Cyanobacterial blooms and the presence of cyanotoxins in small high altitude tropical headwater reservoirs in Kenya

Francis Mwaura, Anderson O. Koyo and Ben Zech

ABSTRACT

The phytoplankton community in three small (0.065–0.249 km^2) reservoirs in the stepped plateau landscape in the Kinangop area above the Rift Valley floor in Kenya were studied between 1998 and 2000. Approximately 70 species of phytoplankton were identified. The community was dominated by chlorophytes, cyanobacteria and chrysophytes. Diatoms were rare. The phytoplankton assemblage was frequently dominated by cyanobacteria in the dry season. The phytoplankton assemblage transformed to a mixture of cyanobacteria, chlorophytes and chrysophytes at the onset of the long rains, and mixture of cyanobacteria and chlorophytes after the long rains. Thereafter the phytoplankton assemblage consisted mainly of a mix of cyanobacteria and chrysophytes until the onset of the short rains when cyanobacterial dominance re-emerged. The most common phytoplankton species included *Microcystis* spp., *Botryococcus braunii*, *Ceratium hirundinella*, *Anabaena* spp. and *Euglena viridis*. The dry season cyanobacterial blooms produced cyanotoxins that included microcystin and endotoxins. The concentrations were well above the recommended safe limits for drinking water. The patterns of cyanotoxin production showed that the growth of the toxin-producing cyanobacteria was regulated by water temperature, pH and nutrients. The appearance of cyanotoxins in the small reservoirs is a serious public health issue in rural Kenya because such reservoirs are key sources of water for humans, livestock and wildlife.

Key words | algal blooms, cyanobacteria, cyanotoxins, endotoxins, eutrophication, microcystin, public health

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INTRODUCTION

Despite their widespread distribution, our limnological knowledge of small reservoirs is limited, particularly in Africa (ICOLD 1998). The lack of information reflects a historical bias by scientists towards studying the riverine and lake ecosystems (ICSU-SCOPE 1972). Reliable information on, for example, the status of essential nutrients or the presence of potentially harmful algal species is critical for holistic and integrated management of aquatic ecosystems (Naiman & Decamps 1990; Harper 1992). One of the critical environmental problems facing the management of reservoirs worldwide is the regular occurrence of algal blooms as a result of progressive nutrient build-up.

The occurrence of algal blooms and biotoxins has mostly been related to lakes and reservoirs in low-lying, highly populated and often urbanised environments (Annadotter *et al.* 1999). Such events are rare in highland and mountain areas except in cases of severe environmental degradation. Algal blooms usually occur because of the progressive eutrophication of water bodies. As a result of heavy nutrient leakage into the waterways, eutrophication is becoming a common problem in the high population density areas in the tropics. When nitrogen and phosphorus are increased, eutrophication within the system increases and primary production is accelerated (Harper 1992). When a severe state of eutrophication is reached, primary production can exceed the rate of consumption by zooplankton, fish and invertebrates. This leads to the accumulation of organic matter, first as planktonic algal blooms and, thereafter, as oxygen-consuming detritus.

Eutrophication normally stimulates excessive growth of algae in a phenomenon referred to as ‘algal blooming’. The ensuing competition ultimately results in sudden death or ‘algal crash’. The decomposition of the dead organic matter generated from such death uses a lot of dissolved oxygen, which can trigger temporary de-oxygenation and culminate in the death of aquatic organisms including fish. Caraco (1995) reported that greatly increased production of phytoplankton can cause severe alterations of aquatic systems. Some of the common consequences are: (i) decreases in water clarity, (ii) increase of anoxia, (iii) extensive toxic algal growth, and (iv) loss of some benthic life-forms and fish (Harper 1992).

During blooms, phytoplankton composition is narrowed by the dominance of cyanobacteria while the biomass is usually very close to carrying capacity and insufficient light and nutrient supply temporarily limit any further growth. In Lake Mjosa, Norway, for example, studies have revealed a successional sequence from *Oscillatoria agardhii* to *Anabaena flos-aquae* under the influence of cultural eutrophication (Holtan 1979, cited in Tilman *et al.* 1982). In South Africa, Thornton (1986) recorded a similar presence of *Anabaena* in Rietvlei Dam.

Cyanobacteria, which are a natural component of many inland waters, can undergo sudden exponential growth, if the hydrologic, physico-chemical and biological conditions are favourable. Such blooms are typified by the water turning very green and having thick surface slicks and scums, which cause bad taste and odour in water. According to Codd (1995), some of the African countries where findings of toxic cyanobacterial blooms are recorded include Egypt, Ethiopia, Morocco, South Africa and Zimbabwe. Other tropical countries experiencing the problem include Brazil, India, Bangladesh, Thailand, Malaysia and Australia (Codd 1995).

Cyanobacteria are known to have a competitive advantage over other forms of phytoplankton, especially during the dry season, mainly because of their ability to fix nitrogen (Bowling & Baker 1996). They are also known to have gas vacuoles, which enhance buoyancy and enable them to constantly migrate into the hypolimnetic zone for nutrient replenishment. These conditions enable them to survive under nutrient deficiency. The results of lake fertilisation experiments conducted by Schindler (1977), cited in Harper (1992), showed that controlled reduction in the ratio of nitrogen to phosphorus in fertilisers added to two separate lakes resulted in the appearance of nitrogen-fixing cyanobacteria of the genera *Anabaena* and *Aphanizomenon*. In South Africa, Thornton (1986) recorded that nearly 50% of the biological nitrogen input in Rietvlei Dam was attributed to *Anabaena*.

The prolific growth of certain algae, particularly the blue-greens, is also known to release toxicants such as hepatotoxins and lipopolysacharide endotoxins in the water (Harper 1992; Annadotter *et al.* 1999). Microcystin, a cyclic peptide consisting of seven amino acids, is one of the most frequent hepatotoxins. The endotoxins, which are also known as lipopolysaccharides (LPS), also derive from the cell membrane of the cyanobacteria. Prolific growth of *Mycrocystis aeruginosa*, for example, is known to produce toxins, which cause liver ailments in water birds. The mysterious flamingo deaths, which have taken place in Kenya within the saline Rift Valley lakes (Motelin *et al.* 1995), may be associated with such changes in phytoplankton composition towards toxin producing cyanobacteria.

The eutrophication studies undertaken in Kenya have mainly focussed on the chemical composition of lakes without dwelling strictly on the issue of algal blooms and cyanobacterial toxins (Melack 1976; Njuguna 1982; Kalff 1983; Kalff & Watson 1986; Harper *et al.* 1993). The work by Pacini (1994) on Masinga Dam was one of the few eutrophication studies in Kenyan reservoirs. Consequently, there is a need to monitor phytoplankton populations in small African man-made reservoirs because most are used as sources of water for domestic and livestock use. This paper discusses the occurrence of algal blooms in three small, high-altitude, headwater reservoirs in Kenya and compares them with lowland water bodies in both the Kenyan and African region and other parts of the world. The paper also considers the presence of cyanotoxins and its implication for community health.

Table 1 | The characteristics of study reservoirs in the Kinangop Plateau

Reservoir	Location	Age (years)	Area (km^2)	Catchment area (km^2)	Volume (10^3 m^3)	Z_{max} (m)
Muruaki	0°38′S, 36°33′E	45	0.102	29.1	230	3.5
Kahuru	0°37′S, 36°32′E	46	0.088	31.4	240	4.5
Murungaru	0°36′S, 36°30′E	48	0.116	57.3	280	3.8

STUDY AREA

The study reservoirs are located 100–200 km north-west of Nairobi in the central section of the eastern Rift Valley, whose floor at 1,700–1,800 m above sea level, is flanked to the east by the Kinangop Plateau. The reservoirs are drained by first- to third-order streams, which originate from the Aberdare (Nyandarua) Ranges. The reservoirs are fed primarily by surface drainage through river flow. Both Muruaki and Kahuru are hydrologically distinct because the former overflows into the latter during periods of high water. Table 1 and Figure 1 show the general features of the study reservoirs.

The climate in the area is cool and sub-humid within the uplands, but dry and semi-arid within the rift floor, with a mean annual rainfall of 800 and 1,100 mm in the rift floor and upland, respectively (GoK-JICA 1992). The rainfall pattern is predominantly bimodal with ‘long rains’ between April and June and ‘short rains’ in October and November. Like most other parts of Kenya, the period from January to March is the driest. During this time, water levels in most reservoirs can be low and most reservoirs become hydrologically isolated because of the absence of surface-water flow. The mean human population density in the area is 100–200 individuals per km^2, while the average density of housing surrounding the reservoirs is 100 units per km^2.

METHODS

Fieldwork was undertaken between 1998 and 2000. Sampling involved fixed area tri-zonal stratified sampling, which is similar to the single stratified sampling technique used by Balon & Coche (1974) in Lake Kariba. It is based on longitudinal, heterogeneous, biophysical zonation, which is common to most reservoirs according to previous research (Kimmel & Groeger 1984; Rast & Ryding 1989; Tundisi 1993). This strategy minimises the clustering effects of simple random sampling (Smartt & Grainger 1974).

The focus of the study was on free-floating planktonic algae, which are more abundant in water and much easier to sample. The assessment of composition and density was made from 1-cm^3 aliquots sampled from 500 cm vertical water samples fixed with buffered 5% formaldehyde. The sub-samples were extracted using a pipette after thorough shaking of the sample. The cells were identified and counted from transects in the Sedgewick-Rafter counting chamber using a Leitz inverted microscope (magnification: $200 \times D = 0.48$ mm 1–3 diagonals). The cell densities were initially expressed as individuals/ml and later converted to cells/l. The collection, handling, identification and counting of phytoplankton followed techniques of Lund *et al.* (1958), Brower & Zar (1977) and Padisak (1993).

In April 2000, three 15-cm^3 water samples were collected in pyrogen-free tubes from the Kinangop reservoirs, frozen and sent to the Department of Limnology at Lund University in Sweden. The samples were analysed for microcystin using the enzyme-linked immunosorbent assay (ELISA) procedures according to Meriluoto (1997). They were also analysed for endotoxins using the chromogenic limulus amoebocyte lysate assay test (CLALA) (Annadotter *et al.* 2001). Another set of samples was collected from the reservoirs in April 2001 and the same

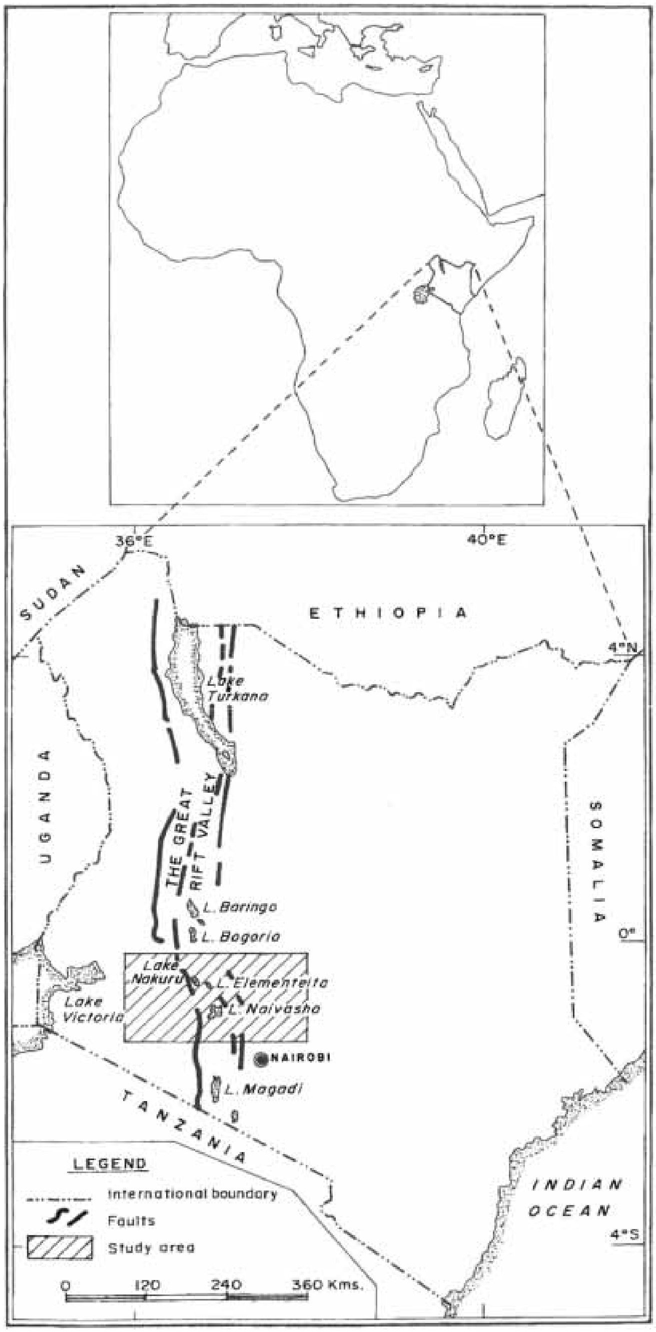

Figure 1 | Location and characteristics of the study area.

analyses (ELISA and CLALA) undertaken in the Natural Products Laboratory in the Department of Zoology at University of Nairobi. The samples of year 2000 were taken during an extremely dry period, the reservoirs were almost permanently endorheic during this period. The second samples were taken in the second week of the long rains during which the reservoirs had hydrologically opened up. In the second samples, microcystin levels were analysed spectrophotometrically using the EnviroGard Microcystins Quantitube Test Kit No. 77000. The kit could only detect and measure microcystins dissolved in water.

RESULTS

Figure 2 shows the variability of phytoplankton taxa between the different months sampled. Approximately 70 species of phytoplankton were identified with the community being dominated by chlorophytes, cyanobacteria and chrysophytes; diatoms were rare. The mean range of species number was three to six per reservoir, with the most dominant ones being *Microcystis aeruginosa*, *M. viridis*, *M. flos-aque*, *Botryococcus braunii*, *Ceratium hirundinella*, *Euglena viridis* and *Anabaena* spp. The reservoirs were dominated by cyanobacteria during the dry season in February. At the onset of the long rains in March, a mixture of cyanobacteria, chlorophytes and chrysophytes was prominent in the reservoirs. The chlorophytes and cyanobacteria also dominated in June, thereafter giving way to a mixture of cyanobacteria and chrysophytes in July. The September assemblage was very similar to the assemblage of June. Overall, the cyanobacterial concentration in the escarpment reservoirs was lower compared to the blooms in the plateau reservoirs. Diatoms were rare and only increased slightly in July and September. This was probably due to deficiencies in certain nutrients. Similarly, euglenophytes were always rare in all the reservoirs.

There was an increase in phytoplankton cell density and a decrease in diversity during the months of February and June. This indicated eutrophication and a possibility of algal blooming. This assumption is supported by the presence of cyanobacteria, especially in the plateau reservoirs.

The presence of cyanobacterial blooms in the plateau reservoirs necessitated an investigation into possible biotoxin contamination in years 2000 and 2001. The need was also motivated by the farmers living around some of the reservoirs who reported that livestock deaths were common especially at the end of the dry season. The investigation was conducted in Kinangop area for both microcystins and lipopolysaccaride endotoxins (see Table 2).

The qualitative analyses of phytoplankton species at the time of cyanotoxin analyses showed the most common cyanobacteria were *Anabaena circinalis*, *A. crassa*, *Microcystis aeruginosa*, *M. elachista*, *M. flos-aque*, *M. wesenbergii*, *M. botrus*, *Chroococcus* spp. and *Osillatoria limosa*. The quantitative analyses indicated that both *Microcystis* and *Anabaena* were the most dominant species. The previous years *Botryococcus braunii* was also common.

The official WHO tolerable daily intake for microcystin-LR is 1 μg/l (Tarczynska *et al.* 2001). Some scientists have argued that is far too high and suggested an upper limit at 0.1 μg/l (Annadotter *et al.* 2001). Presently, there are no guidelines for lipopolysaccaride endotoxins in drinking water but the occurrence of endotoxin related symptoms has been observed at 50 EU/ml (Annadotter *et al.* 2001). Results of this study confirmed the presence of cyanotoxins in the Kinangop reservoirs and the microcystin level of 2.85 μg/l in Kahuru was more than twice the WHO's total daily intake (TDI).

DISCUSSION

The composition and biomass of phytoplankton in the reservoirs was quite similar to the Rift Valley lakes (Kalff & Watson 1986). Kalff & Watson (1986) observed a period of low biomass in Lake Naivasha between October and December, which was quite similar to the pattern observed within the study reservoirs. One major difference between the reservoirs and lakes is the poor diatom community in the reservoirs. Diatoms have, for example, been found to be quite dominant in Lake Naivasha. At Lake Masinga, which is relatively young, Pacini (1994) established that the main taxa comprised mainly of diatoms and cyanobacteria.

The scarcity of diatoms in the small reservoirs investigated in this study was probably caused by low water

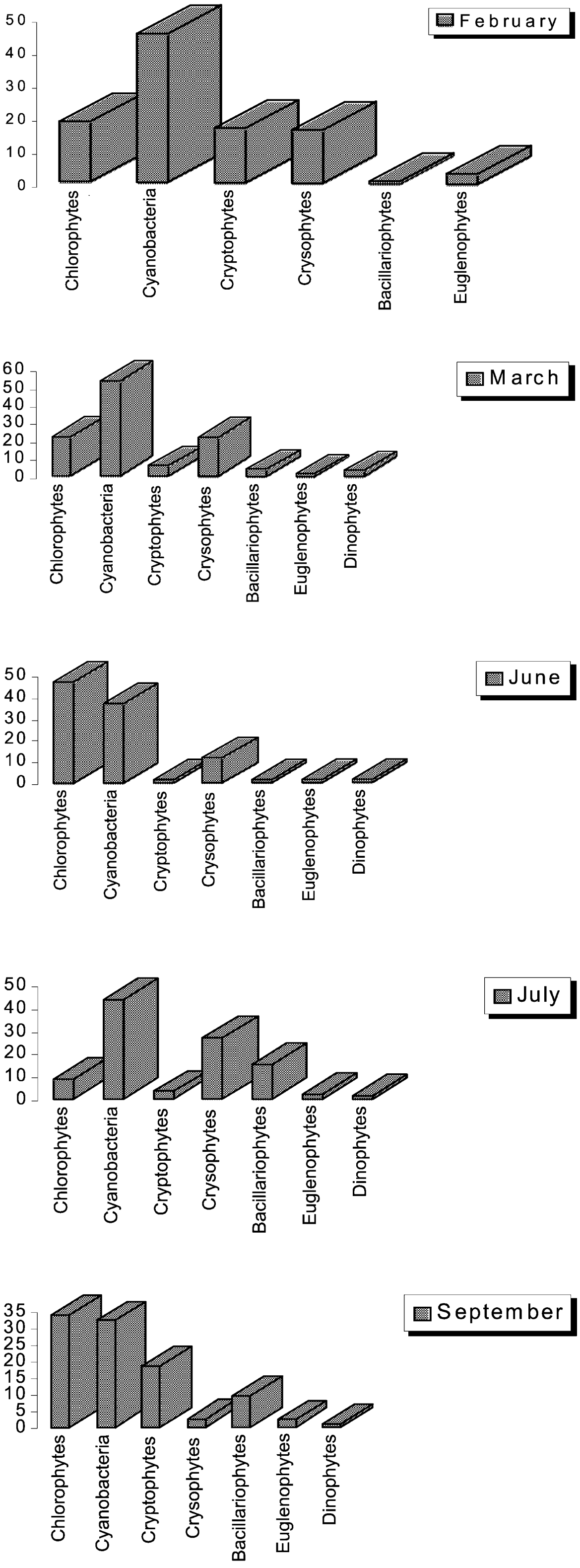

Figure 2 | Monthly profiles of reservoir phytoplankton taxa.

Table 2 | The results of cyanotoxin analyses in the Kinangop reservoirs

	Microcystin (μg/l)		**Endotoxin (EU/ml)***	
	Sample 1 (30.04.00)**	**Sample 2*** (16.04.01)**	**Sample 1 (30.04.00)**	**Sample 2 (16.04.01)**
Muruaki				
Site 1	1.08	nd	nd	nd
Site 2	0.63	nd	nd	nd
Site 3	1.56	nd	nd	nd
Kahuru				
Site 1	0.56	n	n	n
Site 2	1.00	0.64	n	2,500
Site 3	1.09	2.85	90	2,500
Murungaru				
Site 1	0.33	n	68	n
Site 2	0.13	0.12	4,269	2,500
Site 3	0.12	0.06	68	2,500

*The concentration of endotoxins was expressed as Endotoxin Units (EU) where 10 EU is equivalent to 1 ng.
**Intracellular toxin concentration.
***Total toxin concentration; nd—not determined; n—negligible.

transparency. The range of mean Secchi disk depth was 0.1–0.8 m (Mwaura 2003). The diatom scarcity could also be attributed to the shading effect of the chlorophytes, chrysophytes and cyanobacteria which dominated at the water surface.

The increasing dominance of cyanobacteria in the small reservoirs appears to be a common feature in many water bodies throughout the built-up areas of Kenya. The dominance by cyanobacteria in the study reservoirs especially in March and June was likely to have been nutrient-driven. The mean concentrations of total phosphorus and total nitrogen in March and June were 318 and 182 μg/l, and 2,058 and 3,900 μg/l, respectively. Concentrations were 51 and 15,600 μg/l, respectively in December (Mwaura 2003). The high concentration of phosphorus in March and June could have caused nitrogen deficiency due to greater competition.

In the Baltic Sea, Kononen (2001) established that surplus phosphorus created nitrogen deficiency in the individual phytoplankton cells. If this happens, the phytoplankton which dominate are those which can undertake downward migration towards the nitrogen reserves in the bottom sediments. The cyanobacteria are capable of undertaking these movements (Tarczynska *et al.* 2001). The condition in the reservoirs appeared to indicate constant nutrient enrichment because of the common presence of *Microcystis aeruginosa* which is not known to thrive in nutrient poor waters (Finni *et al.* 2001). The shallow nature of the reservoirs would also facilitate constant mixing.

The problem with cyanobacteria is their ability to produce toxins that may cause death if ingested in sufficient concentration by domestic animals and wildlife. The development of cyanobacterial blooms has been associated with toxicity, which causes problems of livestock health in many parts of the tropics. In South Africa, cyanotoxins have been responsible for frequent cattle deaths (Thornton 1987; Marshall & Maes 1994). In Australia, the cyanobacterial blooms which occurred in the calm and sluggish sections of the Barwon-Darling River, caused livestock deaths (Bowling & Baker 1996). In the United Kingdom, *Microcystis* blooms are known to produce toxins whose ingestion by domestic dogs and grazing animals often causes death or sickness (Harper 1992).

Cyanotoxins can pose significant health risks to humans if ingested in sufficient concentrations. They are known to cause gastroenteritis and skin irritations (Bowling & Baker 1996). However, the effects on human health have not been thoroughly investigated within the tropics. According to Tarczynska *et al.* (2001), one well-documented case of human cyanobacterial toxicity within the tropics occurred in Brazil in 1996, where more than 50 dialysis patients died displaying hepatotoxic and neurotoxic symptoms. The concentration of microcystin in the water source was about 0.8 μg/l. Zilberg (1966), cited in Thornton (1987), also found a correlation between gastro-intestinal infections in children and the occurrence of algal blooms in Lake McLlwaine.

One of the most common forms of cyanotoxins in many parts of the world is the hepatotoxins. Microcystin, a cyclic peptide consisting of seven amino acids, is one of the most frequently present hepatotoxins. The endotoxins, which are also known as lipopolysaccharides (LPS), are derived from the cell membrane of the cyanobacteria. They have no primary target organ like the hepatotoxins but usually affect any exposed tissue and are therefore less harmful, unless when drunk by an unhealthy individual. Their impact in the Kenyan study area can be high because of the low immunity associated with the prevalence of HIV.

In Lake Chivero, a subtropical drinking water reservoir in Zimbabwe, the occurrence of toxin-producing blue-green algae has recently been discovered (Annadotter *et al.* 1999). The alga, *Microcystis aeruginosa*, was found to produce microcystins and lipopolysacharide endotoxins. The total dissolved concentration of the two toxins, which ranged between 1.5 and 13.9 μg/l in the reservoir, and 1.5 and 3.9 μg/l in the tap water, was found to have significant effects on public health. The Lake Chivero toxin concentrations were higher than the concentrations for the Kenyan study reservoirs, which are also smaller in size.

According to Robarts & Zohary (1987), cited by Bowling & Baker (1996), high water temperatures of 25 to 30°C were optimal for the cyanobacterial growth in the Barwon-Darling River, Australia. Dissolved oxygen and pH values were also high, especially at sites with abundant cyanobacteria. According to Bowling & Baker (1996), total phosphorus concentration in the Barwon-Darling River was very high at the time of the bloom. In Japan, Kuwabara *et al.* (2001) observed that the growth of *Microcystis aeruginosa*, one of the toxin-producing phytoplankton species, was faster at higher temperatures although it could still survive at low temperatures. These results reflect high toxin vulnerability in the Kenya reservoirs due to high water temperature.

CONCLUSIONS AND RECOMMENDATIONS

The toxin results of this study indicated that the cyanotoxin concentrations were well above the recommended WHO safe limits for drinking water in the three water bodies examined. Monitoring is therefore recommended where the drinking water is taken from reservoirs with regular cyanobacterial blooms. In Kenya, the conditions of cyanotoxin intoxication are quite similar to those of malaria and typhoid fever, which means that incorrect diagnosis is quite possible in the absence of careful laboratory analysis and good scientific collaboration between medical and water resources scientists.

The following considerations and adjustments could eventually improve the quality and quantity of reservoir resources and minimise the risk of future disasters, especially those of disease epidemics:

(a) Regular monitoring of cyanotoxins where the drinking water is taken from reservoirs with a regular presence of cyanobacterial blooms, in order to alert the users when the TDI exceeds the standard set by WHO. Alternative sources of water are needed for algal bloom-prone areas like Kinangop.

(b) The serious problem of eutrophication, cyanobacterial blooms and microcystins in some reservoirs, like Kahuru, require immediate attention, because long-term exposure to people and livestock could increase the risk of liver ailments, particularly cancer. One simple and cost-effective method of dealing with the problem, in a participatory way, is to increase the concentration of activated sediment carbon in the reservoirs to reduce phosphorus content in the water. The local community can achieve this simply by regularly introducing waste charcoal into the affected reservoirs preferably through streams, which run through the village and eventually discharge into the water supply reservoirs. Kitchen ash is a cheap source of carbon from fuel-wood and charcoal, and most people have no other use for it.

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