistent with identified drivers for small-scale fishers seeking to minimize revenue risk and maximize resource utility (Njiru et al. 2018, Magego et al. 2021, Oyango et al. 2021). Availability of fish can be driven directly and indirectly by cyanoHABs that (1) can starve the water column of dissolved oxygen resulting in fish die offs; (2) can alter food-web dynamics through outcompeting other phytoplankton for sunlight; and (3) can cause disparate impacts across fish species through chronic exposure to cyanotoxins (Malbrouck and Kestemont 2006, Banerjee et al. 2021). In addition, the physical barrier and nuisance that bloom-laden water can pose to small boat navigation is substantial and further complicated by water hyacinth entanglements.

Fisher community concerns about overfishing and use of illegal gear have been previously documented (Abila et al. 2009) alongside concerns with declining water quality and algal blooms (Njiru et al. 2014, 2018). Fisher community concerns about a rise in the fisher population as a pressure on the system has not been previously documented, and that coupled with increasing access to income diversification and a despondency expressed by a portion of those interviewed may result in decisions to exit the trade. Because income sources were identified in household surveys whereas outlook on the fisheries was assessed in the fisher interviews, we were not able to assess a potential linkage with

Fig. 5. Self-reported most common and most valuable fish catch in Winam Gulf. Approximately 400 female household heads were interviewed, 50 recruited from each fisher village, regarding a host of factors with respect to lake and fisheries resource usage at the household level, including not but not limited to water sources and treatment, and types and value of fishes caught and sold at local markets. *Lates niloticus* occupied the top categories of most commonly caught and sold at market for 56.1% and 58% of the households, respectively.



these data, but it posits a potential area of further exploration. Alternatively, a recognition of the need for conservation could be motivating change at the individual behavior level and amplifying the need within the relational and community spheres.

Fisher observations of eutrophication and impacts of cyanoHABs on fisheries

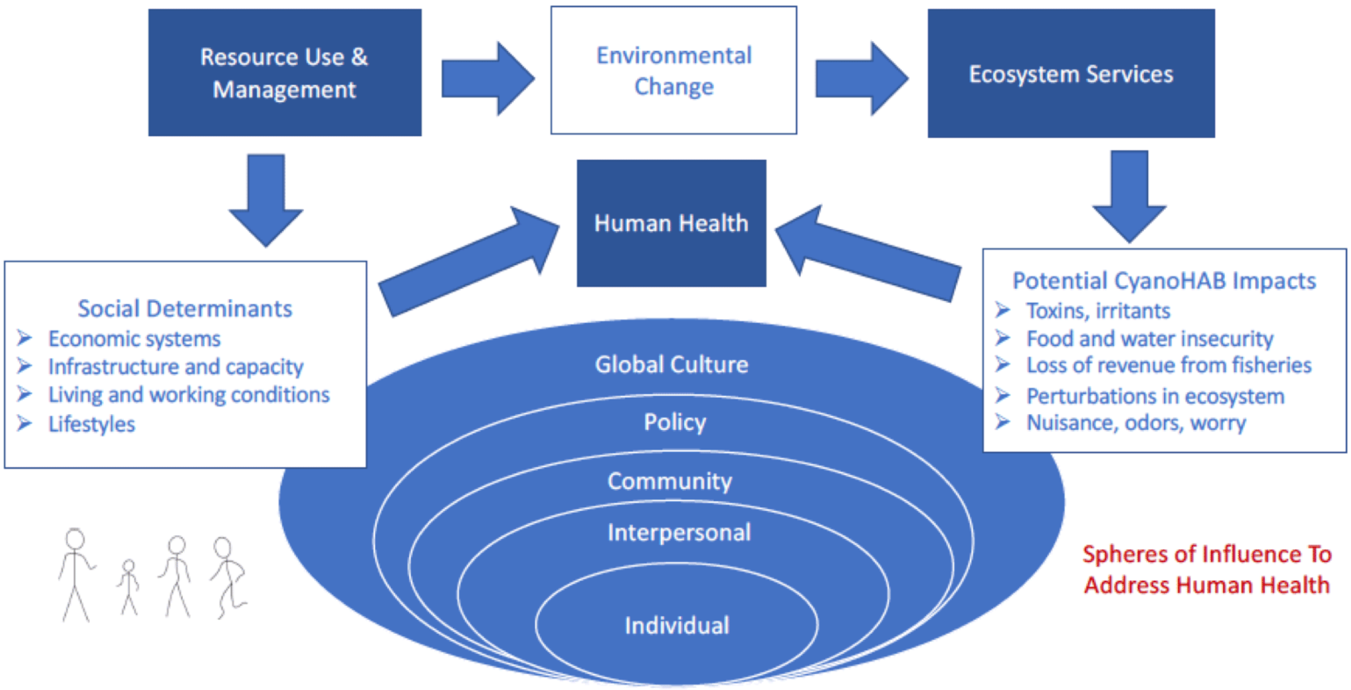
Fishers clearly identified multifactorial impacts of cyanoHABs with direct effects observed on lake water quality, fish catch and availability, and fisheries sustainability as related to their livelihood (Fig. 4B-D). These same patterns have historically been observed in cyanoHABs-impacted freshwaters with impacts on lake water quality (Paerl and Otten 2013, Burford et al. 2020), fish populations and health (Malbrouck and Kestemont 2006, Onyango et al. 2020), and local economy (Culhane et al. 2019, Dudgeon 2019, Gobler 2020, Olokotum et al. 2020). Fishers did not mention concerns about impacts of cyanoHABs on quality, safety, or nutrition provided by fish. Of note, the percentage of respondents that did not see a future in fisheries roughly corresponded with household respondents that reported an alternate primary income source, suggesting some small portion of fisher communities may be contemplating an exit strategy (Njiru et al. 2018, Magego et al. 2021); alternatively, this diversification could represent an individual and or community-level movement toward conservation of a common resource. Frequency and value of catch were consistent with catch data and market value (Odongkara et al. 2005, Wangenchi et al. 2015, Nyamweya et al. 2020, Oyango et al. 2021). Other species reported may indicate niche markets and regional preferences, which could influence consumption patterns and potential human health risk. In addition, it will be important to determine if algal blooms are directly linked to availability of specific species.

Socioecological approaches to defining public health stressors related to cyanoHABs

Global public health has begun to recognize the importance of integrating the multiple levels in society at which an individual's health is influenced, from individual biology and personal characteristics to relationships to societal level determinants of health (Graham and White 2016). These spheres of influence can be applied to impacts of anthropogenic driven environmental change on human health (Fig. 6, adapted from Graham and White 2016 and Cobourn et al. 2018). These spheres represent strata in which intervention or prevention strategies may occur: the individual, the interpersonal or relationships, and the community in forms of organizations and institutions, policies, and culture overall (Golden and Wendel 2020). The degree of human connectivity to the freshwater environment within each sphere of influence may vary considerably across human-natural systems (Liu et al. 2007, 2016, Cobourn et al. 2018) and are further shaped by social determinants (Graham and White 2016; Fig. 6). Thus, sustainable and practical interventions may vary considerably between resource-poor and resource-rich societies, as well as between communities within those societies.

Traditional global public heath guidance has overlooked the importance of integrating meaning, behavior, and lived environmental experience for individual and community health (Golden and Wendel 2020). This applies to existing guidelines for

Fig. 6. Conceptual framework for understanding and approaching interventions for the human health consequences of cyanoHABs with a social-ecological lens. Adapted from Graham and White (2016) and Cobourn et al. (2018). Social determinants and environmental health converge to influence human health at all spheres of influence mediating both risks and potential interventions. Similarly, both social determinants and spheres of influence can mediate how we use and manage our ecosystems, resulting in amplification or lessening of environmental health risks to those users.



freshwater use and fisheries, as related to cyanoHABs. For example, during prolonged cyanoHABs, purchase of bottled water is an economic burden, and access to another source may not be possible. Similarly, fish advisories are impractical because fishers rely on fish as a protein source and a supply of nutritious fatty acids, not to mention the profound economic reliance. Existing guidelines ignore the sense of place and identity tied into small-scale fisheries. In the case of Winam Gulf, Lake Victoria, Kenya, the fisher communities are connected at the individual level for their profession and craft, at the household and individual level for food, water, and livelihood, and tied together through community organizations such as the Beach Management Units. Their perception and use of lake resources are further mediated through interactions with fisheries organizations, researchers and NGOs, tourism, and national and global demand and media. To truly address the health burden imposed by the blooms, first the extent and impacts must be characterized, and subsequently change has to happen at multiple levels of society to improve access to water treatment, to motivate sustainable freshwater and fisheries usage, and to put policies in place to reduce nutrient loading.

Freshwater cyanoHABs are exacerbated by climate change and thus emerge as a global health threat to prioritize, particularly for vulnerable communities that cannot purchase another water source or easily replace dependent fisheries for food and livelihood. Furthermore, these direct resource users can lend insight into unforeseen health consequences, as well as potential interventions not previously considered. To embrace a social-ecological approach, it is essential to begin to characterize the multifactorial stressors emanating from blooms for fisher communities by directly working with the communities themselves (Horowitz et al. 2009). CyanoHABs provide a visually stunning cue and a viscerally pungent odor of the public health disaster that fishers at the lakeside experience daily (Fig. 6). To understand the diverse social, ecological, and health impacts, fisher and community insights and perspectives must be incorporated into the process of understanding the full impact on water quality and fisheries. Although not comprehensive, Appendix 2 provides a snapshot of those daily and long-term considerations. Through thoughtful risk assessment and capturing both use and meaning of freshwater fisheries for these communities, we can begin to define the multitude of public health stressors associated with blooms (Fig. 6). Thus, we may begin to explore practicality, efficacy, and sustainability of interventions at each sphere of potential influence to ultimately reduce health burdens associated with cyanoHABs: individual behavior and empowerment, household behavior and empowerment, BMU and community-based, fisheries management and policy, and regional, national, and global culture. We posit that by enhancing understanding and empathy with fisher communities and hearing fisher voices, we can broadly define the diverse impacts and generate ideas for solutions to pilot and test in partnership with those very impacted communities.

CONCLUSION

CyanoHABs have impacted fisher communities in multiple strata of ecosystem services provided by Lake Victoria. Fishers in Homa Bay and Kisumu Bay have noted the increasing severity and frequency of blooms since the early 2000s and have noted the impact on water quality, fish availability and catch, and net effect in business or profit. Some fishers and households have begun to pivot toward income diversification with declining catch. Average MCs in surface waters exceeded WHO provisional drinking water guidelines at nearshore intakes. Fish consumed during the same time period contained MCs at levels that would exceed provisional tolerable daily intakes set by the WHO. The variability of these toxins in both food and water makes surveillance even more difficult to adequately protect these populations against risk. More work is needed to elucidate seasonal risk from ingestion of water or consumption. However, impacts of cyanoHABs go well beyond risk of toxin ingestion, and cyanoHABs must be addressed with fisher health, well-being, and livelihood at the forefront. This threat to food and water security shape the schema in which fishers engage at the individual, household, organizational, management, and cultural level, and addressing the social-ecological consequences of cyanoHABs necessitate focus at all levels. Given their profound ecological knowledge of the fisheries, as well as the impact of fishing practices, strategies, and behaviors, any sustainable and effective intervention must engage with these populations to ensure the longevity of the fishery and to adequately protect human health.

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Data Availability:

The data/code that support the findings of this study are available on request from the corresponding author, AR. None of the data/code are publicly available because of IRB restrictions for the survey portion of this study. We have included other water quality and fish data as supplemental files. Ethical approval for this research study was granted by KEMRI/Scientific and Ethics Review Unit (SERU) Protocol No. KEMRI/SERU/CMR/P00033/3248 and UC Davis IRB 826854.

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APPENDIX A: STUDY TOOLS FOR HOUSEHOLD SURVEYS

ADULT CONSENT TO BE A RESEARCH PARTICIPANT IN HOUSEHOLD SURVEYS

Critical evaluation of challenges presented by cyanobacterial blooms to lakeside fishing communities at Lake Victoria and analysis of feasibility of interventions employing a mixed methods approach

Conducted by the Kenya Medical Research Institute
Written consent form for participants in household surveys

Researchers' Statement

I would like to tell you about a study being conducted by researchers from the Kenya Medical Research Institute (KEMRI). The purpose of this consent form is to give you the information you will need to help you decide whether or not to be part of the study. You may ask questions about the purpose of the research, what happens if you take part in the study, the possible risks and benefits, your rights as a volunteer, and anything else about the research or this form that is not clear. When we have answered all your questions, you can decide if you want to be in the study or not. This process is called 'informed consent.' We will give you a copy of this form for your records.

A. WHAT IS THIS STUDY ABOUT?

The researchers listed above are conducting a research study with fishing community members to better understand problems faced by the declining water quality in Lake Victoria in your community and neighbouring communities. We want to have you fill out a survey that will ask you questions about your household, how you obtain water and other activities that you might due in relation to lake waters.

We will use the information gathered to provide information about community risks, challenges and concerns related to the lake waters and other services provided, to evaluate potential ways in which each community can reduce overall health risks derived from the lake, and to identify ways in which outside agencies might help to look for solutions.

B. HOW WERE PARTICIPANTS SELECTED FOR THIS STUDY?

A list of potential participants from communities within Kisumu County, Homa Bay and Mfangano Island was generated through FACES fisherfolk community outreach working with the BMUs. The participants were randomly selected from the lists. W

C1. WHAT WILL HAPPEN IF YOU DECIDE YOU WANT TO BE IN THIS RESEARCH STUDY?

If you agree to participate in this study, the following things will happen:
You will sign this form to show that you have agreed. You can work with an interviewer in a private room to fill out the survey form.

Your participation is completely voluntary and you can decline to participate in the survey or decline to answer any particular question at any time. Any information you give as an individual is strictly confidential and no specific information identifying you as an individual will be reported. Some FACES program staff will know that you are participating in the study, but no other staff will find out information about what you say specifically while filling out the survey. Nobody will have access to the information you give in a manner that is linked to your identity.

C2. WHAT WILL HAPPEN IF YOU DECIDE NOT TO BE IN THIS RESEARCH STUDY?

If you decide not to participate in the interview, there will be no repercussions on you. You can continue receiving services at FACES clinics as usual. No-one will fine you or refuse to give you service because of not participating. You may also decide to withdraw from the interview at any time during the session without any penalty or repercussions.

D. WILL ANY PARTS OF THIS STUDY HURT OR HAVE OTHER RISKS?

Participating in this study is completely voluntary. You do not have to agree to participate. You have the right to end participation at any time. If there are any questions you do not want to answer, you can skip them or refrain from engaging in discussion. You have the right to refuse to participate in or any questions or discussion during the interview. Everything you tell us is kept as confidential as possible. We will keep all paper records from this study in a locked file cabinet. We will not discuss your responses within the interview any way that identifies you with clinical staff, other participants in the study, or anyone else.

E. BENEFITS

There is no direct benefit to participating in this study. The information you provide will help us better understand the challenges and concerns associated with declining water quality and fisheries of Lake Victoria for your community and how we might engage with your community to help. This information help guide any community based attempts to improve water quality and reduce health risks for your communities or improve your economic livelihood.

F. COSTS

There will be no costs to you as a result of taking part in this study.

G. REIMBURSEMENT

You will be reimbursed for your transportation to the clinic to a maximum amount of 100 Kenyan shillings to the BMU or clinic. Some refreshments will also be provided at the interview site.

I. WHAT ARE YOUR CHOICES?

Your decision to participate in this study is completely voluntary. You are free to decline participation in the study and you can withdraw from the study at any time. After you have read this consent form and understood the study procedures. You will be given a copy of this consent form to keep for your records. Please sign below if you agree to participate in the household surveys.

Consent obtained by: ________________ ________________ ___________

Staff name Staff signature Date

Given by: ________________ ________________ ___________

Participant name Participant signature Date

Witnessed by: ________________ ________________ ___________

(If unable to read) Witness name Witness signature Date

Household Survey Questions (Regarding Resources Provided by Lake)

Critical evaluation of challenges presented by cyanobacterial blooms to lakeside fishing communities at Lake Victoria and analysis of feasibility of interventions employing a mixed methods approach

Household

1) How large is your household (number of persons)? __________
2) How does your household make money? Circle all that apply. a) Fish b) Plants collected from lake c) Plants collected elsewhere d) Selling Fruits e) Selling Vegetables f) Selling eggs or meat g) other, specify: ____________________

Water

1) **Collection.** Who collects the household water? a) husband b) wife c) children d) neighbor e) other, specify: ___________
   Is the water collected from Lake Victoria and stored for household use? Y/N Is water collected or used water from other sources? Y/N If yes, from where else is water use/collected? _____________ is there any reason you would decide not to collect water from a specific location?
   ____
2) **Storage.** How does your household store water? ______________How much do you store at a time? _________ How often do you re-fill? _____________
3) **Treatment.** Is collected water treated prior to use? Y/N if yes, a) Boil b) treat with Aquaguard c) cloth filter d) other ____________
4) **Collection Site Selection.** Do you wash clothes and dishes in the same location from which you collect drinking water? Y/N Do you collect from the same location in the lake every day? Y/N If no, how do you decide from where to collect the water? _____________________________________
5) **Quantity/Quality.** Do you have enough water for daily use? Y/N Do you have any specific concerns related to the water?
   ____

Plants

1) Do you collect plants from Lake Victoria? Y/N From a different location? Y/N If yes to either, what kinds of plants do you collect? Water Hyacinth Papyrus Other ___________ **(if no plants collected, skip the rest of questions in this section)**
2) How do you collect plants? A) wade in water B) collect from boat C) children collect D) other____________
3) Do you sell plants? Y/N; Use them in your home? Y/N If you sell plants collected from the lake or another water source, how much do sell them for?
   ____

Fish

1) Do any women fish in your household? Y/N if Yes, how many? ____________
2) What fish is sold the most? a) Nile perch b) Tilapia c) dagaa d) other ________
3) What fish is the most profitable a) Nile perch b) Tilapia c) dagaa d) other ________
4) Is all the fish sold locally? Y/N If N, where else is the fish sold? ______________________

APPENDIX B: STUDY TOOLS FOR FISHERMEN SURVEYS

ADULT CONSENT TO BE A RESEARCH PARTICIPANT IN HOUSEHOLD SURVEYS

Critical evaluation of challenges presented by cyanobacterial blooms to lakeside fishing communities at Lake Victoria and analysis of feasibility of interventions employing a mixed methods approach

Conducted by the Kenya Medical Research Institute
Written consent form for participants in fishermen surveys

Researchers' Statement

I would like to tell you about a study being conducted by researchers from the Kenya Medical Research Institute (KEMRI). The purpose of this consent form is to give you the information you will need to help you decide whether or not to be part of the study. You may ask questions about the purpose of the research, what happens if you take part in the study, the possible risks and benefits, your rights as a volunteer, and anything else about the research or this form that is not clear. When we have answered all your questions, you can decide if you want to be in the study or not. This process is called 'informed consent.' We will give you a copy of this form for your records.

A. WHAT IS THIS STUDY ABOUT?

The researchers listed above are conducting a research study with fishing community members to better understand problems faced by the declining water quality in Lake Victoria in your community and neighbouring communities. We want to have you fill out a survey that will ask you about your fishing activities, state of the fisheries, and impact of blooms on fisheries.

We will use the information gathered to provide information about how the algal blooms are impacting fisheries, along with other challenges, and to identify ways in which outside agencies might help to look for solutions.

B. HOW WERE PARTICIPANTS SELECTED FOR THIS STUDY?

A list of potential participants from communities within Kisumu County, Homa Bay and Mfangano Island was generated through your BMUs. The participants were randomly selected from the lists.

C1. WHAT WILL HAPPEN IF YOU DECIDE YOU WANT TO BE IN THIS RESEARCH STUDY?

If you agree to participate in this study, the following things will happen:
You will sign this form to show that you have agreed. You will work with a trained interviewer in a private room to fill out the survey form.

Your participation is completely voluntary and you can decline to participate in the survey or decline to answer any particular question at any time. Any information you give as an individual is strictly confidential and no specific information identifying you as an individual will be reported. Some FACES program staff will know that you are participating in the study, but no other staff will find out information about what you say specifically while filling out the survey. Nobody will have access to the information you give in a manner that is linked to your identity.

C2. WHAT WILL HAPPEN IF YOU DECIDE NOT TO BE IN THIS RESEARCH STUDY?

If you decide not to participate in the interview, there will be no repercussions on you. You can continue receiving services at FACES clinics as usual. No-one will fine you or refuse to give you service because of not participating. You may also decide to withdraw from the interview at any time during the session without any penalty or repercussions.

D. WILL ANY PARTS OF THIS STUDY HURT OR HAVE OTHER RISKS?

Participating in this study is completely voluntary. You do not have to agree to participate. You have the right to end participation at any time. If there are any questions you do not want to answer, you can skip them or refrain from engaging in discussion. You have the right to refuse to answer any questions or during the survey. Everything you tell us is kept as confidential as possible. We will keep all paper records from this study in a locked file cabinet. We will not discuss your responses within the interview any way that identifies you with clinical staff, other participants in the study, or anyone else.

E. BENEFITS

There is no direct benefit to participating in this study. The information you provide will help us better understand the challenges and concerns associated with declining water quality and fisheries of Lake Victoria for your community and how we might engage with your community to help. This information help guide any community based attempts to improve water quality and reduce health risks for your communities or improve your economic livelihood.

F. COSTS

There will be no costs to you as a result of taking part in this study.

G. REIMBURSEMENT

You will be reimbursed for your transportation to the clinic to a maximum amount of 100 Kenyan shillings to the BMU or clinic. Some refreshments will also be provided at the interview site.

I. WHAT ARE YOUR CHOICES?

Your decision to participate in this study is completely voluntary. You are free to decline participation in the study and you can withdraw from the study at any time. After you have read this consent form and understood the study procedures. You will be given a copy of this consent form to keep for your records. Please sign below if you agree to participate in the fishermen survey.

Consent obtained by: ________________ ________________ ___________

	Staff name	Staff signature	Date
Given by:	________________ Participant name	________________ Participant signature	____________ Date
Witnessed by: (If unable to read)	_________________ Witness name	________________ Witness signature	____________ Date

Household Survey Questions (Regarding Resources Provided by Lake)

Basic Information:

1. Please identify yourself as one of the following: a) boat owner, b) fish trader, c) crew (how many people are in the boat: ____), d) boat renter, d) other:______________
2. Male: ____ Female:_____ Number of children:______
3. Age:_____

Fisheries Involvement:

1. How long have you been involved with fisheries (# of years)? _____
2. If fishing on the lake (skip question, if not):
   a. Approximately how many trips do you make each month to go fishing? _______
   b. What areas do you go fishing regularly (show area on map)? Why (select all that apply)? a) fishing quality, b) place is close, c) water quality, d) other:__________
3. Have you noticed a change in the fish catch since when you started? Y/N
   a. If yes, how? a) size of fish: increase/decrease/no change
      b) quantity of fish: increase/decrease/no change
      c) type of fish: more/less/same
   b. What do you think has contributed to the change(s)? a) change in the quality of gear (improve/degraded), b) number of people fishing (more/fewer), c) unregulated fishing activities (uncontrolled catch/fishing in breeding grounds/other:__________), d) pollution in lake, e) climate change, f) other:____

Lake Health:

4. During your time with fisheries, what major changes have you noticed taking place in and around the lake (for each example, if yes, please describe type of change and whether seasonal or directional)
   a. Water clarity? Y/N
   b. Water smell? Y/N
   c. Fish species presence/absence? Y/N
   d. Total fish abundance? Y/N
   e. Type of plants in the water? Y/N
   f. Total plant abundance? Y/N
5. When did you first notice algal blooms in the lake?
6. What effects do you think algal blooms have on the following:
   a. Lake water quality
   b. Fishery business
   c. Fish in the lake
7. What do you think causes the algal blooms? a) natural causes, b) pollution, c) rain, d) fish, e) water hyacinth, f) warm/cold temperatures, g) fertilizer
8. Do you think future generations will be able to fish in Lake Victoria? Why or why not? How might it differ from current practices?

Appendix 2. Concerns and considerations voiced by fishers and household heads in open ended questions. Words clouds from responses of open-ended questions from fisher (top) and household (bottom), with the top 250 employed words mapped at a logarithmic scale.

Appendix 3. Raw Water Quality Data File

Please click here to download file ‘appendix3.xlsx’.

Appendix 4. Raw Fish Data File

Please click here to download file 'appendix4.xlsx'.