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Harmful Algal Blooms Threaten the Health of Peri-Urban Fisher Communities: A case study in Kisumu Bay, Lake Victoria, Kenya

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Abstract

Available guidance to mitigate health risks from exposure to freshwater harmful algal blooms (HABs) is largely derived from temperate ecosystems. Yet in tropical ecosystems, HABs can occur year-round, and resource-dependent populations face multiple routes of exposure to toxic components. Along Winam Gulf, Lake Victoria, Kenya, fisher communities rely on lake water contaminated with microcystins (MCs) from HABs. In these peri-urban communities near Kisumu, we tested hypotheses that MCs exceed exposure guidelines across seasons, and persistent HABs present a chronic risk to fisher communities through ingestion with minimal water treatment and frequent, direct contact. We tested source waters at eleven communities across dry and rainy seasons from September 2015 through May 2016. We measured MCs, other metabolites, physicochemical parameters, chlorophyll a, phytoplankton abundance and diversity, and fecal indicators. We then selected four communities for interviews about water sources, usage, and treatment. Greater than 30% of source water samples exceeded WHO drinking water guidelines for MCs (1μg/L), and over 60% of source water samples exceeded USEPA guidelines for children and immunocompromised individuals. 50% of households reported sole use of raw lake water for drinking and household use, with alternate sources including rain and boreholes. Household

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Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee [Kenya Medical Research Institute (KEMRI) Scientific Research Unit (SERU), Protocol No. KEMRI/SERU/CMR/P00033/3248), and University of California, Davis, Institutional Review Board] and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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chlorination was the most widespread treatment utilized. At this tropical, eutrophic lake, HABs pose a year-round health risk for fisher communities in resource -limited settings. Community-based solutions and site-specific guidance for Kisumu Bay and similarly impacted regions is needed to address a chronic health exposure likely to increase in severity and duration with global climate change.

Keywords

algal blooms; microcystins; Lake Victoria; fisherfolk; estimated daily intake; cyanobacterial metabolites

Introduction

Lake Victoria's expansive freshwater fishery provides livelihood and food security for tens of millions within its nearshore environment (FAO 2014; Hecky et al. 2010; Kundu et al. 2017; Sitoki et al. 2010). Winam Gulf encompasses the majority of the Kenyan portion and connects to the profoundly deeper, open lake through Rusinga channel (Fig. 1) . This shallower region has suffered profound ecological change since the 1980s with declining water quality, invasive water hyacinth, introduced species, oxygen depletion, and increasing algal biomass, while the lakeside population has grown substantially over the past 20 to 30 years (Omwega et al. 2006), further increasing agricultural, industrial, and wastewater contaminants into the lake (Fiorella et al. 2017; Hecky et al. 2010; Sitoki et al. 2010). This nutrient loading has supported toxin-producing freshwater harmful algal blooms (HABs), which threaten the health of nearshore fisher populations (Haande et al. 2011; Mbonde et al. 2015; Sitoki et al. 2010; Sitoki et al. 2012), already facing multifactorial health challenges. In addition to high prevalence of environment-associated infectious diseases like malaria and schistosomiasis (Minakawa et al. 2012; Ofulla et al. 2013), this Nyanza Province has the highest prevalence (26%) of HIV in the nation (Ministry of Health KHCP, 2016; Kwena et al. 2012), 70% living below the national poverty line, and rampant food insecurity (Fiorella et al. 2017; Nagata et al. 2015; Omwega et al. 2006).

While freshwater HABs can be caused by proliferation of diverse microorganisms, including cyanobacteria, and may produce a range of toxins (Ibelings et al. 2015; Liyanage et al. 2016; Rastogi et al. 2015), the most common category of cyanotoxins produced is a family of cyclic peptides- microcystins (MCs). Both human and animal deaths have been ascribed to ingestion of these potent acute liver toxins (Ibelings et al. 2015; Hilborn and Beasley 2015). MCs have also been linked to chronic pathologies within liver, intestine, kidney, lung, brain, heart and reproductive systems (Massey et al. 2018), and epidemiologic data supports links to neurodegenerative disease (Mello et al. 2018) and liver cancer (Svircev et al. 2017). Developmental models indicate that both MCs and other HAB components may result in neurotoxicity, teratogenicity and endocrine disruption (Jonas et al. 2015; Qian et al. 2018), putting young children, with their lower body weight, indiscriminate behavior, and physiology at particular risk from chronic HAB exposure (Weirich and Miller 2014).

In 2014, the lakeside city drinking water intake of Kisumu (Sitoki et al. 2012), the third largest population center in Kenya at the center of Winam Gulf, measured MC concentrations several fold higher than WHO guidelines (Herrie et al. 2017; Steffen et al. 2017). The WHO provides a provisional guideline of 1 μg/L MC-LR (with over 200 congeners) equivalent based on a Tolerable Daily Intake (TDI) guideline of 0.4 μg/kg for a life time exposure (WHO 2017). The US Environmental Protection Agency (USEPA) has issued a 10-day Health Advisory limit of 0.3 μg/L for pre-school age children and younger, and some public health officials advocate for even more stringent standards given links to developmental and chronic toxicity, in particular for children, elderly and immunocompromised individuals (Herrie et al. 2017; Ibelings et al. 2015; Weirich et al. 2014). Peri-urban subsistence fisher communities around Kisumu rely directly on nearshore water (Haande et al. 2011; Mbonde et al. 2015). There is scant human health data or risk assessment in the context of freshwater HABs in subsistence communities in tropical regions, facing HABs for extended periods of time (Merel et al. 2013; Mowe et al. 2015), though climate change is projected to increased intensity and severity of HABs (Paerl 2018; Walls et al. 2018). No guidelines are provided in East Africa.

Our objectives were several-fold: 1) to measure MCs and other HAB metabolites in nearshore fisher community waters around Kisumu; 2) to identify potential spatial or temporal variation; and 3) to characterize community use of lake water, exposure routes, and estimated daily MC toxin exposure.

Methods

Study area and sampling design

To determine water quality concerns for human health, we worked with Kenya Medical Research Institute (KEMRI) and Family AIDS Care & Education Services (FACES) to empirically identify highly bloom-impacted communities. We sampled lake water from the shorelines of eleven fisher communities in three different districts around Kisumu Bay, outside of the urban center of Kisumu (Fig. 1). To coordinate environmental sampling with community permission, transparency, and trust, community mobilizers and health workers with longstanding relationships were utilized. The climate in the region has two rainy seasons, a short and long one, hence sampling was conducted quarterly to capture both rainy seasons (November 2015 and April 2016, hereafter, “short rain” and “long rain”) and the intermittent dry seasons (October 2015 and February 2016, hereafter, “oct dry” and “feb dry”). In each season, samples were taken from each site within the same week. A quarterly water sample was also taken by boat from close to the intake of the drinking water intake for the city of Kisumu.

Environmental sampling

Each sampling included assessment of physicochemical parameters, phytoplankton counts and biomass, fecal indicators, and cyanotoxins, in order to assess potential temporal and seasonal trends, as well as potential predictors for toxin presence or concentration. We recorded water temperature, dissolved oxygen (DO), pH, conductivity, and total dissolved solids (TDS) using a field multiparameter sonde (WQC-24, DKK-TOA, Cambridge, UK). Water samples were collected through near shore grabs at community source waters or by boat; precise GPS locations are given in Table 1. Phytoplankton samples were fixed with

Lugol's solution while other samples were kept in a cooler until processed at the Kenyan Marine Fisheries Research Institute Laboratory (Kisumu). Samples for nutrient analyses (total nitrogen, nitrate, nitrite, total phosphorus, silica, soluble reactive phosphorus) were collected in acid washed polyethylene bottles, stored at 4°C and analyzed within 72 hours of collection. Samples for bacteriological and toxin analysis were stored and transported in amber-colored glass bottles. Bacteriological samples were kept at 4°C and analyzed within 24 to 48 hours of collection. Routine analytical approaches for nutrients, phytoplankton, and bacteriological samples are detailed in Appendix A. For chlorophyll-a, 50 mLs was filtered through GFC filters (0.7 μm nominal pore size, Sigma Aldrich, St. Louis, MO) using a hand pump and the filters were then frozen at −20 C. For intracellular cyanotoxin analysis, 50 mLs were filtered through a GFC filter and then immediately dried in an oven at 40°C for 48 hours, and then frozen at −20°C wrapped in aluminum foil until further extraction and analysis (see Appendix E.1 for "spike and recovery").

Extraction and quantification of cyanobacterial metabolites

For cyanotoxin extraction, filters were cut into four pieces using sterilized scissors and suspended in 5% acetic acid in water. Cells were lysed on the filters using three freeze-thaw cycles for 30 min at −80°C and thawing 10 min at 50°C with vortexing between cycles. After the final thaw, methanol (MeOH) was added to 67% with acetic acid at 5%. Filters were sonicated 50°C for five minutes and then centrifuged. The supernatant was transferred to a scintillation vial. The remaining filter and biomass in each tube was washed again with 100% MeOH and 5% acetic acid with vortexing; after centrifuging, the supernatant was added to the scintillation vial. The full extract was dried with nitrogen gas at 37°C. Dried extracts were re-suspended in 1 ml of 70% MeOH and spiked with $^{13}C_6$-phenylalanine prior to analysis via LC-MS/MS to monitor for ion suppression. The following MCs and related cyanopeptides were quantified using LC-MS/MS (est. detection limit= 0.02 μg/L, particulate fraction): MCLR, -YR, -RR, -LA, Dha7-MC-LR (dmLR), nodularin, cyanopeptolins 1041, 1020, 1007, anabaenopeptins A, B, and F, and microginin 690. The analysis was conducted as previously described (Beversdorf et al. 2017; Beversdorf et al. 2018). Sum of all measured MC congeners (Sum MC) were then determined. Peptides other than MC also were targeted since these have been found to co-occur with MCs in other surveys and display deleterious effects in some animal models.

Risk Assessment for Ingestion of MCs through Drinking Water

Assessment of risk of exposure to contaminants in lake water for human health has been carried out widely over the world, but also can be overlooked with respect to risk for populations most directly dependent upon lake ecosystem services (Bhateria et al. 2016; Ford et al. 2017; Wu et al. 2017; Li et al. 2017). In our study, risk of exposure to MCs was estimated using the WHO Tolerable Daily Intake (TDI) guideline 0.4 μg/kg/d for a life time exposure (WHO 2003a, 2017) and the sum concentration of all MC congeners (Sum MC) as microcystin equivalents. We assumed a daily drinking water intake of 2 L per day for 60 kg-adults and 1.5 L per day for 13 kg-children, and added an accidental ingestion during recreational intake (in this case, bathing, swimming or collecting water) of 0.1 L per day for children.

$$\text{Estimated Daily Intake }(EDI) = \frac{[MC \quad or \quad MC \quad equiv] * L * P}{b.w.}$$

Where MCs or MC equiv are in μg/L, L is the daily water ingestion rate in liters per day and b.w. is body weight in μg/kg. P refers to proportion of water obtained from impacted water source.

Application of WHO Criteria for Recreational Risk

We assessed risk for adverse health effects utilizing WHO recreational and source water criteria. The WHO has identified additional criteria (cyanobacterial biovolume and cell counts, chlorophyll-a, and fecal indicators) in risk assessment for recreational water usage, and monitoring agencies employ similar tiered guidelines to trigger alert and action levels. For cyanobacteria, a moderate level of risk of adverse health effect is reached at 50 μg/L chlorophyll-*a,* 100,000 cyanobacterial cells/L, or 20 μg/L MC in the top 4 m of the water column. High risk from 100-fold accumulation of scum is reached at 5,000 μg/L chlorophyll *a* or 10,000,000 cells/L, with a very high risk from high winds sweeping cells to accumulate levels above 50,000 μg/L or 100,000,000 cells/L. The WHO recognizes that no level of Fecal Indicator Bacteria (FIB) are permissible for drinking water (“none detected in any 100-mL sample”) and also suggests a tiered approach for assessing risk from recreational and source waters (WH0 2003b). The most frequently utilized risk classification in assessing interventions in low to middle income countries is based on the number of indicator organisms in a 100 mL sample with low risk between 1–10, medium risk between 10–100, and high risk for >100 (Bain et al. 2014).

Statistical Analysis

One-way ANOVAs were performed to examine temporal and spatial variability of physicochemical parameters and health risks (cyanobacterial metabolites and fecal indicators). Pair wise post hoc tests were then performed using Tukey’s methods (significance defined as adjusted $p<0.05$). Multivariable logistic regression was utilized to identify possible predictor variables for total MCs exceeding the WHO provisional guideline (1 μg/L) and available chronic and developmental guidelines. Linear regression of MC concentration with respect to nutrients, cyanobacterial cell count and abundance, diversity indices (species richness, Shannon’s and Simpson’s diversity indices) and fecal indicators was also carried out; log transformation was performed where appropriate. Statistical analyses were performed and data graphed in the R modeling environment (R version 3.4.2, 2017).

Beach Management Unit (BMU) Informant Interviews and Household Surveys

To characterize community use of water and assess risk, four communities were selected for interviews. We selected these communities based on those with cyanobacterial cell counts above WHO guidelines, i.e., communities with high risk of adverse health effects from lake water. Within each community, informant interviews were conducted with several elected officials in BMUs and surveys with 50 heads of household. More detailed description of methods, including survey and interview tools, are included in Appendix B. Local, trained, multilingual interviewers conducted all recruitment, interviews, and transcription. Human subject approval for interviews was obtained through Kenya Medical Research Institute (KEMRI) Scientific Research Unit (SERU) (Protocol No. KEMRI/SERU/CMR/P00033/3248) and University of California, Davis, Institutional Review Board (IRB).

Results

Eutrophic Waters at Fisher Community Shores

The women within fisher villages utilized and retrieved water for washing, cleaning, and household drinking from "soup pea" green surfaces at the lake shores during the period of this study. Blooms were not consistently visually detectable to the naked eye, but cell counts indicated presence of blooms (4,000 cells/mL or greater) 95% of time. There was high variability of water temperature across seasons (F-stat=11.13, p=0.0000221), ranging from 22.4 to 30.5 degrees C, although it was not a predictor for toxins or cyanobacterial cell counts. No trends were identified among other physical parameters, although conductivity (min=73.5 μS, max=184 .0 μS), pH (min=7.1to max=8.8), and dissolved oxygen (min=2.87 to max 8.97 mg/L) varied widely across sites and seasons. Total nitrogen (TN), total phosphorus (TP), and chlorophyll-a (Chl-a) were consistently elevated, with TP and Chl-a indicating eutrophic to hypertrophic states, based on Carlson's Trophic State Index (Carlson, 1977). TN and TP ranged from 54.86 to 5675.75 μN/L and 71.125 to 332.57 μP/L, respectively. Chlorophyll ranged from 4.64 to 706.09 μg/L. Amidst this elevated nutrient environment, fecal coliforms varied by season (F=3.01, p=0.0434), with the highest loading occurring typically during "long rain", although no particular trend was observed for *E. coli.* TN (F-stat=9.85), ammonium (F-stat=6.65), and silicates (F-stat= 15.34) varied across seasons with the highest levels occurring during the oct dry season for TN and silicates and short rain for ammonium, likely due to differences in biochemical cycling of nitrogen and of silicates during those time periods. Table 2 contains mean seasonal physicochemical data and the complete raw data is available in Appendix E.2.

Cyanobacteria and Cyanotoxins Profiles of Nearshore Water

Known toxicogenic genera of cyanobacteria, *Microcystis spp* and *Anabaena* (renamed *Dolichospermum) spp,* were consistently identified within samples collected from community waters, as well as at the Kisumu City drinking water intake. MCs were detected in 32 out of 43 community samples, with the majority of non-detects occurring during "oct dry." The highest biovolumes occurred during the short rainy season (Table 3), and *Microcystis spp.* typically dominated the cyanobacterial biomass, with some notable exceptions (e.g. Kaguel during short rain and feb dry)(Fig D.2). No significant correlation was found between biovolume and counts of specific cyanobacteria with MC concentration. Biodiversity indices (Appendix E) were not correlated with MC concentrations.

Sum MCs exceeded the WHO drinking water guidance of 1 μg/L in 13 out of the 43 community water samples, with six of those occurring during "feb dry." The source waters exceed the USEPA 10-day health advisory levels for infants and pre-school aged children in over 60% of samples, with the least in "oct dry." All MC congeners tested (MCLR, MCYR, MCLA, MCRR, dmLR) were detected and individually exceeded 1 μg/L at least once (Table

4). In contrast, city water intake did not exceed any thresholds and had a limited number of detects, suggesting a greater risk from those drawing water from the nearshore environment. Sum MC concentrations varied seasonally based on an ANOVA ($F=3.54$, $p<0.05$) (see Appendix C) with highest levels observed during "short rain" season. No significant patterns emerged with individual congeners. Fig. 2 illustrates seasonal variability across individual communities and Kisumu city intake. No significant predictor variables ($p<0.01$) were identified for MC concentrations or exceeding categorical thresholds for risk, following WHO or USEPA criteria.

Of note, additional metabolites Anabaenopeptin A and Cyanopeptolins 1007, 1020, 1041 were identified across seven of the community sites and distributed across all seasons (Fig. D.3). There is no regulatory guidance available for these compounds

Risk Assessment for Recreational or Activity Use

Cyanobacterial counts were consistently elevated-71 % of samples collected overall would have fallen into a high risk of adverse health effect based on cell count and an additional 16 % moderate risk from recreational exposure. Fig. D.1 provides a heat map of level of risk according WHO guidelines based on risk assessment. Similarly, fecal coliforms were consistently elevated, with 85% of samples collected exceeding 10 MPN/100 mL and 59% exceeding 100 MPN/100 mL of *E. coli,* with wide variability between location and season in total coliforms and *E. coli* (Fig. 3). Even though samples were collected at the same locations and days as those measured for MCs, we found no correlation between cell counts, fecal coliform levels, and MCs. No significant patterns were identified by location.

Community Utilization of Water & Household Risk Assessment

BMU interviews detailed water insecurity with respect to alternate sources to lake water and concerns about quality of water retrieved directly from the lake for drinking and household needs (Table 5), in addition to food and job insecurity. Boreholes may be available during rainy seasons, but dry up during the hot, dry periods, when blooms are often visually present. BMU leaders reported use of AquaGuard (small packets of chlorine), sieving (cloth filter), and boiling— a result of public health outreach to address infectious disease. Elected leaders make recommendations to minimize health risk from bloom exposure and reduce localized nutrient loading (e.g. refrain from washing and bathing in lake and avoid herding cattle into the lake, respectively), but lack means for enforcement. BMU officials emphasized the need for infrastructure, capital in the form of microloans, and capacity building to ensure water and food security.

The individual household head responses to questions regarding water collection, use, and treatment are illustrated in Fig. 4. 100% of identified heads of households were women. Over the 198 responding households, 88.9% rely on a child or woman of child-bearing age (or both) for collection of water, increasing their risk of exposure to bloom-contaminated waters Approximately 50% of respondents said there was no source for water other than the lake. The next most common drinking water sources, borehole (28.1%) and rainwater (11.1%), are seasonally dependent. By far the most common form of treatment is chlorination (68.9% households reporting chlorination), and 46.5% of respondents indicated they were concerned about water quality, in general, with an additional 9.1% concerned about disease, 6.1% about the algal blooms and 5.1% concerned about availability, specifically. Household heads also mentioned concerns with lasting odor, lack of available treatment options, and crocodiles (making fetching the water unsafe).

Fig. 5 shows the estimated daily intake of MCLR and SumMC at these four community locations projected from the seasonal sampling at each site. Our conservative assessment assumes children and adults use lake water as their sole drinking water source and that removal by treatment is absent or ineffective. Fig. 5 illustrates that children in these communities are likely exposed to chronic levels of MCs exceeding the TDI through oral ingestion.

Discussion

We hypothesized that Kenyan peri-urban fisher communities around Kisumu are disproportionately impacted by HABs, facing increased risk of exposure to cyanotoxins through multiple routes. We found that: 1) MC levels in raw waters used for drinking and cooking exceeded provisional and developmental guidelines across multiple seasons (Fig. 2); 2) cyanobacterial cell counts reflected a “high likelihood of adverse effect” in the majority of seasons for nearshore communities (Fig D.1); 3) these communities utilize the water for drinking, and women and children are in contact with lake water in carrying out daily activities. In direct contrast, toxin levels at the city intake serving the urban center, where there is some treatment, were either non-detectable or several fold lower at the same time point. We did not identify any consistent seasonal or spatial trends, or any reliable predictors of MC presence or concentration.

Awareness and concern about potential health risks associated with the HABs from contact and ingestion exists in these communities, but households therein possess few alternative options for drinking water, domestic use, and livelihood (Table 5). Fisher and children in rural communities in China have faced chronic adverse health consequences from a similar, subsistence exposure (Chen et al. 2009; Li et al. 2011, 2017; Wu et al. 2017). Specific villages collect rainwater and have a borehole, but availability of water from those sources is limited to rainy seasons, and appears to be some inter household variability in terms of access to alternative options, presumably correlated with socioeconomic status (Fiorella et al. 2017). The high reported levels of chlorination and boiling reported may actually increase the concentration of MC or other by-products in household water through evaporation of water, cellular lysis, and oxidation processes. The stable MCs resist degradation through boiling, and while chlorination can be effective, after cellular filtration and within specific water quality parameters (Codd et al. 2005; Herrie et al. 2017; Ibelings et al. 2015), the local chlorination products (Aquaguard, Aquatabs) have not been tested for efficacy. The cost of removal of MCs from drinking water is a large burden for drinking water treatment plants; in a resource limited setting, it becomes disproportionately more costly for resource dependent populations (Codd et al. 2005; Herrie et al. 2017; Ibelings et al. 2015; Roegner et al. 2014; Westrick et al. 2010).

Our conservative risk assessment approach illustrates that nearshore HABs represent a significant health burden through chronic exposure to MCs, with particular implications for the health of young children, elderly and immunocompromised individuals. Yet we may have also underestimated risk for the following reasons: 1) We assumed treatment of raw water within households would not reduce risk, though, as discussed, boiling could augment MC concentrations, in household water; 2) Our analysis only included intracellular MCs, so we have underrepresented risk from dissolved or free MCs present in the water column, higher in aging or dying HABs. Bacteriophages involved in gene transfer inducing lysis (Stough et al. 2017; Yoshida-Takashima et al. 2012), as well as environmental factors (Paerl 2018; Walls et al. 2018), are believed to control extent of dissolved MCs released into the water column; 3) The estimated daily intake (EDI) did not account for: 1) lower BMI associated with HIV and other endemic diseases in the region (Nagata et al. 2015) and 2) potential increased water intake under intensity of the heat (annual average temperature of 22.82 °C and 22.76 °C. for 2015 and 2016, respectively), particularly when performing hard labor in the sun.

We also did not account for ingestion of MCs is via consumed fish species (Supplemental Fig. 1), especially relevant in a population that relies on fish as a protein source and for overall food security (Fiorella et al. 2016; Nagata et al. 2015.) WHO guidelines for chronic exposure assumed the majority of daily ingestion to come from drinking water (80%), relative to other sources such as food, was not developed in the context of heavy fish consumption. Indeed, small sundried fishes fed whole to children as small snacks or meals, *Rastrineobola argentea* (locally name dagaa), have documented high levels of MCs in their gut contents, particularly in the Kisumu region (Fiorella et al. 2016; Simiyu et al. 2018). Generally, MCs have been documented at higher levels in Lake Victoria fishes than typically seen in freshwater species in temperate zones of the world (Codd et al. 2005; Nyakairu et al. 2010; Poste et al. 2011), and Chinese fishers have had elevated levels of MCs in serum linked directly to their fish intake, alongside biochemical markers indicative of liver damage (Chen et al. 2009). The contribution of diet to daily MC intake in these fisher populations must be explored further. In addition to fish, accumulation of MCs within terrestrial agricultural crops has been well documented (Corbel et al. 2014; Pham and Utsumi 2018), though no risk assessment executed for populations consuming those plants. During our study, we frequently observed small plots of vegetables within these communities, in addition to domesticated animals, such as free-range chickens and cattle utilizing the same water and plant sources (Codd et al. 2005; Corbel et al. 2014; Saqrane and Oudra 2009) (Supplemental Fig. 1).We found that the WHO risk guidance criteria for HABs for recreational waters had little practical use within this tropical setting where 1) there was little temporal variability in the consistently elevated cell counts and no predictive power with respect to MCs and 2) subsistence daily use cannot be avoided. Cyanobacterial cell counts exceeded the level for likely adverse risk health effect during recreational exposure (WHO, 2003b) in 73% of the samples collected. Following WHO guidelines, the majority of beaches would be closed for public use based on high risk of adverse health effects across multiple seasons (Fig.D1). Thus, fisher communities may also confront direct gastrointestinal effects from accidental oral ingestion during bathing or recreating, skin irritation from lipopolysaccharides and other components, and unfavorable odor and taste compounds(Funari and Testai 2008; Ibelings et al. 2015) given the direct use of water for a wide range of activities, including washing clothes, bathing, and fishing. These waters also exceeded the recreational guidelines for moderate (100% and 89.7% of 39 samples for coliforms and *E. coli*, respectively) and severe (48.7% and 46.2%) risk. High fecal loading is of particular concern given that breast-feeding women and children are frequently in direct contact with the near shore water, as there are established developmental risks associated with poor water, sanitation and hygiene (Ngure et al. 2014). Future work should include investigation into the adverse health consequences of daily use and contact, alongside interventions to minimize risk.

Conclusions

In summary, the health of peri-urban fisher communities near Kisumu is further threatened by the consumption and use of lake water contaminated with MCs and other HAB components.

- Multiple MCs were detected across seasons and locations, exceeding guidelines for children and vulnerable groups in the majority of the samples analyzed.
- Developmental toxicants, anabaenopeptins and cyanopeptolins, were also repeatedly detected in community source waters.
- Cyanobacterial cell counts were consistently elevated and did not emerge as reasonable criteria for monitoring risk of toxins present in water source.
- These cell counts and FIB combined with interview data suggested increased likelihood of adverse effect from contact with water during household and daily activities.
- Household treatment methods employed are inadequate to remove MCs and may increase the concentration.

Given the lack of infrastructure for water treatment, lack of alternative water sources, and other health vulnerabilities, it is critical to characterize risk from ingestion via foodstuffs, identify drivers of localized nutrient input, understand local triggers for toxin production, and develop sustainable, community-based interventions for the region, with implications globally for freshwater tropical fisher populations.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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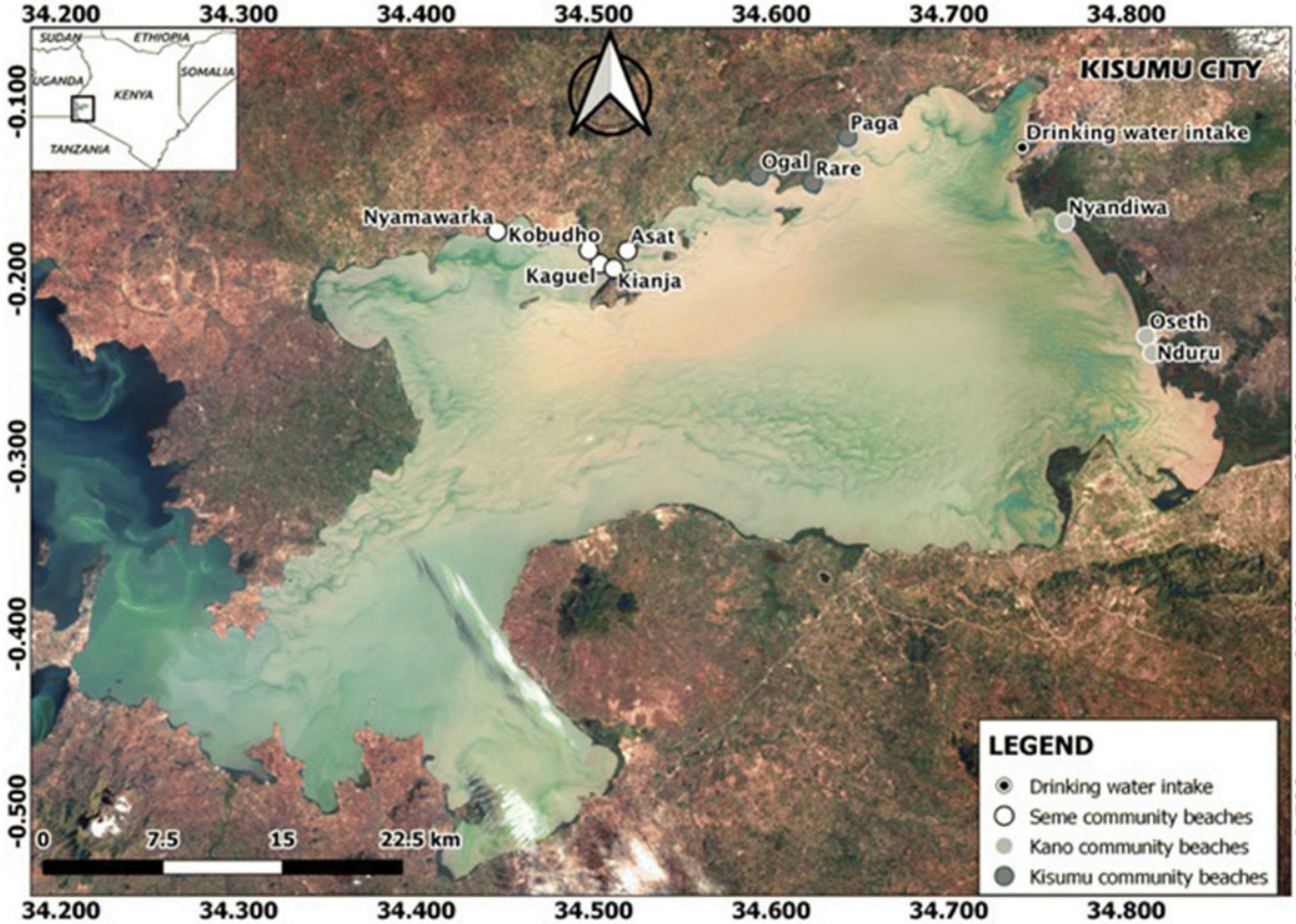

Fig. 1. Remote Sensing Image and Map of Winam Gulf and Study Sites.

Image was downloaded from glovis.usgs.gov and a D0S1 atmospheric correction was performed in QGIS V3.0, with layering of stacked bands 2–7. Green depicts cyanobacterial blooms in absence of water hyacinth.

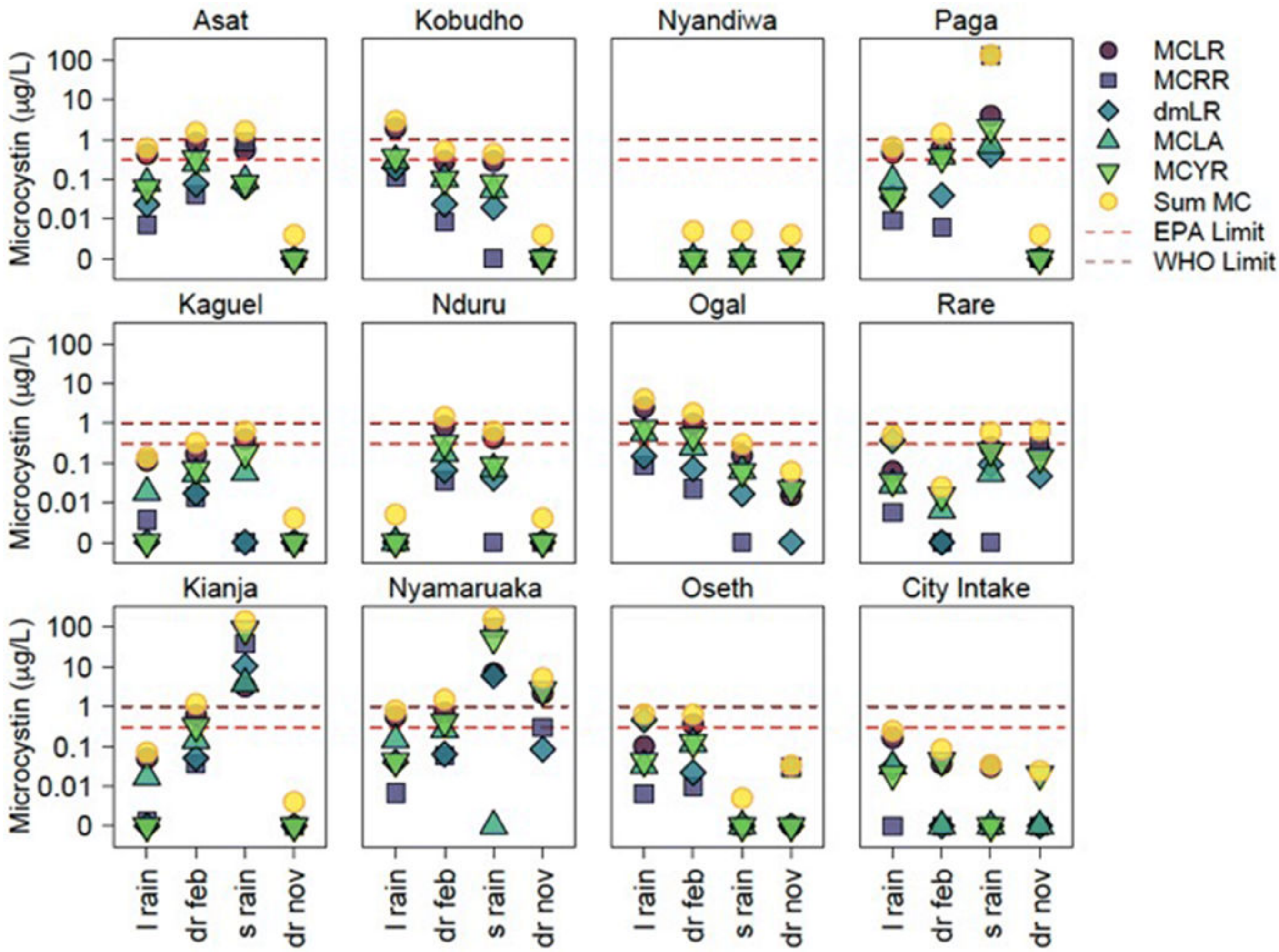

Fig. 2. MC Congener Concentrations Across Rainy and Dry Seasons at Fishing Village Drinking Water Source from Lake Victoria and at Kisumu City Intake.

The log distribution of each congener and Sum MC at each community location and at the Kisumu city intake is depicted with the red line demarcating the WHO provisional guideline and the light pink line demarcating the USEPA health guideline for children and infants.

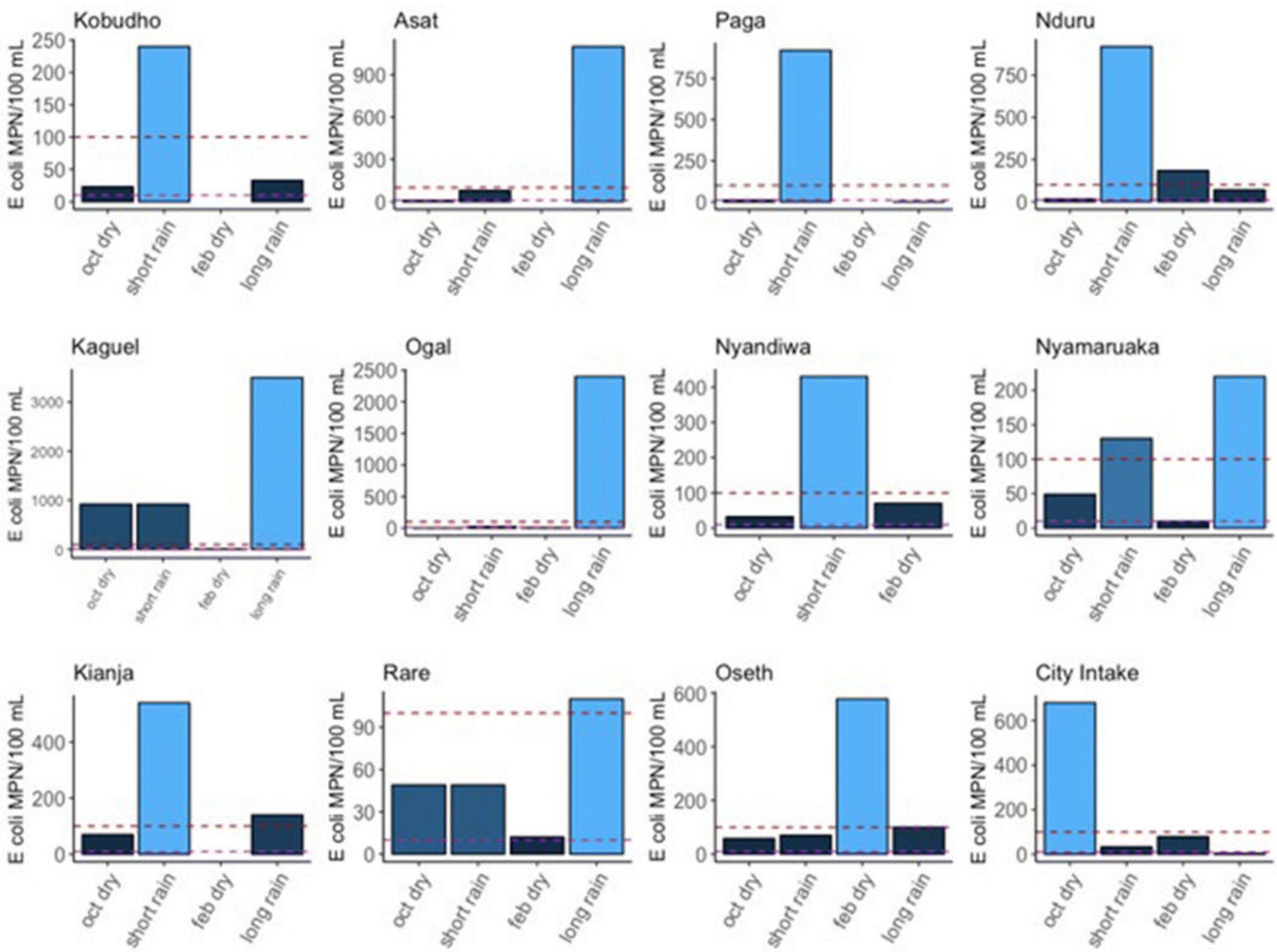

Fig. 3. *E coli* Most Probable Number (MPN) per 100 ML Across Rainy and Dry Seasons at Fishing Village Drinking Water Source from Lake Victoria and at Kisumu City Intake.

The dark red line indicates severe risk (100 MPN/100 mL) and the purple line moderate risk (10 MPN/100 mL) of adverse health effect. No levels are permissible for drinking water.

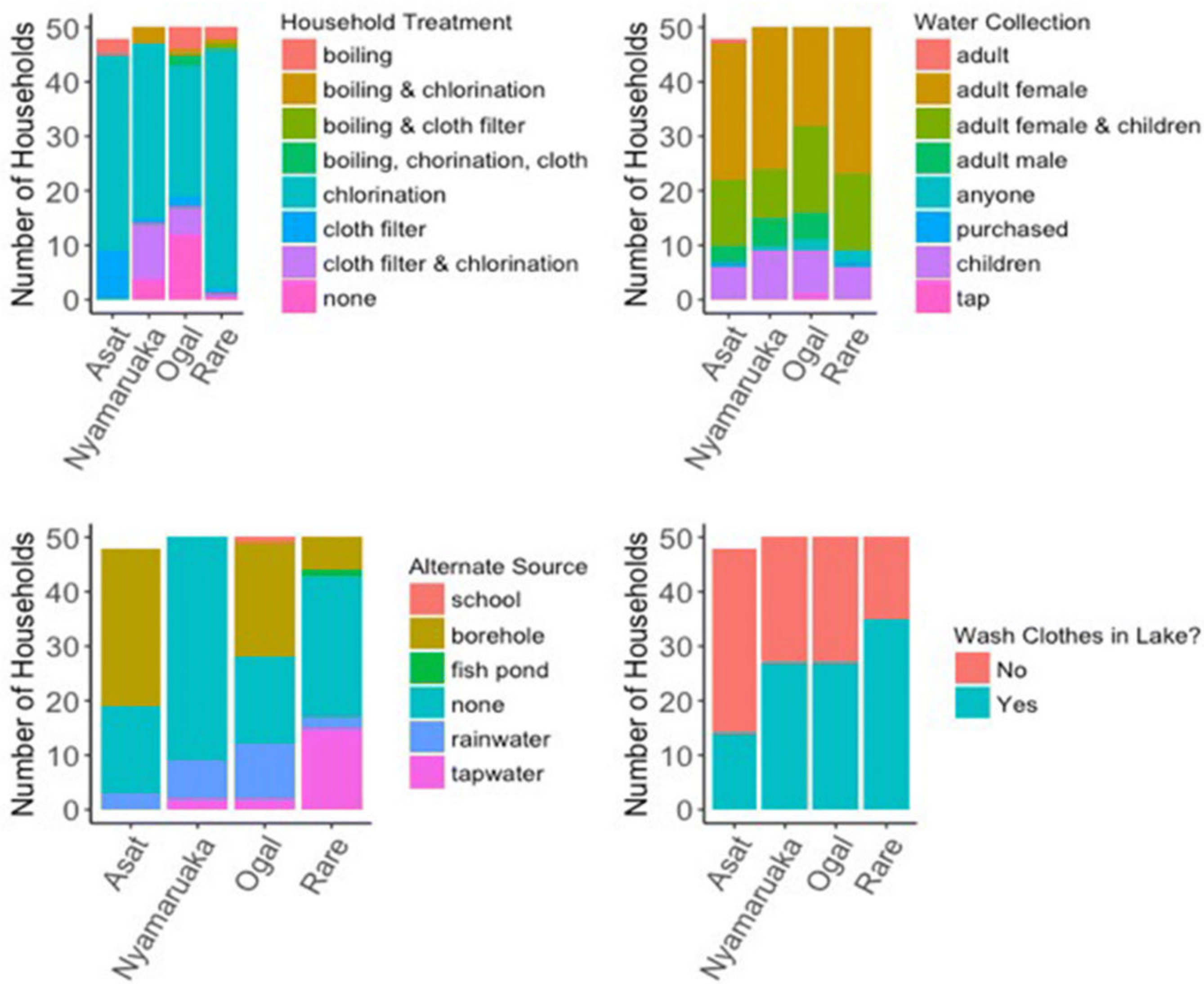

Fig. 4. Household Self-reported Water Usage Characteristics Across Representative Fisher Communities Impacted by CyanoHABs.

Responses were recorded by interviewers with approximately 50 respondent per community. All heads of households were women of variable ages.

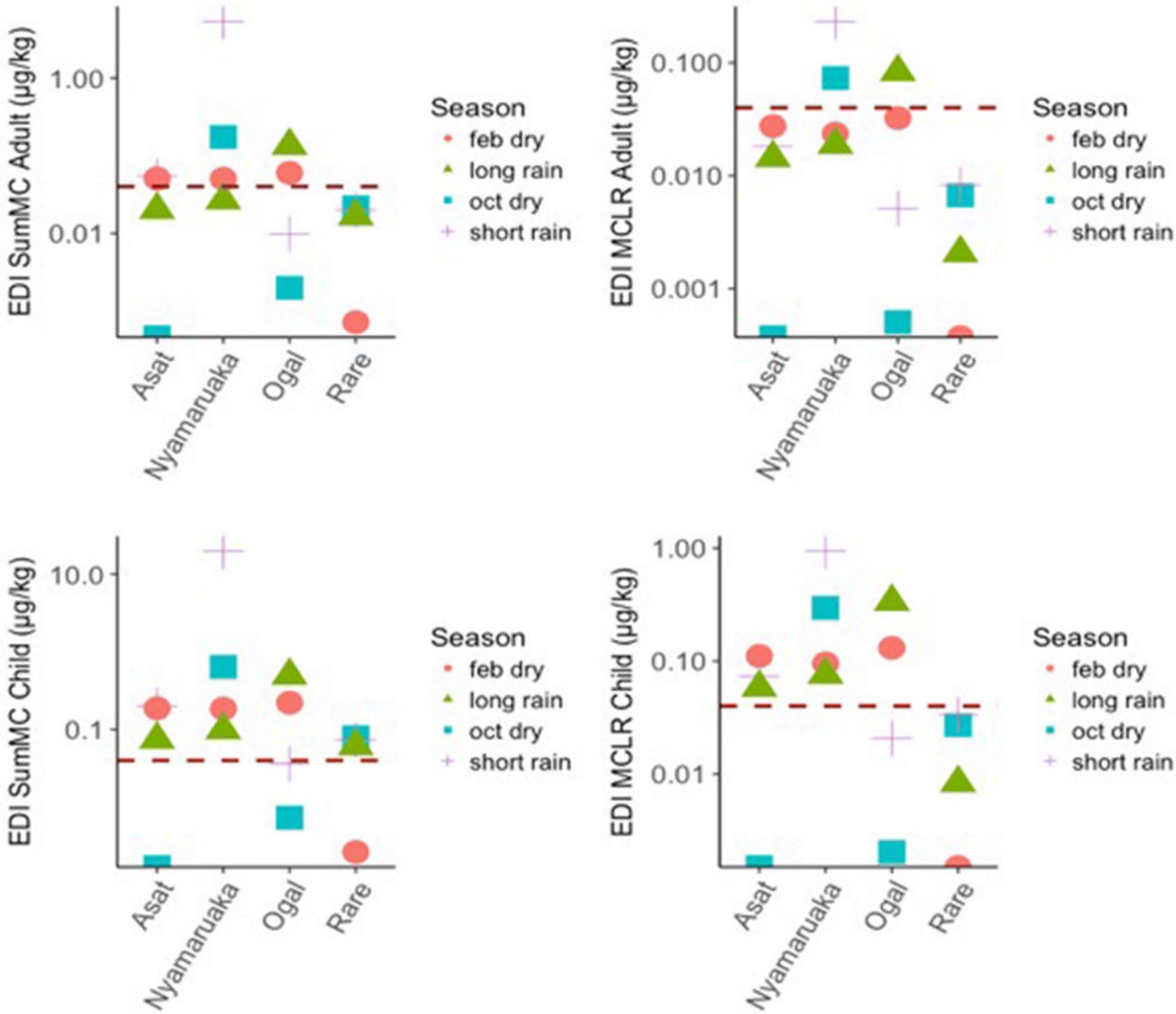

Fig. 5. Estimated Daily Intake of MCLR and Sum Total of MCs through Oral Ingestion of Water for Children and Adult.

Dashed lines represent TDI based on 0.4 µg/kg for 60 kg adult and 13 kg child. Assumes intake of 2 L from drinking water for adult per day and 1.5 L intake from drinking water and 0.1L for accidental ingestion.

Table 1

Community Site Names, Descriptions, and GPS

Site	Description	Latitude	Longitude
Kaguel	*Seme Community Beaches*	−0.19123	34.50341
Kobudho		−0.18377	34.49713
Nyamawarka		−0.17295	34.44543
Kianja		−0.19400	34.51123
Asat		−0.18391	34.51890
Paga	*Kisumu Community Beaches*	−0.12000	34.64274
Ogal		−0.14175	34.59273
Rare		−0.14572	34.62312
Oseth	*Kano Community Beaches*	−0.23207	34.81104
Nduru		−0.24159	34.81452
Nyandiwa		−0.16771	34.76533
City Intake	*Municipal Drinking Water Intake*	−0.12579	34.74124

Table 2

Seasonal and Mean Nutrient Concentrations and Physical Parameters

Parameters		TN[a]	Nitrites	Nitrates	NH_4[a]	TP[a]	SRP	Silicates	Temp	DO	Cond	pH
		μgN/L	*μgN/L*	*μgN/L*	*μgN/L*	*μgP/L*	*μgP/L*	*mg/L*	*°C*	*mg/L*	*μS*	
Seasonal Means	oct dry	2354.2	34.1	49.1	196.0	232.6	351.2	28.1	27.8	4.82	149.2	7.8
	short rain	606.4	27.4	84.8	198.1	171.5	105.3	18.1	26.9	5.49	137.4	7.9
	feb dry	113.7	42.2	20.5	70.3	173.4	163.4	17.2	25.7	4.99	141.7	7.8
	long rain	338.3	22.3	25.0	19.9	214.5	129.8	23.7	24.4	3.99	139.7	8.1
Overall	mean	784.3	32.6	38.6	97.4	211.3	197.6	23.9	26.3	4.86	142.1	7.9
	stdev	1176.9	19.0	59.7	113.1	67.3	124.3	9.7	1.9	1.27	16.9	0.3
	min	54.9	9.8	10.0	14.6	109.1	64.9	14.6	22.4	2.87	73.5	7.1
	max	5675.8	107.5	287.6	520.6	332.6	498.9	47.5	30.5	8.97	184.0	8.8

[a] TN, TP, SRP, and DO represent total nitrogen, total phosphate, soluble reactive phosphorus, and dissolved oxygen.

Table 3

Location Means, Seasonal Descriptive Statistics, and Overall Statistics for Cyanobacterial Counts and Biovolumes

Mean Cyanobacterial Counts and Biovolumes		Cyanobacterial Count#	Cyanobacterial Biovolume#
		cells/mL	*mm^3/L*
Site Averages	Asat	659918	137.5
	Kaguel	146665	135.3
	Kianja	794467	77.6
	Kobudho	409851	78.7
	Nduru	135524	55.5
	Nyamaruaka	935432	52.3
	Nyandiwa	191465	6.4
	Ogal	228015	85.7
	Oseth	69341	68.4
	Paga	239448	56.6
	Rare	813200	80.0
Overall	mean	432813	76.0
	stdev	616802	89.1
	min	1400	0.3
	max	2788172	388.1
	median	173465	58.5
Seasonal Cyanobacterial Counts and Biovolumes		**Cyanobacterial Count**	**Cyanobacterial Biovolume**
		cells/mL	*mm^3/L*
oct dry	mean	176,035	14.4
	stdev	197,870	21.8
	min	3,067	0.4
	max	643,860	61.8
	median	150,965	5.9
short rain	mean	193,753	167.5
	stdev	128,439	115.7

Mean Cyanobacterial Counts and Biovolumes		Cyanobacterial Count#	Cyanobacterial Biovolume#
		cells/mL	***mm^3/L***
	min	25,766	3.2
	max	400,096	388.1
	median	184,531	177.0
feb dry	mean	510,059	42.2
	stdev	431,476	31.7
	min	1,400	0.3
	max	1,236,921	85.5
	median	429,696	32.2
long rain	mean	1,008,378	81.3
	stdev	1,116,742	56.6
	min	5,133	5.1
	max	2,788,172	184.9
	median	619,378	89.4

#Values represent mean across four seasons or eleven community sites, respectively.

Table 4

Number of Samples Exceeding WHO Guideline and USEPA 10-day Health Advisory (2015) for Children for Each MC Congener

Type of Collection	Categories	MCLR	MCYR	MCLA	dmLR	MCRR	Sum MC
Near shore community surface water grab	Non-Detect	6	7	8	21	23	11
	Detect	37	36	35	22	20	32
	Exceeding 1 μg/L	2	3	1	2	3	12
	Exceeding 0.3 μg/L	13	11	4	5	4	26
Kisumu City water intake surface water grab	Non-Detect	1	1	3	3	4	0
	Detect	3	3	1	**1**	**0**	**4**
	Exceeding 1 μg/L	0	0	0	0	0	0
	Exceeding 0.3 μg/L	0	0	0	0	0	0

Table 5

Summaries of Key Informant Interviews with Elected Beach Management Units (BMU)[#]

Site	Alternate water source	Drinking water treatment	Management recommendations for lake water usage	Previous NGO or research projects	Identified challenges for water	Identified challenges to fisheries	Community needs
Asat	Borehole	None	No washing at the lakeshore. No Bathing in the lakeshore. Advice on water treatment & boiling.	Distribution of water tanks to schools, hospitals; distribution of water treatment (chemicals).	Bathing in lake. Washing in the lake. Inability to enforce rules.	Fishing in breeding areas. Use of illegal fishing gear. Absence of loans, capital. Lack of water security. Water hyacinth. Pollution and lack of enforcement. Overpopulation.	Boreholes. Community buy-in to rules. Security in lake. Regulation of fishing gear by government. Micro-loans and insurance Fishpond cultivation.
Rare	None	None	No washing at the lakeshore. Treatment of water. No washing of fish in lake. No swimming in lake because of crocodiles. No fishing while drunk. No passing of waste around lake. Use racks when drying fish.	Building of compostable latrines	Bathing in lake. Washing in lake. Inability to enforce rules. Diseases.	Use of illegal fishing gear. Water hyacinth. Pollution and lack of enforcement.	Micro-loans, funding cooperatives.
Nyamaruaka	None	AquaGuard chlorination-Sieving	No harvesting wood at the lakeshore. No washing in the lakeshore. Use of legal fishing gear.	Distribution of AquaGuard (chlorination) and education about water treatment	Cattle drinking in lake. Washing in lake. Cultivation near lake.	Overfishing. Poorly trained fisherman. Lack of capacity and enforcement. Poverty. Water hyacinth.	Piped water. Infrastructure for education. Capacity building.
Ogal	None	AquaGuard chlorination-Sieving	No swimming in the Lake. No washing in the Lake	HIV awareness education	Cattle herding in lake. Washing in lake. Inability to enforce rules. Diseases.	Overpopulation. Overexploitation of fishery. No reinvestment into lake. Water hyacinth and algal bloom. Uncontrolled cage culture	Capacity building on water quality. Assistance to dig boreholes. Ability to enforce fishing rules and regulations.

[#]In-depth interviews (IDIs) were conducted between July and October of 2016. Two to three members of the BMU were asked to discuss alternative sources of water, treatment options available, existing recommendations or guidelines for water usage, perceived water quality and challenges and community needs from outside partners.