Pioneering water quality data on the Lake Victoria watershed: effects on human health

Tamie J. Jovanelly, Julie Johnson-Pynn, James Okot-Okumu,
Richard Nyenje and Emily Namaganda

ABSTRACT

Four forest reserves within 50 km of Kampala in Uganda act as a critical buffer to the Lake Victoria watershed and habitat for local populations. Over a 9-month period we capture a pioneering water quality data set that illustrates ecosystem health through the implementation of a water quality index (WQI). The WQI was calculated using field and laboratory data that reflect measured physical and chemical parameters (pH, dissolved oxygen, biological oxygen on demand, nitrates, phosphates, fecal coliform, and temperature turbidity). Overall, the WQI for the four forest reserves reflect poor to medium water quality. Results compared with US Environmental Protection Agency and World Health Organization drinking water standards indicate varying levels of contamination at most sites and all designated drinking water sources, with signatures of elevated nitrates, phosphates, and/or fecal coliforms. As critical health problems are known to arise with elevated exposure to contaminants in drinking water, this data set can be used to communicate necessary improvements within the watershed.

Key words | fecal coliform, Lake Victoria watershed, Uganda, water quality, WQI

Tamie J. Jovanelly (corresponding author)
Department of Geology,
Berry College,
2277 Martha Berry Hwy,
Mount Berry,
GA 30149, USA
E-mail: *tjovanelly@berry.edu*

Julie Johnson-Pynn
Department of Psychology,
Berry College,
2277 Martha Berry Hwy,
Mount Berry,
GA 30149, USA

James Okot-Okumu
Department of Environmental Management,
Makerere University,
Kampala, Uganda

Richard Nyenje
Department of Environmental Sciences,
Makerere University,
Kampala, Uganda

Emily Namaganda
Makerere University,
Kampala, Uganda

INTRODUCTION

In developing countries, scientific approaches to collecting, interpreting, and disseminating water quality data are scarce (Kaurish & Younos 2007). There is a significant need to establish a scientific basis for gauging the impact of development and human encroachment on the quality of the water within an ecosystem, as water quality is undoubtedly a significant indicator of public health risk (UNEPGEMS 2008). This is especially true in developing countries, where primary water sources for human drinking, cooking, and bathing cause ill effects through intentional and accidental ingestion of contaminated water (Hass *et al.* 1999; Steyn *et al.* 2004; Westrell *et al.* 2004; Schonning *et al.* 2007). Physical and chemical stressors on ground and surface water sources are exacerbated by flooding and droughts brought on by extreme weather conditions. Equatorial ecosystems have been notably vulnerable to climate change. For example, rates of malaria in East Africa have increased dramatically due to warming of water bodies (e.g. on the slopes of Mt Kilimanjaro) and cumulating bodies of stagnant water in urban centers with inadequate infrastructure. Rapid and unregulated development that has marked the urbanization of East Africa's city centers for over a decade has pushed the poor to slum settlements lacking waste management systems (e.g. use of plastic bags, or 'flying toilets'). A report by Uganda's Ministry of Water and Environment noted an average of 50–60 pupils per single latrine in primary schools (Uganda Ministry of Water & Environment Sector Report

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2011). Not surprisingly, poor sanitation has provoked cholera outbreaks.

Environmental degradation's effects on human health are attenuated by rapid population growth in Uganda, a country whose culture values large families. The doubling of Uganda's human population over the last 20 years has dramatically reduced the natural forest cover and disrupted watersheds, creating ecological islands surrounded by impoverished communities who depend on their natural resources for daily needs. Environmental threats, particularly in the Lake Victoria Basin, will intensify given the projected population of 50 million in the next 20 years. Intensifying pressure on forest land and products coupled with institutional weaknesses (e.g. limited management capacity and control) constrain sustainable development (USAID 2006; McDonald *et al.* 2011). Expanding industries such as fish farming and horticulture of exotic flowers further pollute and deplete water resources. Concerns about water quality, and implications for human health, will only be amplified (Mugisha 2002; Naughton-Treves & Chapman 2002; Baranga 2004; Worldwatch Institute 2014). Moreover, the degradation of Lake Victoria's ecological functions and water quality may have serious long-term consequences for the ecosystem and may threaten social welfare in the countries bordering its shores (Verschuren *et al.* 2002).

The current study

To date, there has been no systematic longitudinal monitoring of watershed health in Uganda's Lake Victoria basin because of the lack of laboratory analysis capacity, equipment, and material resources. The method we employed combined measurements of multiple parameters with minimal equipment to establish a water quality index, a straightforward indication of overall watershed health. This aligns with the World Health Organization's call for simple and accessible procedures for determining water quality. In this project, we determined water quality by comparing the physical and chemical characteristics of water bodies in four Ugandan forest reserves on the outskirts of Kampala, Uganda's capital city, with a water quality index (WQI) and standards set by both the US Environmental Protection Agency (USEPA) and the World Health Organization (WHO). Zika, Kitubulu, Mabira, and Mpanga forest reserves are an important contaminant catchment of the Lake Victoria watershed. Despite government designation as forest reserves, Jovanelly *et al.* (2012) documented alarming environmental degradation at each of the four forest reserves caused by human encroachment (e.g. unmonitored farming, logging, and mining). By combining parameters into a single rank value (poor, moderate, etc.), the WQI indicates changes in watershed health that can be easily communicated to forest communities adjacent to reserves. The WQI has not been used to communicate watershed health in Uganda but its use elsewhere has led to long-term water quality monitoring, notable improvements, and increased community involvement (BASIN 2008). Moreover, it can serve as a monitoring tool for conservationists and forest managers to guide decisions for protecting valuable forest resources.

METHODS

We describe the unique characteristics of the four forest reserves, as well as the parameters that make up the WQI, below. The data collection procedures and analyses are also presented.

Forest reserves

Two evergreen lowland rainforests (Zika Forest, 10 hectares; Kitubulu Forest, 80 hectares) lie on the northeast side of Entebbe Bay, south of Kampala City (Figure 1). These small

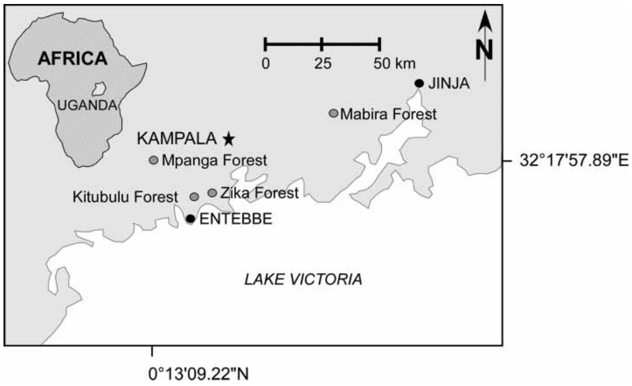

Figure 1 | Site map of the four forest reserves located near Uganda's capital city, Kampala (Jovanelly *et al.* 2012).

forest reserves are important remnants of the lowland forests adjacent to Lake Victoria, and filter water pollutants and silt that threaten the basin. Kampala City and its surroundings are home to 1.6 million residents (Uganda Bureau of Statistics 2011). The proximity of this many people to Zika and Kitubulu Forests strains the forests' natural resources and homesteads adjacent to the reserves. Despite the recent positive attention that Kitubulu Forest Reserve has had (e.g. the commemorative tree planting that involved delegates from the National Forest Authority and the Queen of the UK during the Commonwealth meeting in Uganda in 2007), sections of the lake shore have been sold to developers. A disturbing trend under Uganda's current government is to change land use regulations to accommodate the desires and short-term interests of private developers who often forego sustainable development practices for short-term gain (Obbo 2007). A prime example of this is the illegal extraction of clay, which is not only necessary for creating bricks that are highly sought-after owing to the surrounding construction demands, but is also crucial for curbing erosion on the lakeshore. Waste disposal, including that of hazardous chemicals from car washing car-washing bays (which are common on the Entebbe–Kampala road) and biomedical waste from neighboring clinics, has been documented for several years. These practices, however, have not been halted successfully, largely due to insufficient human resources to monitor Zika and Kitubulu Forest Reserves (Ssebuyira 2011; Johnson-Pynn *et al.* 2014). Residential community members do their best to assist the limited government staff; however, these forests are particularly vulnerable to encroachment.

Mabira Forest Reserve, a semi-deciduous forest with hills and valleys containing papyrus swamps, located east of Kampala, is the largest of the four forest reserves at 30,000 hectares (Figure 1). Although designated as a forest reserve since 1932, the Ugandan government and foreign developers have pushed plans to clear one-third of the land for a sugar cane plantation (Businge 2007). Mabira contains tributaries from discharge of the nearby Nile River and is also downstream from a sugarcane refinery that commonly disposes waste products in the river.

Mpanga Forest Reserve (453 hectares) protects an extensive patch of compact remnant tropical, moist evergreen, and swamp forest (Figure 1). Located west of Kampala, this forest reserve combines about 40 small adjoining reserves to form a corridor of forested land totaling some 25,100 hectares. The dominant tree species, *Celtis mildbraedii* and *Bosquilela phobero*, are intensely sought after by traditional drum makers in the nearby Mpambire village. Upon dedication as a forest reserve in 1953, researchers visiting Mpanga created a system of footpaths to promote accessibility to field sites. Unfortunately, these footpaths make for easy conduits for the removal of illegally felled trees and water from tapped springs.

Water quality index

Data for eight parameters, dissolved oxygen (DO), biochemical oxygen demand (BOD), pH, turbidity, nitrates, phosphates, fecal coliforms, and temperature, were used to calculate the WQI as specified under the National Sanitation Foundation guidelines (Brown *et al.* 1970; Mitchell & William 2000). WQI reflects the overall health of a water system by assigning weighted values to the parameters.

Water quality data were collected in each of the forest reserves by the research team once a month for a 9-month period (Figure 1). During each site visit, the researchers collected water samples. Some of the eight water quality parameters (pH, temperature, fecal coliforms, DO, BOD, nitrates, total phosphates, and turbidity) were measured on site using field instrumentation, while others were determined in the laboratory. A handheld Texas Instrument Nspire CX calculator was used with corresponding DO, pH, and turbidity probes that connected directly to the instrument allowing for immediate field sampling. All probes were calibrated prior to each field visit using the manufacturer's instructions. A portable LaMotte SMART 3 Colorimeter was used to measure nitrate and phosphorus at the field location. The instrument was calibrated for each parameter independently prior to use according to the instrument guidelines. Nitrates were determined using a zinc reduction method (code 3689-SC) and the phosphorus was established using the vanadomolybdophosphoric acid method (code 3655-SC). Temperature was measured on-site using a mercury thermometer.

At each sample site, water was collected in 250 mL Nalgene amber sample bottles and transported to the laboratory. The fecal coliform test was completed in the laboratory (usually within 4 hours of sample collection) using 3M Petrifilm Coliform Count Plates by inoculating 1 mL water sample according to the manufacturer's guidelines. The plates were incubated at room temperature for 24 hours. After 24 hours, the colonies on the slide were counted and recorded.

The remaining water samples was capped tightly and placed in a dark cabinet for 5 days and incubated at room temperature. The water sample were tested again after 5 days for DO using the TI-Nspire CX calculator and probe, and BOD was calculated.

After 9 months of continual monitoring, a baseline WQI (that represents seasonal variability) for each forest reserve was established.

RESULTS

WQI monthly averages for each of the four forest reserves are displayed in Figure 2(a)–(g); monthly averages of the nine WQI parameters measured are shown in Figure 3. Raw data used to calculate WQI are provided in the appendix (available online at http://www.iwaponline.com/jwh/013/001.xls).

Zika

The WQI at Zika Forest ranged between 55.79 and 70.27%. Of the 9 months, all fell in the medium range. DO ranged between 1.0 and 5.30 mg/L and was lowest during the month of February (1.5–1.8 mg/L). BOD ranged between 0.10 and 2.67 mg/L. Only one reading at Z5 in July recorded elevated levels of microorganisms degrading organic compounds in the water. For this reason, the majority of BOD values were ranked between 96 and 100%. The water acidity ranged between pH 5.10 and 6.40 resulting in WQI values for pH from below average (30%) percentages to 68%. The seeping groundwater temperature was 19–22 °C. Nitrates were found in some samples at Zika Forest (0–21 mg/L). Sites Z3 and Z5 often had elevated nitrates compared with sites Z1, Z2, and Z4. The lowest nitrates at all sample locations occurred in January. Phosphates ranged between 0 and 16 mg/L. July recorded the overall lowest levels of phosphates. Fecal coliform levels at Zika Forest produced WQI index values between 86 and 92%. None of the samples was devoid of fecal coliforms. The water from Zika Forest had turbidity as high as 115.80 nephelometric turbidity units (NTU), but the lowest documented turbidity was 6.13 NTU.

Kitubulu

The average WQI of Kitubulu Forest ranged between 43.54 and 61.88%, representing bad to medium water quality. Measured DO ranged between 2.7 and 7.13 mg/L. Elevated DO levels occurred in September (K1, 6.40 mg/L; K2, 7.13 mg/L) and April (K1, 5.00 mg/L; K2, 6.8 mg/L). Little change occurred between the initial and final BOD; all values reported are <1.0 mg/L. The pH ranged between 5.30 and 7.38. The highest nitrate concentration was 39 mg/L, while the lowest was 2.67 mg/L. Phosphate concentrations ranged between 3 and 49 mg/L. Fecal coliform concentrations of 220 colonies/100 mL were detected every month. Turbidity was also elevated (26.97–219.67 NTU).

Mabira

The average WQI at Mabira Forest was good to medium (60.43–73.20%). Measured DO ranged from 4.0 to 6.10 mg/L at all sites except Ma4, which showed much lower DO levels (0.9–2.60 mg/L). Changes in BOD at Mabira Forest ranged between 0 and 1.3 mg/L. The pH was within 5.68–7.69. Elevated nitrates, phosphates, and fecal coliforms were only detected at Ma4.

Mpanga

The average WQI at Mpanga Forest ranged between 55.61 and 68.85%, a medium classification. DO ranged between 1.2 and 6.60 mg/L. The DO concentrations were higher in April at all sample sites (see appendix). Some microbial activity was recorded by measuring BOD (0.0–1.23 mg/L); however, the majority of the values were below 1. The lowest pH measured (5.37) signified some acidity; however the majority of the samples were between a normal range of pH 6.0 and 6.60. Elevated nitrate (3–21 mg/L) and phosphate (1–33 mg/L) concentrations were found at all sampled locations during November; generally, Mp1 and Mp2 had the highest concentrations of nitrates and phosphates. The highest fecal coliform levels were found at Mp1 (ranging

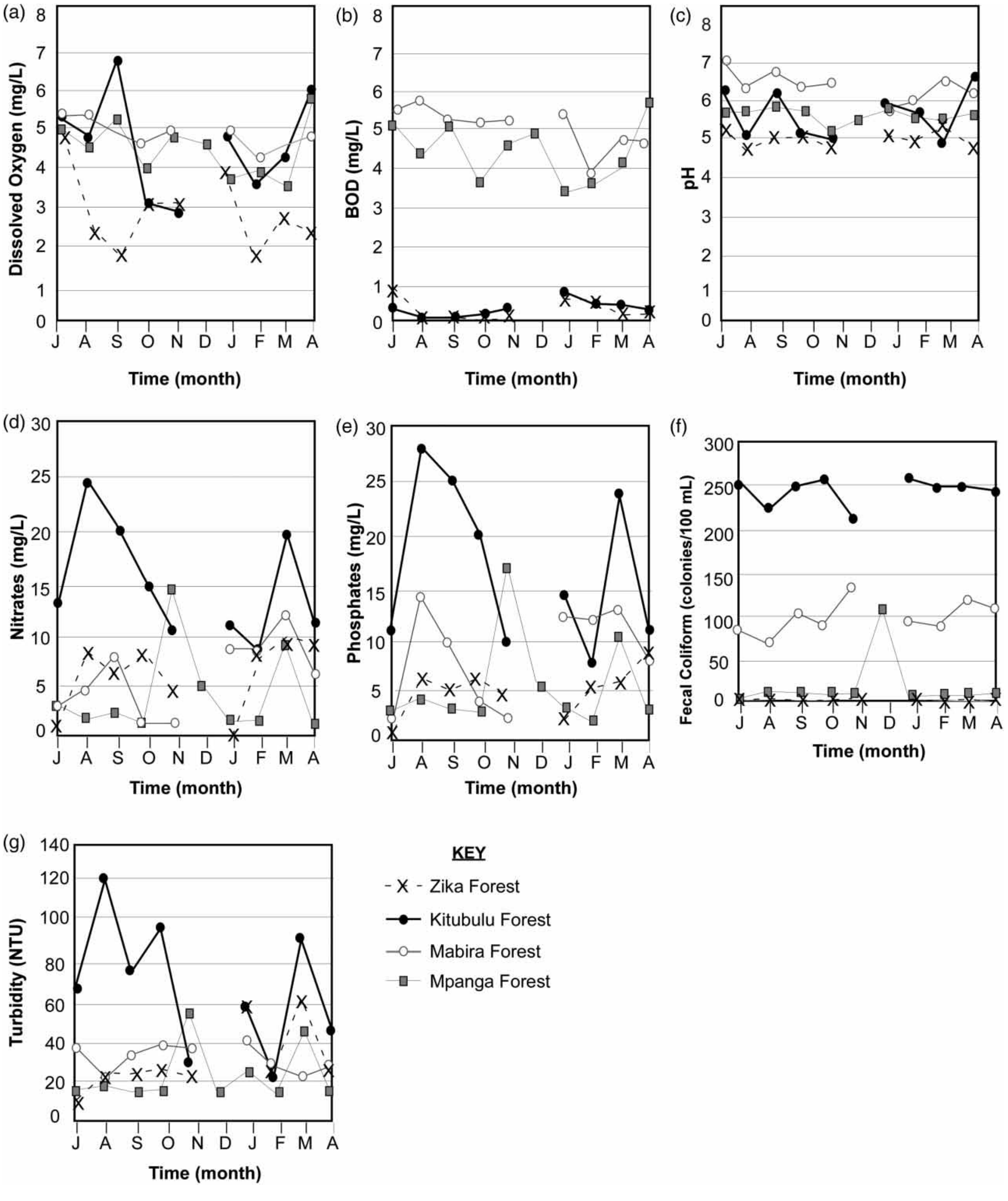

Figure 2 | Monthly averages for water quality parameters measured at each forest reserve.

from 20 to 50 colonies/100 mL). The water at Mpanga had elevated turbidity at all five sites each month.

A comparison of the USEPA and WHO minimum standards for drinking water (Table 1) to water quality variables measured at each forest reserve was carried out (Figure 2(a)–(g)). The minimum drinking water values listed in Table 1 were used to carried out a minimum WQI for the USEPA and WHO of 92 and 94%, respectively. Elevated levels of nitrates, phosphates, fecal coliforms, and turbidity were documented at Kitubulu Forest (Figure 2). Two sites at

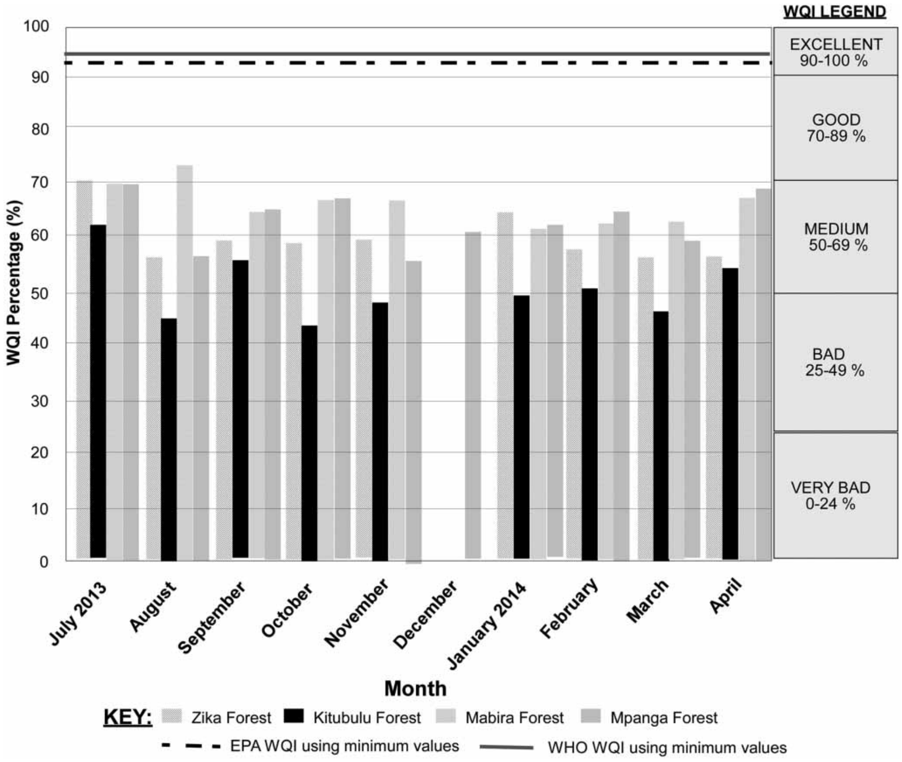

Figure 3 | Average monthly water quality indices for four forest reserves compared with the USEPA and WHO WQI calculated using minimum values from Table 1.

Table 1 | A comparison chart of USEPA and WHO drinking water standards for the parameters used in this study (USEPA 2010; WHO 2011)

Optimal drinking water standards

Chemical parameter	EPA (mg/L)	WHO (mg/L)
Nitrate (NO_3)	0.01–3.0	0.01–5.0
Phosphate (PO_4)	<0.1	0.1
Physical parameter	EPA (mg/L)	WHO (mg/L)
pH	6.5–8.5	6.5–8.0
DO	4.0–9.0	6.0–8.0
Turbidity (NTU)	<52	5
BOD	<1	<1
Temperature	None	None
Total suspended solids	<30	None
Microbiological parameter	EPA (cfu/100 mL)	WHO (cfu/100 mL)
Escherichia coli count	<1	<1

Mabira Forest (Ma1 and Ma2) met both the USEPA and WHO minimum drinking water standards more than other locations monitored in this study (Figure 4). Of the 9 months sampled at Mpanga Forest, the USEPA and WHO minimum standards for phosphate were met once in October at Site Mp2 (Figure 4(d)). USEPA and WHO minimum standards for fecal coliforms were never met at Mpanga Forest.

DISCUSSION

Each of the four forest reserves had unique hydrological settings making strict comparisons of WQI impossible. However, an individual comparison of each system to USEPA and WHO drinking water standards helps to guide the discussion about human health concerns and solutions.

Of all the forest reserves investigated, Zika Forest consistently had the lowest levels of DO (1.4–5.3 mg/L) and the lowest levels compared with all monthly averages. This resulted in few instances that met the minimum USEPA and WHO drinking water standards. Likely, this is the result of measuring water from ground water seeps in low-lying raffia palm swamp environments, as it was the only source available. Higher concentrations of DO ($\leq$4.0 mg/L) always correlated

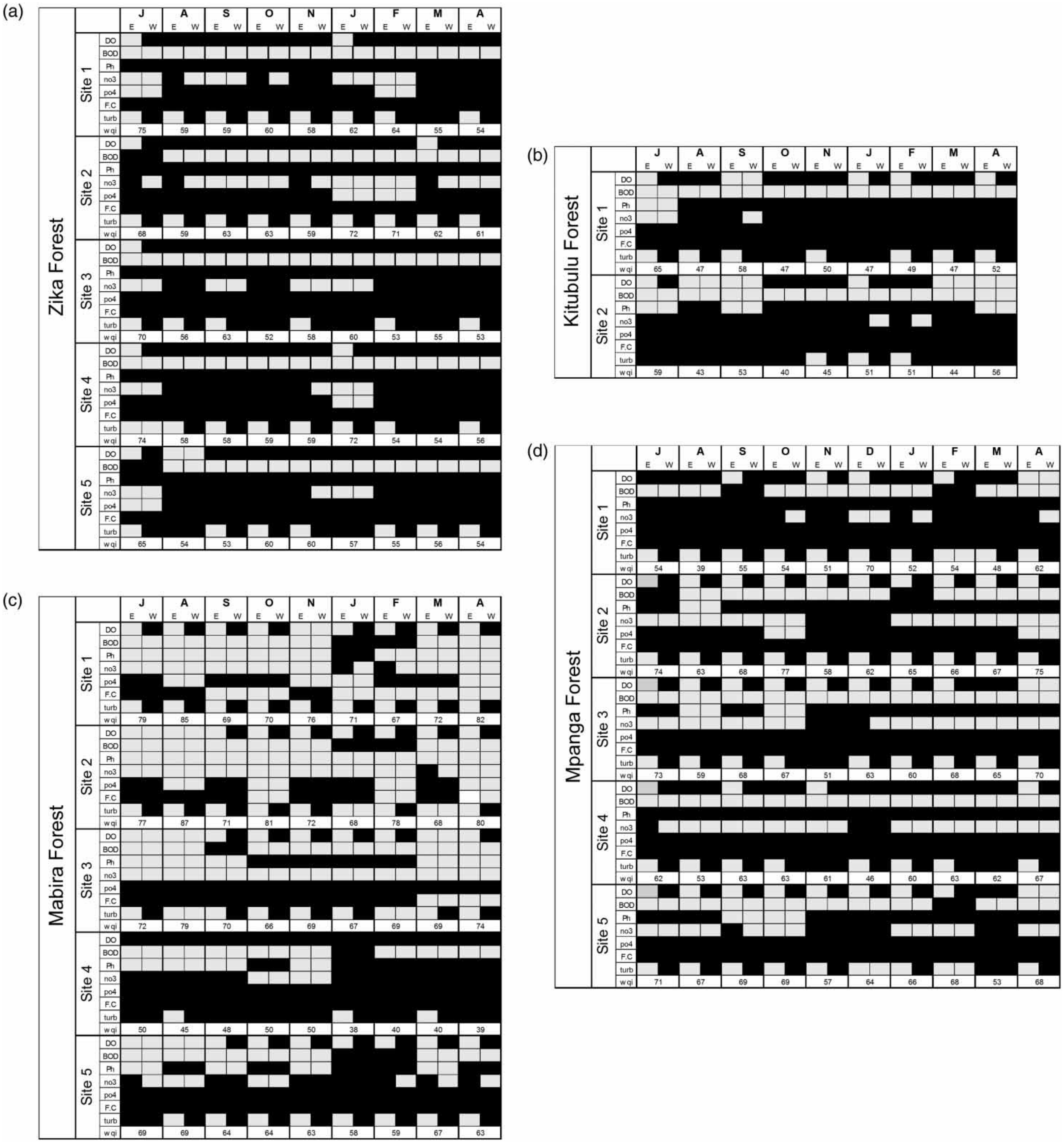

Figure 4 | A comparison of the USEPA and WHO minimum standards for each forest reserve by month starting in July. The black box indicates that the parameter did not meet minimum standards listed in Table 1; the grey box indicates that it did.

with rainfall events due to the mixing of surface water from previous or concurrent rainfall events (e.g. October, November). If those instances are eliminated from the analysis, the average monthly WQI ranged between 65.55 and 77.21%. The WQI, however, still maintained the same medium classification. Other signatures that negatively influenced the average monthly WQI at Zika Forest were the pH, nitrate, and phosphate levels (Figure 2(c)–(e)). The plausible source of nitrate and acidity was the natural decay of dense forest cover settling near the sampling sites. Dryer months (July/August and September/November) with slower organic decay rates had lower nitrates and often met USEPA minimum standards for drinking water (Figure 2(a)). The high phosphate concentrations may be linked to several environmental factors. When some plants decay, phosphorus is returned to open water as soluble inorganic phosphates (Horne & Goldman 1994). Furthermore, nearby forest fires may have mobilized phosphates into sediment entering the system. The high phosphate concentrations (>0.05 mg/L) could also lead to eutrophication, resulting in low DO (Muller & Helsel 1999). Human action may have spurred high turbidity (<10 NTU) levels recorded at Zika Forest (excluding site Ma4). During the entire study, one acre of land immediately adjacent to the main entrance of Zika Forest was being developed for new homesteads. Construction stopped approximately 500 m from the forest boundary. Obvious runoff into the forest from local sand used as matrix building material was documented at each site visit. Moreover, 10 acres of swampland adjacent to the southern boundary of Zika Forest continued to smolder throughout our study. Ash runoff into the forest was also documented at each site visit.

The environment of Kitubulu Forest is quite different from the other reserves for two reasons. Kitubulu Forest boundary ends at the Lake Victoria shoreline. Secondly, although larger than nearby Zika Forest, the resources at Kitubulu Forest have been exploited extensively by the local population of inhabitants for fire wood, sand mining, bathing, livestock watering, and drinking water. Site K1, a small tributary that filters directly into Lake Victoria, is a spot from where the local population collects drinking water. Site K2 was previously used as a fish pond. These two were the only open water sources within the 80 hectare area. Kitubulu Forest experienced the worst water quality of all forest reserves investigated in this study (44.72–62.75%). Its water quality was classified as medium to bad (Figure 3). Its temperature, nitrate, phosphate, and fecal coliform levels were the highest of all forest reserves, except Ma4 (Figure 2(d)–(f)). Elevated nitrates at K1 and K2 were most likely due to the runoff of agriculture waste, as both sites were downstream of farms. Phosphates may be from multiple sources including, agricultural fertilizer, livestock manure, and laundry detergents. Fecal coliform was evidently from human and livestock excrement adjacent to the creek. Ultimately, all three of these parameters can lead to anoxic conditions resulting in low DO. Moreover, the stagnant water conditions with localized deforestation contributed to elevated water temperatures, which in turn decreased the DO in the water column.

Mabira Forest was the largest forest reserve in this study and was continually threatened by surrounding large-scale sugarcane industries, who requested more land for expansion. Mabira Forest had the best WQI recorded during the month of August (73.20%; classification good). However, Ma4 was a notably contaminated site for various reasons. Increased accessibility due to the clearing of dense forest near the stream made this site a prime spot for local drinking water collection and livestock watering. The effluent discharged from an upstream sugarcane manufacturing company led to water temperatures of 23–27 °C, nitrate concentrations of 8–45 mg/L, and phosphate concentrations between 10 and 57 mg/L. Farming activity also likely contributed to the pollution. Moreover, livestock watering contributed to the high fecal coliform levels. The other sites at Mabira Forest (Ma1, Ma2, Ma3, Ma5) had lower levels of all measured parameters. Site Ma4 is atypical, and if it is discarded, the average monthly WQI for Mabira Forest improved by 3.81–7.10% (Figure 4(c)) with over half (5/9 months) registering good-quality water. When the mean monthly average of each parameter is compared with the other three forest reserves, the measured values are similar. In the dry season of January and February, however, BOD spiked, pH decreased, and nitrate and phosphate concentrations peaked. The elevated concentrations may indicate a concentration effect resulting from less dilution.

The water quality at Mpanga Forest was classified as medium for all 9 months (Figure 3). The average monthly data for each parameter often fell closely in line with the other forests (Figure 2). BOD is an anomaly in the dry season of January and February at Mpanga Forest, as well as a decrease in pH, temperature, and an increase in nitrates and phosphates (Figure 2(b)–(e)). Site Mp1 is of particular concern as it is a popular drinking water collection and bathing site for the local population. Mp1 is the most contaminated of the five sites investigated in Mpanga. Nitrates (4–28 mg/L), phosphates (5.55–31), and fecal coliform (20–33 mg/L) levels at Mp1 were always the highest. The overuse and multiple use of the water source by the local population accounted for the fecal coliform and phosphate contamination. Nitrates likely resulted from organic decay in stagnant water upstream.

The commonality between the four forest reserves is their proximity within the Lake Victoria watershed to the large urban city centers of Kampala, Entebbe, and Jinja (populations: 1,659,600; 79,700; and 89,700, respectively) (Uganda Bureau of Statistics 2011). As each of the forest reserves differ markedly in hydrology and ecology, it is difficult to make equitable comparisons. Data collected in this study, however, outline similar challenges that impede water quality assessment in the last remaining virgin forested lands in south-central Uganda. In the current study, the data indicate that each forest reserve has at least one site with particularly depleted water quality. In the smaller forest reserves of Zika and Kitubulu this is particularly alarming since the land area is interconnected by groundwater, and thus directly contributes surface water runoff to Lake Victoria. The largest forest in this study, Mabira Forest, had the worst water quality of all 17 sites (Ma4). This is alarming, as this tributary leads directly to the source of the Nile River in Jinja.

Ultimately, each of the forest reserves shares similar stressors in conservation of water. Mainly, the demand on resources continues to increase as the population of Uganda continues to grow at 3.3% per year (Uganda Bureau of Statistics 2011). With one of the highest growth rates in the world (Worldwatch Institute 2014), increases in human population intensify the demand on urban and rural areas, resulting in the need for more agriculture in regions that have increased per capita demand for land (Kairu 2001). Hence, more land, including wetlands and forests, is cleared to create the additional space required for these sectors (Kairu 2001; Gichuki 2003). Environmental degradation at each of the four forest reserves was noted by Jovanelly *et al.* (2012) and further documented during this study with the loss of acreage at every forest reserve (Lugumya, personal communication). The human challenges facing these reserves include illegal sand and clay mining, deforestation, homesteading, laundering, livestock watering, and other misuse induced by densely populated rural villages.

As in other developing countries, open water sources are often accessed for drinking. In the water samples collected from forest reserves in the Lake Victoria Basin, most did not meet the minimum drinking water standards set by the USEPA or WHO. In fact, only Mabira Forest sites Ma1 and Ma2 met all of USEPA drinking water standards, but only in the month of April. Of immediate concern are the sites known to be designated as drinking water collection sites for the local population, which show the highest levels of contamination (Ma4, Mp1, and K2) with regards to nitrates, phosphates, fecal coliforms, and turbidity.

Critical health problems are known to arise with elevated exposure to contaminants in drinking water. Nitrate exposure to infants below 6 months of age can lead to methemoglobinemia (blue baby syndrome) and shortness of breath, both of which can be fatal (Super *et al.* 1981; WHO 1998). Methemoglobinemia is caused by the decreased ability of blood to carry vital oxygen to the body. Malnutrition and infection increase the risk of this and other diseases (McDonald & Kay 1988). Although elevated phosphates alone pose no health risk, too much phosphate will cause algal blooms and deplete DO needed for fish and other aquatic organisms (Gray 2008). Likewise, elevated fecal coliform levels are not a direct health concern. However, if these organisms are detected, other organisms causing giardiasis, cholera, and cryptosporidiosis are likely.

CONCLUSION

Lacking infrastructure and inadequate water treatment methods, Ugandans using the forest reserves in the Lake Victoria Basin are left with limited options for drinking water, as it is contaminated when compared with the drinking water standards set by either the USEPA or WHO. Working to obtain minimum drinking standards should become a high priority of local governments and their constituents. Maintaining the health of the forest reserves is not only a conservation objective, but also an environmental social justice concern. The establishment of a simple and accessible long-term water quality monitoring system is a logical and feasible step to track the effectiveness of government and non-governmental policies. It would also provide for interventions aimed at increasing water safety and security in the Lake Victoria Basin.

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