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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.

Conflict of Interest: The authors declare they have no conflict of interest.

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 (Omweaga 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; Omweaga 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 ¹³C₆-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 (Beverdors et al. 2017; Beverdors 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.

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

Where MCs or MC equiv are in $\mu\text{g/L}$, L is the daily water ingestion rate in liters per day and b.w. is body weight in $\mu\text{g/kg}$. 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 $\mu\text{g/L}$ chlorophyll-*a*, 100,000 cyanobacterial cells/L, or 20 $\mu\text{g/L}$ MC in the top 4 m of the water column. High risk from 100-fold accumulation of scum is reached at 5,000 $\mu\text{g/L}$ chlorophyll *a* or 10,000,000 cells/L, with a very high risk from high winds sweeping cells to accumulate levels above 50,000 $\mu\text{g/L}$ 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 (WHO 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 $\mu\text{g/L}$) 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 μ S, max=184 .0 μ S), pH (min=7.1 to 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 μ N/L and 71.125 to 332.57 μ P/L, respectively. Chlorophyll ranged from 4.64 to 706.09 μ g/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 μ g/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 μ g/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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References

- APHA (American Public Health Association), AWWA (American Water Works Association), WEF (World Economic Forum) (2017) 9223 ENZYME SUBSTRATE COLIFORM TEST. In: Standard Methods For the Examination of Water and Wastewater, 23rd edn. 10.2105/SMWW.2882.194
- Bhateria R, Jain D. Water quality assessment of lake water: a review (2016). *Sustain. Water Resour. Manag.* 2: 161–173. doi:10.1007/s40899-015-0014-7
- Bain R, Cronk R, Wright J, Yang H, Slaymaker T, Bartram J (2014) Fecal contamination of drinking-water in low- and middle-income countries: A systematic review and meta-analysis. *PLoS Med* 11:e1001644. 10.1371/journal.pmed.1001644
- Beversdorf LJ, Rude K, Weirich CA, Bartlett SL, Seaman M, Kozik C, et al. (2018) Analysis of cyanobacterial metabolites in surface and raw drinking waters reveals more than microcystin. *Water Res* 140:280–290. 10.1016/j.watres.2018.04.032 [PubMed: 29729580]
- Beversdorf LJ, Weirich CA, Bartlett SL, Miller TR (2017) Variable cyanobacterial toxin and metabolite profiles across six eutrophic lakes of differing physiochemical characteristics. *Toxins (Basel)* 9(2): 62. 10.3390/toxins9020062
- Carlson RE (1977) A trophic index for lakes. *Limnology and Oceanography* 22(2): 361–369.
- Chen J, Xie P, Li L, Xu J (2009) First identification of the hepatotoxic microcystins in the serum of a chronically exposed human population together with indication of hepatocellular damage. *Toxicol Sci* 108:81–89. 10.1093/toxsci/kfp009 [PubMed: 19151163]
- Codd GA, Morrison LF, Metcalf JS (2005) Cyanobacterial toxins: Risk management for health protection. *Toxicol Appl Pharmacol* 203:264–272. 10.1016/j.taap.2004.02.016 [PubMed: 15737680]
- Corbel S, Mougín C, Bouaicha N (2014) Cyanobacterial toxins: Modes of actions, fate in aquatic and soil ecosystems, phytotoxicity and bioaccumulation in agricultural crops. *Chemosphere* 96:1–15. 10.1016/j.chemosphere.2013.07.056 [PubMed: 24012139]
- Faltermann S, Zucchi S, Kohler E, Blom JF, Pernthaler J, Fent K (2014) Molecular effects of the cyanobacterial toxin cyanopeptolin (cp1020) occurring in algal blooms: Global transcriptome analysis in zebrafish embryos. *Aquat Toxicol* 149:33–39. 10.1016/j.aquatox.2014.01.018 [PubMed: 24561424]
- FAO (Food and Agriculture Organization of the United Nations) (2014) The State of World Fisheries and Aquaculture 2014. Rome. pp. 223. <http://www.fao.org/3/a-i3720e.pdf>. Accessed 5 June 2018
- Fiorella KJ, Milner EM, Salmen CR, Hickey MD, Omollo DO, Odhiambo A, Mattah B, Bukusi EA, Fernald LCH, Brashares JS (2017) Human health alters the sustainability of fishing practices in East Africa. *Proc Natl Acad Sci U S A* 114:4171–4176. [PubMed: 28377522]
- Fiorella KJ, Seto K, Gavenus E, Milner EM, Omollo DO, Mattah B, Fernald LCH, Brashares J (2016) Examining local fish consumption in the globalized Lake Victoria fishery. *The FASEB Journal* 30(1): supplement. 10.1096/fasebj.30.1_supplement.894.4
- Ford L, Bharadwaj L, Mcleod L, Waldner C (2017) Human Health Risk Assessment Applied to Rural Populations Dependent on Unregulated Drinking Water Sources: A Scoping Review. *Int J Environ Res Public Health* 14(8): 846. doi: 10.3390/ijerph14080846
- Funari E, Testai E (2008) Human health risk assessment related to cyanotoxins exposure. *Crit Rev Toxicol* 38:97–125. 10.1080/10408440701749454 [PubMed: 18259982]
- Haande S, Thomas R, Semyalo RP, Brettum P, Edvardsen B, Lyche-Solheim A, Sorensen K, Larsson P (2011) Phytoplankton dynamics and cyanobacterial dominance in Murchison Bay of Lake Victoria (Uganda) in relation to environmental conditions. *Limnologica - Ecology and Management of Inland Waters* 41:20–29. 10.1016/j.limno.2010.04.001

- Hecky RE, Mugidde R, Ramlal PS, Talbot MR, Kling GW (2010) Multiple stressors cause rapid ecosystem change in Lake Victoria. *Freshwater Biology* 55: 19–42. 10.1111/j.1365-2427.2009.02374.x
- Herrie T, Plummer S, Roberson JA (2017) Occurrence and state approaches for addressing cyanotoxins in US drinking water. *American Water Works Association* 109:40–47. 10.5942/jawwa.2017.109.0022
- Hilborn ED, Beasley VR (2015) One health and cyanobacteria in freshwater systems: Animal illnesses and deaths are sentinel events for human health risks. *Toxins (Basel)* 7:1374–1395. 10.3390/toxins7041374 [PubMed: 25903764]
- Ibelings BW, Backer LC, Kardinaal WE, Chorus I (2015) Current approaches to cyanotoxin risk assessment and risk management around the globe. *Harmful Algae* 49:63–74. 10.1016/j.hal.2014.10.002 [PubMed: 26435706]
- Jonas A, Scholz S, Fetter E, Sychrova E, Novakova K, Ortmann J, Benisek M, Adamovsky O, Giesy JP, Hilscherova K (2015) Endocrine, teratogenic and neurotoxic effects of cyanobacteria detected by cellular in vitro and zebrafish embryos assays. *Chemosphere* 120:321–327. [PubMed: 25170595]
- Kenya HIV County Profiles 2016. Ministry of Health. National AIDS Control Council. 1–238. <https://nacc.or.ke/wp-content/uploads/2016/12/Kenya-HIV-County-Profiles-2016.pdf>. Accessed 01 June 2018
- Kundu R, Aura CM, Nyameweya C, Agembe S, Sitoki L, Lung'ayia H, Ongore C, Ogari Z, Werimo K (2017) Changes in pollution indicators in Lake Victoria, Kenya and their implications for lake and catchment management. *Lakes and Reservoirs: Research and Management* 22:199–214. 10.1111/lre.12187
- Kwena ZA, Bukusi E, Omondi E, Ng'ayo M, Holmes KK (2012) Transactional sex in the fishing communities along Lake Victoria, Kenya: A catalyst for the spread of HIV. *Afr J AIDS Res* 11:9–15. 10.2989/16085906.2012.671267 [PubMed: 25870893]
- Lenz KA, Miller TR, Ma H (2018) Anabaenopeptins and cyanopeptolins induce systemic toxicity effects in a model organism the nematode *Caenorhabditis elegans*. *Chemosphere* 214:60–69. [PubMed: 30253257]
- Li Y, Chen JA, Zhao Q, Pu C, Qiu Z, Zhang R, Shu W (2011) A cross-sectional investigation of chronic exposure to microcystin in relationship to childhood liver damage in the Three Gorges Reservoir region, China. *Environ Health Perspect* 119:1483–1488. 10.1289/ehp.1002412 [PubMed: 21561830]
- Li P, Feng W, Xue C, Tian R, Wang S (2017) Spatiotemporal variability of contaminants in lake water and their risks to human health: a case study of the Shahu Lake tourist area, northwest China. *Expo Health* 9(3):213–225. 10.1007/s12403-016-0237-3
- Liyanage HM, Arachchi DN, Abeyssekara T, Guneratne L (2016) Toxicology of freshwater cyanobacteria. *J Environ Sci Health C Environ Carcinog Ecotoxicol Rev* 34:137–168. 10.1080/10590501.2016.1193923 [PubMed: 27229761]
- Lung'ayia H, Sitoki L, Kenyanya M (2001) The nutrient enrichment of Lake Victoria (Kenyan waters). *Hydrobiologia* 458:75–82. 10.2478/v10102-009-0006-2
- Massey IY, Yang F, Ding Z, Yang S, Guo J, Tezi C, Alosman M, Kamegni RB, Zeng W (2018) Exposure routes and health effects of microcystins on animals and humans: A mini-review. *Toxicol* 151:156–162. 10.1016/j.toxicol.2018.07.010 [PubMed: 30003917]
- Mbonde A, Sitoki L, Kurmayer R (2015) Phytoplankton composition and microcystin concentrations in open and closed bays of Lake Victoria, Tanzania. *Aquatic ecosystem health & management* 18:212–220. 10.1080/14634988.2015.1011030 [PubMed: 28077928]
- Mello FD, Braidy N, Marcal H, Guillemin G, Nabavi SM, Neilan BA (2018) Mechanisms and effects posed by neurotoxic products of cyanobacteria/microbial eukaryotes/dinoflagellates in algae blooms: A review. *Neurotox Res* 33:153–167. 10.1007/s12640-017-9780-3 [PubMed: 28836116]
- Merel S, Villarin MC, Chung K, Snyder S (2013) Spatial and thematic distribution of research on cyanotoxins. *Toxicol* 76:118–131. 10.1016/j.toxicol.2013.09.008 [PubMed: 24055553]
- Minakawa N, Dida GO, Sonye GO, Futami K, Njenga SM (2012) Malaria vectors in Lake Victoria and adjacent habitats in Western Kenya. *PLoS One* 7:e32725. 10.1371/journal.pone.0032725

- Mowe M, Mirovic S, Lim RP, Furey A, Yeo D (2015) Tropical cyanobacterial blooms: A review of prevalence, problem taxa, toxins and influencing environmental factors. *J Limnol* 74:205–224. 10.4081/jlimnol.2014.1005
- Nagata JM, Fiorella KJ, Salmen CR, Hickey MD, Mattah B, Magerenge R, Milner E, Weiser SD, Bukusi EA, Cohen CR (2015) Around the table: Food insecurity, socioeconomic status, and instrumental social support among women living in a rural kenyan island community. *Ecol Food Nutr* 54:358–369. 10.1080/03670244.2014.995790 [PubMed: 25680030]
- Ngure FM, Reid BM, Humphrey JH, Mbuya MN, Peltó G, Stoltzfus RJ (2014) Water, sanitation, and hygiene (wash), environmental enteropathy, nutrition, and early child development: Making the links. *Ann N Y Acad Sci* 1308:118–128. 10.1111/nyas.12330 [PubMed: 24571214]
- Nyakairu GW, Nagawa CB, Mbabazi J (2010) Assessment of cyanobacteria toxins in freshwater fish: A case study of Murchison Bay (Lake Victoria) and Lake Mburo, Uganda. *Toxicon* 55:939–946. 10.1016/j.toxicon.2009.07.024 [PubMed: 19646467]
- Ofulla AV, Adoka SO, Anyona DN, Abuom PO, Karanja DM, Vulule JM, Okurut T, Matano A, Dida GO, Jembe T, Gichuki J (2013) Spatial distribution and habitat characterization of schistosomiasis host snails in lake and land habitats of WesternKenya. *Lakes and Reservoirs* 18:197–215. 10.1111/lre.12032
- Omweiga RN, Abila RO, Lwenya C. Fishing and poverty levels around Lake Victoria (Kenya). In: Odada E, Olago DO (eds.), vol. 2, pp. 193–199. In: Proceedings of the Proceedings of the 11th World Lakes Conference, 2006, Vol. 2, 193–199.
- Otieno FO, Ndivo R, Oswago S, Magerenge R (2015) Correlates of prevalent sexually transmitted infections among participants screened for an HIV incidence cohort study in Kisumu, Kenya. *International Journal of STD & AIDS* 26:225–237. 10.1177/0956462414532447 [PubMed: 24810218]
- Paerl HW (2018) Mitigating toxic planktonic cyanobacterial blooms in aquatic ecosystems facing increasing anthropogenic and climatic pressures. *Toxins (Basel)* 10(2). pii: E76. 10.3390/toxins10020076 [PubMed: 29419777]
- Pham TL, Utsumi M (2018) An overview of the accumulation of microcystins in aquatic ecosystems. *J Environ Manage* 213:520–529. 10.1016/j.jenvman.2018.01.077 [PubMed: 29472035]
- Poste AE, Hecky RE, Guildford SJ (2011) Evaluating microcystin exposure risk through fish consumption. *Environ Sci Technol* 45:5806–5811. 10.1021/es200285c [PubMed: 21671629]
- Qian H, Liu G, Lu T, Sun L (2018) Developmental neurotoxicity of microcystin aeruginosa in the early life stages of zebrafish. *Ecotoxicol Environ Saf* 151:35–41. 10.1016/j.ecoenv.2017.12.059 [PubMed: 29304416]
- R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.
- Rastogi RP, Madamwar D, Incharoensakdi A (2015) Bloom dynamics of cyanobacteria and their toxins: Environmental health impacts and mitigation strategies. *Front Microbiol* 6:1254. 10.3389/fmicb.2015.01254 [PubMed: 26635737]
- Roegner AF, Brena B, Gonzalez-Sapienza G, Puschner B (2014) Microcystins in potable surface waters: Toxic effects and removal strategies. *J Appl Toxicol* 34:441–457. 10.1002/jat.2920 [PubMed: 24038121]
- Simiyu BM, Oduor SO, Rohrlack T, Sitoki L, Kurmayer R (2018) Microcystin content in phytoplankton and in small fish from eutrophic Nyanza Gulf, Lake Victoria, Kenya. *Toxins (Basel)* 10. 10.3390/toxins10070275
- Sitoki L, Gikuchi J, Ezekiel C, Wanda F, Mkumbo O, Marshall B (2010) The environment of Lake Victoria (East Africa): Current status and historical changes. *International Review of Hydrobiology* 95:209–223. 10.1002/iroh.201011226
- Sitoki L, Kofler W, Rott E (2013) Planktonic needle-shaped Nitzschia species from Lake Victoria, Africa, revisited. *Diatom research* 28:165–174. 10.1080/0269249X.2013.765509
- Sitoki L, Kurmayer R, Rott E (2012) Spatial variation of phytoplankton composition, biovolume, and resulting microcystin concentrations in the Nyanza Gulf (Lake Victoria, Kenya). *Hydrobiologia* 691:109–122. 10.1007/s10750-012-1062-8 [PubMed: 24683268]

- Steffen MM, Davis TW, McKay RML, Bullerjahn GS, Krausfeldt LE, Stough JMA, Neitzey ML, Gilbert NE, Boyer GL, Johengen TH, Gossiaux DC, Burtner AM, Palladino D, Rowe MD, Dick GJ, Meyer KA, Levy S, Boone BE, Stumpf RP, Wynne TT, Zimba PV, Gutierrez D, Wilhelm SW (2017) Ecophysiological examination of the Lake Erie Microcystis bloom in 2014: Linkages between biology and the water supply shutdown of Toledo, OH. *Environ Sci Technol* 51:6745–6755. 10.1021/acs.est.7b00856 [PubMed: 28535339]
- Stough JMA, Tang X, Krausfeldt LE, Steffen MM, Gao G, Boyer GL, et al. (2017) Molecular prediction of lytic v.s. lysogenic states for Microcystis phage: Metatranscriptomic evidence of lysogeny during large bloom events. *PLoS One* 12:e0184146. 10.1371/journal.pone.0184146
- Svircev Z, Drobac D, Tokodi N, Mijovic B, Codd GA, Meriluoto J (2017) Toxicology of microcystins with reference to cases of human intoxications and epidemiological investigations of exposures to cyanobacteria and cyanotoxins. *Arch Toxicol* 91:621–650. [PubMed: 28042640]
- USEPA (2015) Drinking Water Health Advisory for the Cyanobacterial Microcystin Toxins EPA-820R15100 Washington, DC. Available: <https://www.epa.gov/sites/production/files/2017-06/documents/microcystins-report-2015.pdf>. Accessed 19.06.2016
- Valderrama JC (1981) The simultaneous analysis of total nitrogen and total phosphorus in natural waters. *Marine Chemistry*. 21: 109–122. 10.1016/0304-4203(81)90027-X
- Walls JT, Wyatt KH, Doll JC, Rubenstein EM, Rober AR (2018) Hot and toxic: Temperature regulates microcystin release from cyanobacteria. *Sci Total Environ* 610-611:786–795. 10.1016/j.scitotenv.2017.08.149
- Weirich CA, Miller TR (2014) Freshwater harmful algal blooms: Toxins and children’s health. *Curr Probl Pediatr Adolesc Health Care* 44:2–24. 10.1016/j.cppeds.2013.10.007 [PubMed: 24439026]
- Westrick JA, Szlag DC, Southwell BJ, Sinclair J (2010) A review of cyanobacteria and cyanotoxins removal/inactivation in drinking water treatment. *Anal Bioanal Chem* 397:1705–1714. [PubMed: 20502884]
- WHO (World Health Organization) (2003a) Emerging Issues in Water and Infectious Disease. France, 92 4 159082 3pp. 1–22 ISSN 1728–2160.
- WHO(2003b) Chapter 8: algae and cyanobacteria in fresh water. In: Guidelines for Safe Recreational Water Environments, Vol. 1: Coastal and Fresh Waters. World Health Organization, Geneva, Switzerland, 92 4 154580 1, pp. 1–219. www.who.int/water_sanitation_health/bathing/srwg1.pdf.
- WHO (2017) Chapter 12: Chemical fact sheets. In: Guidelines for Drinking-Water Quality: 4th Edn. Incorporating the First Addendum. Geneva, pp. 307–441. License: CCBY-NC-SA 3.0 IGO. Available: http://www.who.int/water_sanitation_health/publications/drinking-water-quality-guidelines-4-including-1st-addendum/en/
- Wu J, Xue C, Tian R, Wang S (2017) Lake water quality assessment: a case study of Shahu Lake in the semi-arid loess area of northwest China. *Environ Earth Sci* 76:232. 10.1007/s12665-017-6516-x
- Yoshida-Takashima Y, Yoshida M, Ogata H, Nagasaki K, Hiroishi S, Yoshida T (2012) Cyanophage infection in the bloom-forming cyanobacteria microcystis aeruginosa in surface freshwater. *Microbes Environ* 27:350–355. 10.1264/jsme2.ME12037 [PubMed: 23047146]

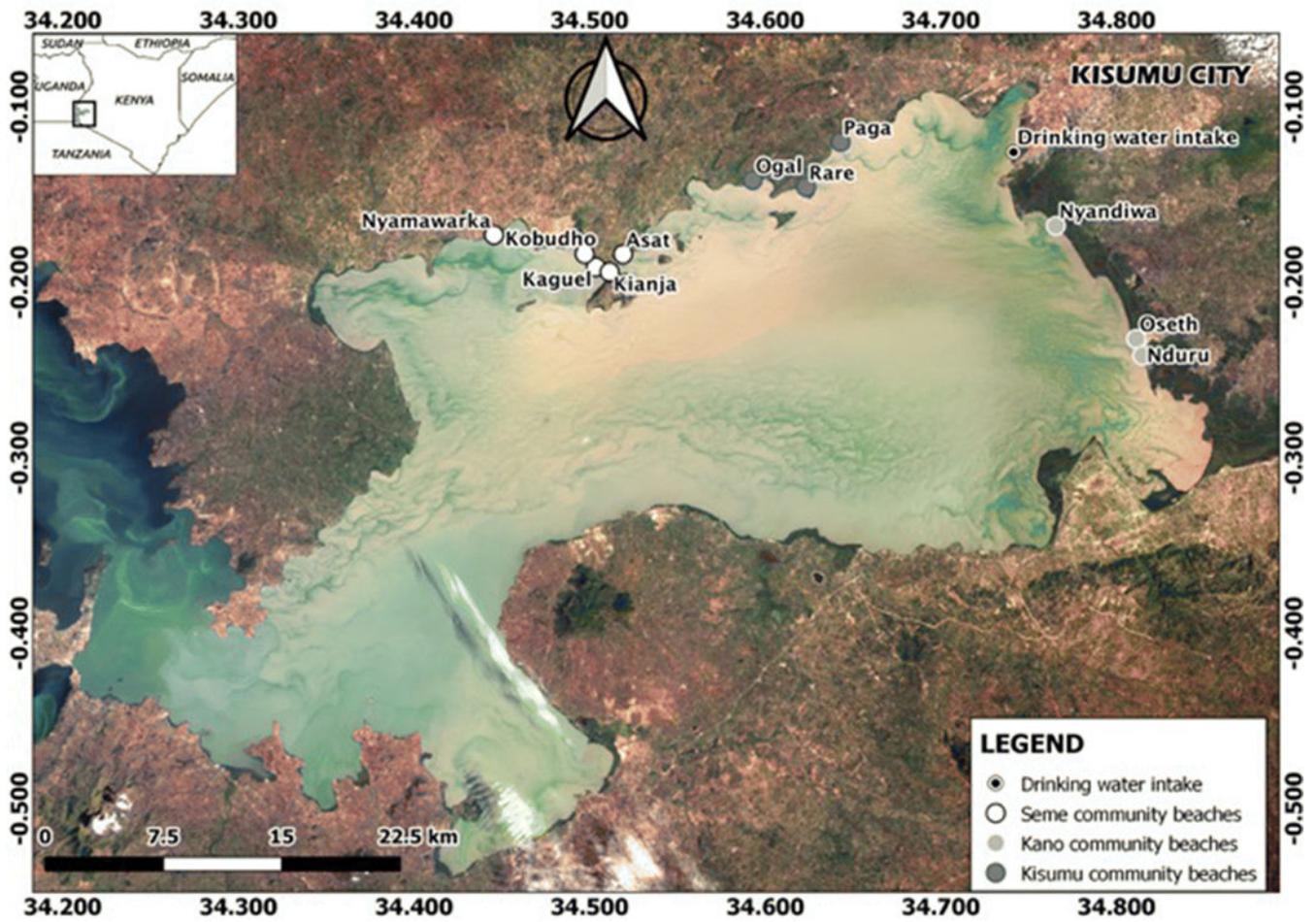


Fig. 1. Remote Sensing Image and Map of Winam Gulf and Study Sites.
 Image was downloaded from glovis.usgs.gov and a DOS1 atmospheric correction was performed in QGIS V3.0, with layering of stacked bands 2–7. Green depicts cyanobacterial blooms in absence of water hyacinth.

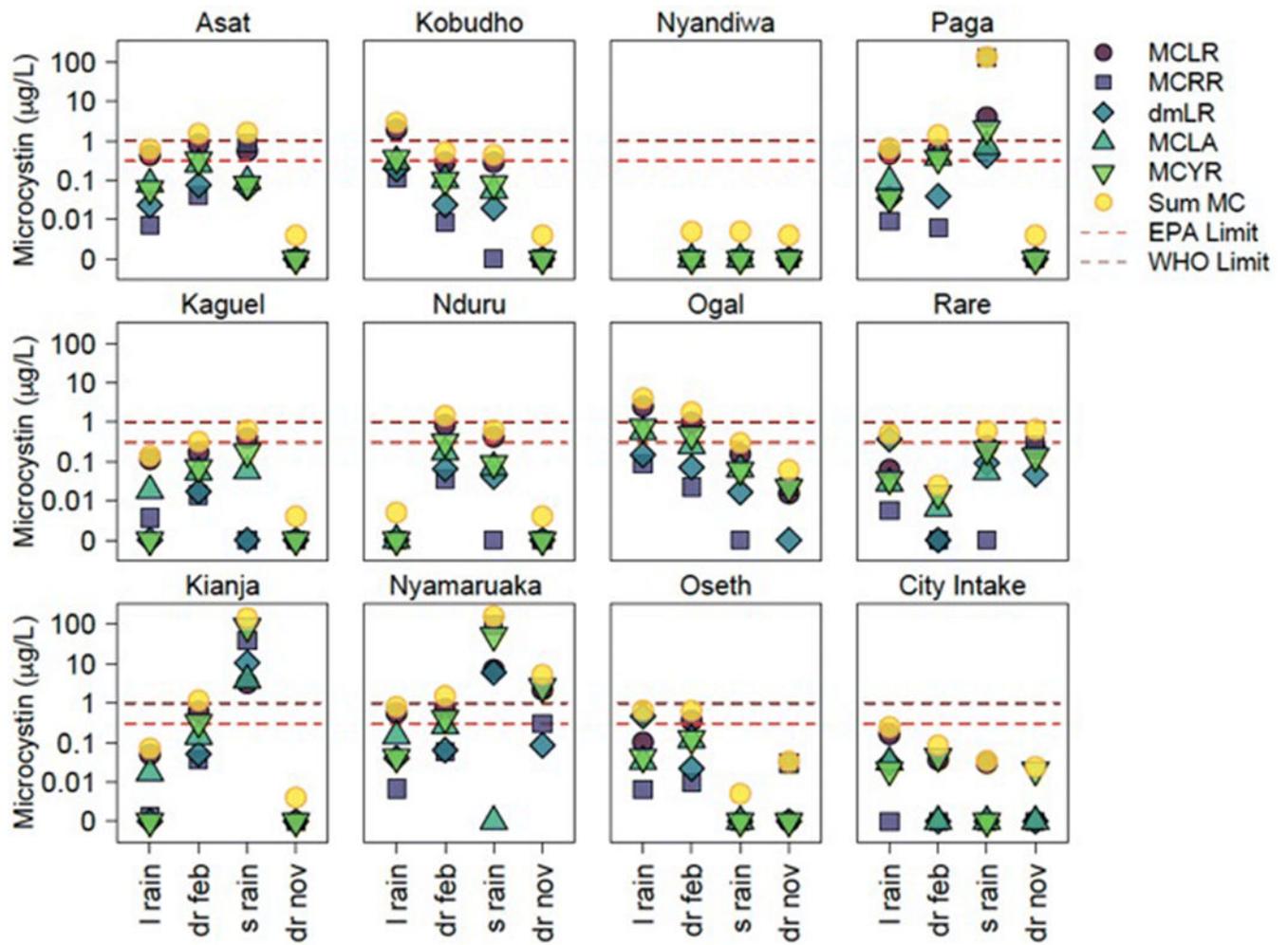


Fig. 2. MC Congener Concentrations Across Rainy and Dry Seasons at Fishing Village Drinking Water Source from Lake Victoria and at Kisumu City Intake.

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.

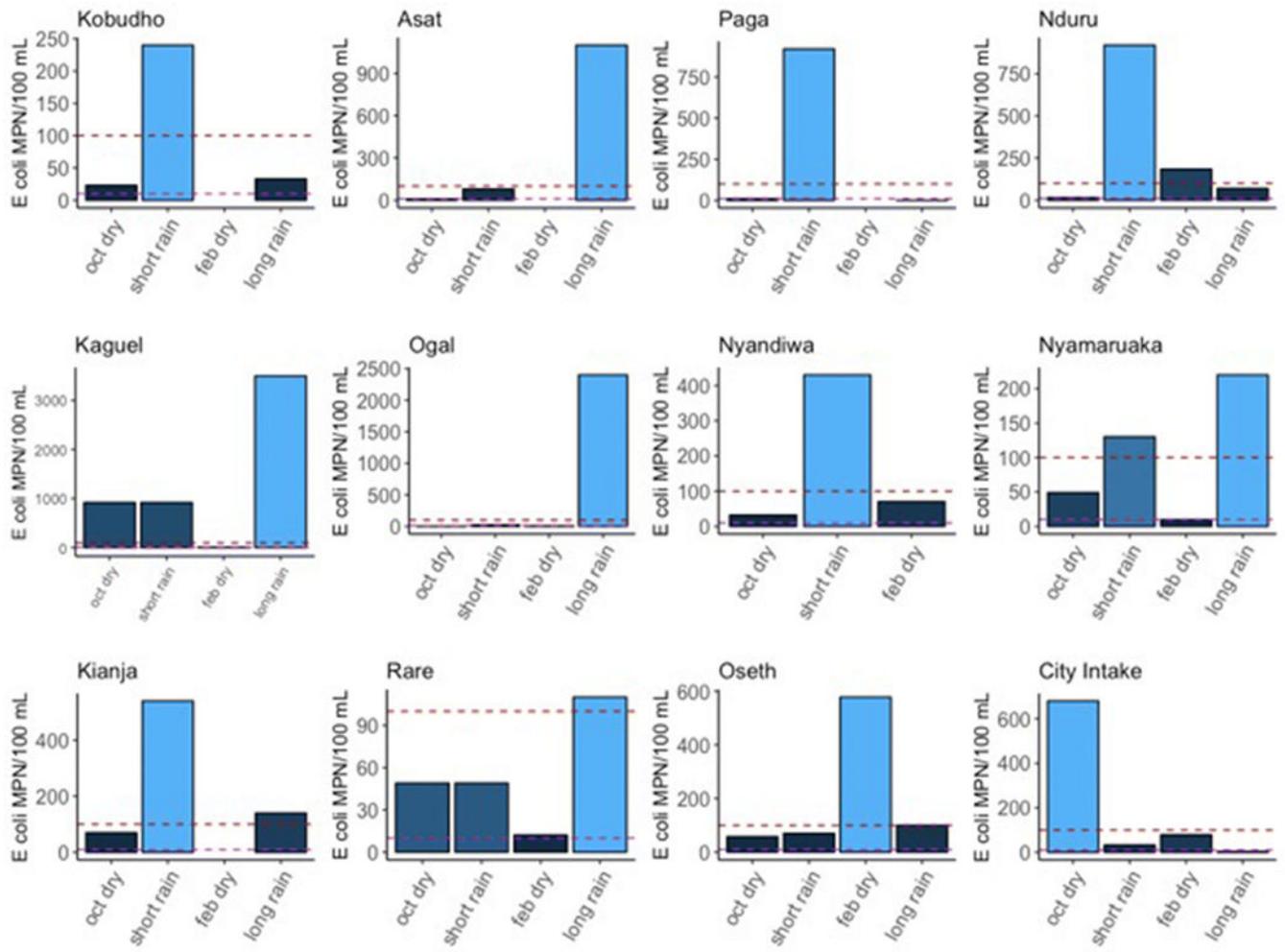


Fig. 3. *E. coli* Most Probable Number (MPN) per 100 ML Across Rainy and Dry Seasons at Fishing Village Drinking Water Source from Lake Victoria and at Kisumu City Intake.
 The dark red line indicates severe risk (100 MPN/100 mL) and the purple line moderate risk (10 MPN/100 mL) of adverse health effect. No levels are permissible for drinking water.

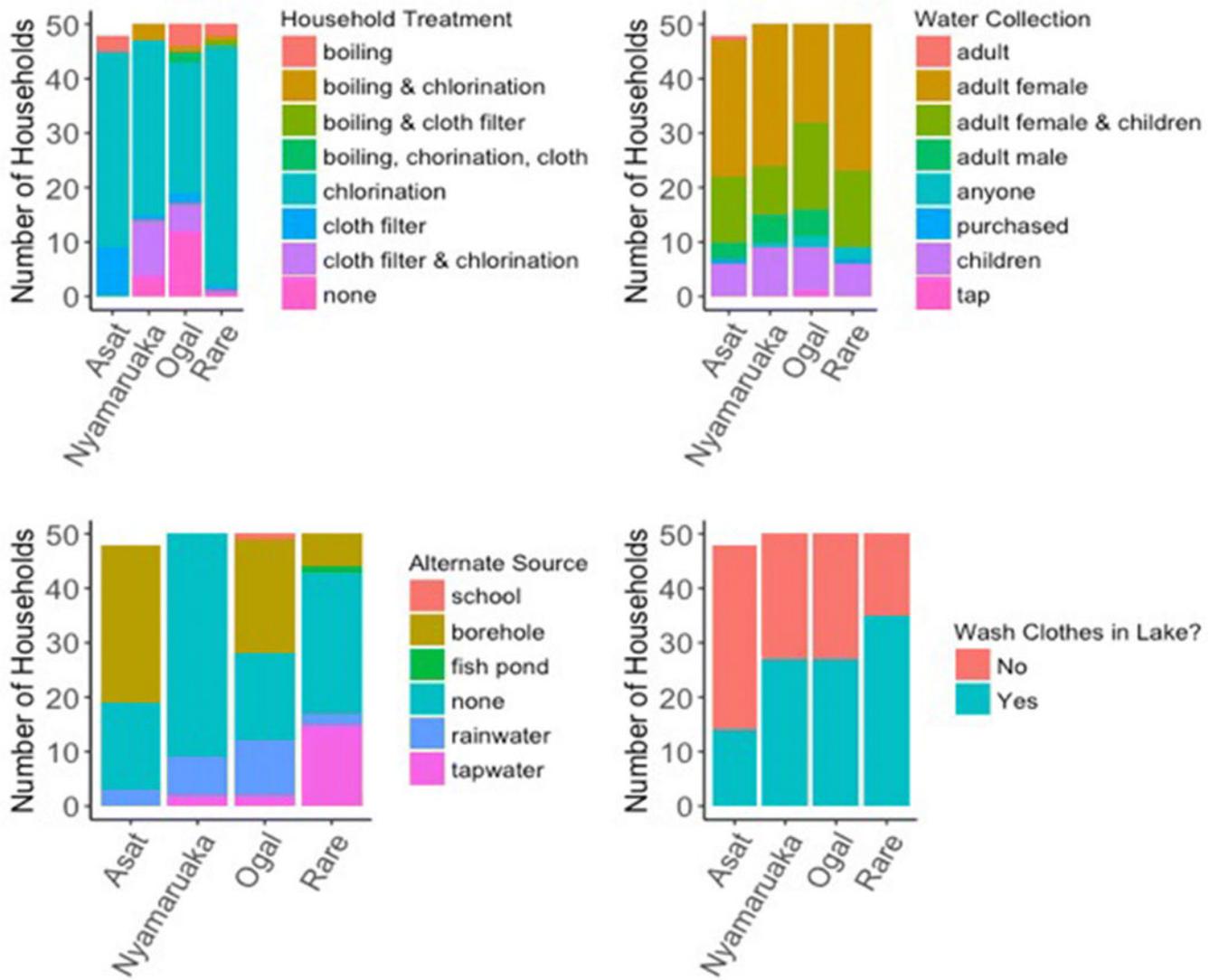


Fig. 4. Household Self-reported Water Usage Characteristics Across Representative Fisher Communities Impacted by CyanoHABs.

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

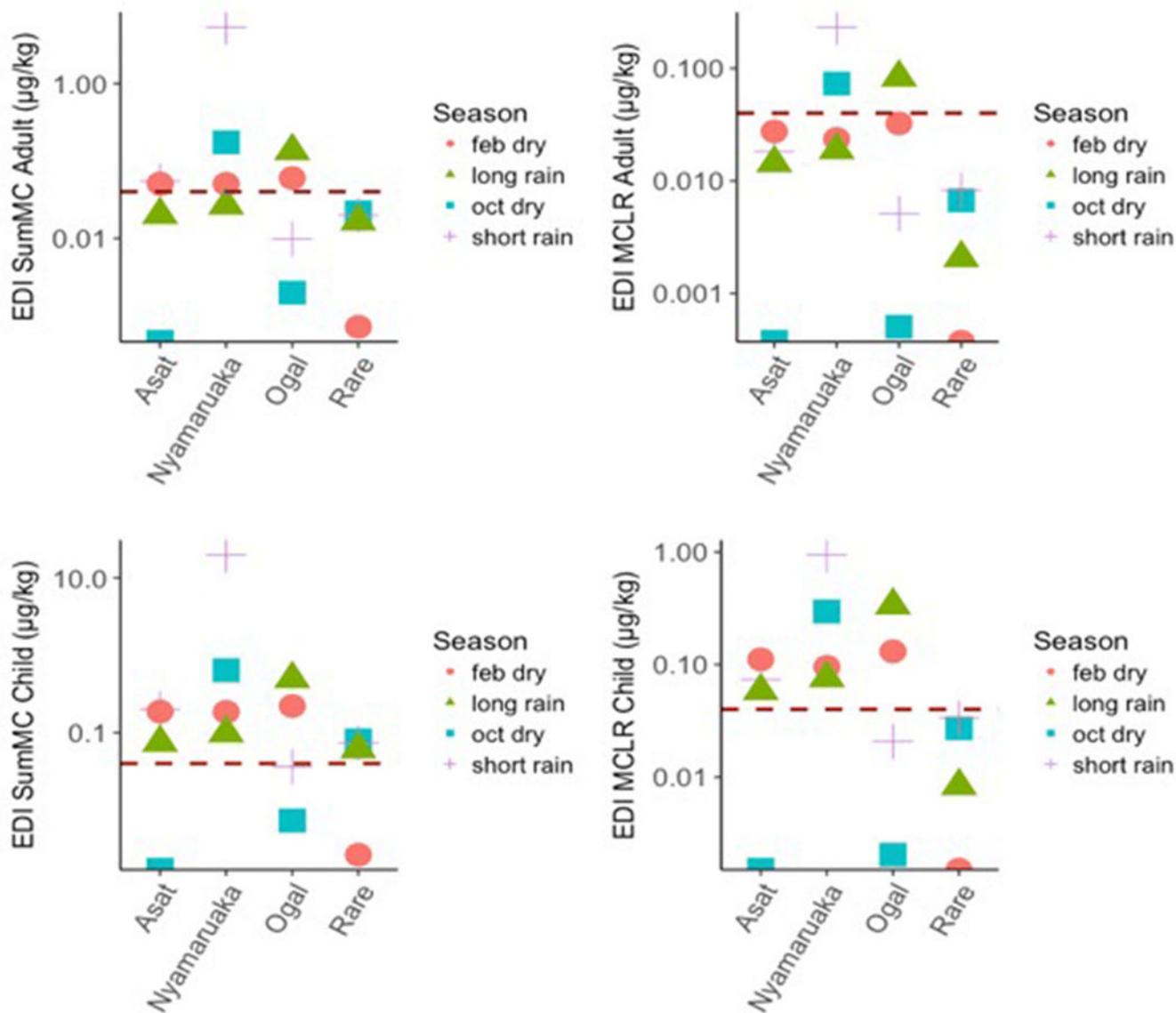


Fig. 5. Estimated Daily Intake of MCLR and Sum Total of MCs through Oral Ingestion of Water for Children and Adult.

Dashed lines represent TDI based on 0.4 $\mu\text{g}/\text{kg}$ for 60 kg adult and 0.1 $\mu\text{g}/\text{kg}$ 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 | <i>Seme Community Beaches</i> | -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 | <i>Kisumu Community Beaches</i> | -0.12000 | 34.64274 |
| Ogal | | -0.14175 | 34.59273 |
| Rare | | -0.14572 | 34.62312 |
| Oseth | <i>Kano Community Beaches</i> | -0.23207 | 34.81104 |
| Nduru | | -0.24159 | 34.81452 |
| Nyandiwa | | -0.16771 | 34.76533 |
| City Intake | <i>Municipal Drinking Water Intake</i> | -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 | |
| 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 |
| 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 |

^aTN, TP, SRP, and DO represent total nitrogen, total phosphate, soluble reactive phosphorus, and dissolved oxygen.

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

Table 3

| Mean Cyanobacterial Counts and Biovolumes | | Cyanobacterial Count# <i>cells/mL</i> | Cyanobacterial Biovolume# <i>mm³/L</i> |
|---|------------|--|--|
| 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 |
| Overall | Rare | 813200 | 80.0 |
| | 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 <i>cells/mL</i> | Cyanobacterial Biovolume <i>mm³/L</i> |
| 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 # |
|---|--------|------------------------|----------------------------|
| | | <i>cells/mL</i> | <i>mm³/L</i> |
| feb dry | min | 25,766 | 3.2 |
| | max | 400,096 | 388.1 |
| | median | 184,531 | 177.0 |
| | 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 |
| | mean | 1,008,378 | 81.3 |
| | stdev | 1,116,742 | 56.6 |
| long rain | min | 5,133 | 5.1 |
| | max | 2,788,172 | 184.9 |
| | median | 619,378 | 89.4 |
| | mean | | |

#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. |
| Nyamauaka | 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.