Research Paper

Investigating the quality of stored drinking water from the Harare water distribution system, Zimbabwe

Pardon Dandadzi, Zvikomborero Hoko and Tamuka Nhiwatiwa

ABSTRACT

This study investigated the effects of different storage conditions (refrigerator, cupboard and sunlight) on the quality of drinking water collected from the distribution system. The study was carried out in the period June–July 2017 and focussed on selected suburbs of Harare. Sampling sites on the distribution system were grouped into three zones (1, 2 and 3) depending on the proximity to the treatment plant, whether there was further chlorination or not and the water flow path. Three water samples were collected in opaque 5 L containers from one site (tap) in each zone and stored under the three storage conditions and periodically analysed for pH, free residual chlorine, temperature and chlorophyll-a. The pH of stored water increased with storage time for all storage conditions and in all zones. The residual chlorine decreased with time in all zones and under all storage conditions. The chlorophyll-a levels also decreased with time under all storage conditions. Refrigerator samples showed the slowest deterioration of water quality and sunlight the highest. Although the pH of stored water increased with time, it remained within both SAZ and WHO guideline values. Household disinfection of stored water is recommended generally after 1 week of storage.

Key words | chlorophyll-a, free residual chlorine, Harare, stored water, water distribution system, water quality

Pardon Dandadzi (corresponding author)
Zvikomborero Hoko
Department of Civil Engineering,
University of Zimbabwe,
P. O. Box MP 167, Mt Pleasant, Harare,
Zimbabwe
E-mail: *pdandadzi@gmail.com*

Tamuka Nhiwatiwa
Department of Biological Sciences,
University of Zimbabwe,
P. O. Box MP 167, Mt Pleasant, Harare,
Zimbabwe

INTRODUCTION

Safe drinking water is crucial for human health and is one of the basic needs of life (Krishna *et al.* 2012). However many people in the world do not have access to this basic need (Nabeela *et al.* 2014). As a result there is use of unreliable water supplies that are of poor quality throughout the developing world (Khadse *et al.* 2012). The available freshwater water resources worldwide are decreasing due to competing demands, climate change, as well as population growth (Savage & Diallo 2005). The contamination of water bodies is a problem experienced worldwide (Sharma & Bhattacharya 2016). Water pollution is mainly caused by undertreated municipal sewage, agricultural livestock wastes, fertilizers, pesticides and industrial wastes (Hsion-Wen & Xagoraraki 2008). Increased economic growth in developing countries has resulted in contamination of water bodies (Savage & Diallo 2005). However, the contaminated water is still used as raw water sources for drinking due to a shortage of better sources of water.

Many African countries face the challenge of providing drinking water of adequate quality and quantity (Abdelrahman 2011; Chalchisa *et al.* 2017). Many utilities and water supply authorities worldwide fail to supply water of acceptable quality (Goyal & Patel 2015) thus exposing customers to health risks (Abdelrahman 2011). Contaminants in drinking water can cause both acute and chronic effects, the acute effects being caused by viruses and bacteria which can be

doi: 10.2166/washdev.2018.107

dangerous to the immune compromised individuals like the elderly and children (Proto *et al.* 2014). Furthermore, water supply is erratic and intermittent in most urban areas of low and middle income countries with over one third in Africa (Nabeela *et al.* 2014). This is worsened by the existence of ageing infrastructure and poor water loss management which has resulted in huge losses reported to be up to 60% (Ndunguru & Hoko 2016). This has resulted in people developing coping mechanisms including resorting to storage of water in overhead tanks and small containers in the household (Schafer & Mihelcic 2012).

Water problems in Harare have been identified as both of a quantity and quality nature mainly due to the pollution of Lake Chivero (Nhapi 2009). The water supply system of Harare has many challenges including high levels of non-revenue water reported to be up to 60% at times (Ndunguru & Hoko 2016). It is reported that the demand is far higher than the supply capacity which has been affected by a breakdown of key water treatment plant units and equipment as well as for critical booster pump stations (Chisango 2012). This coupled with high water losses has resulted in parts of the city getting erratic supplies with some parts not getting water for years. There have been reports of recurrent complaints on the drinking water quality of Harare over the years (Chirisa *et al.* 2017). The quality of water in most parts of the distribution system does not meet the stipulated guideline values (Nhongo *et al.* 2018). The greenish pigment which develops in the water from the network is linked to the presence of algae. The problem of algae comes from the polluted state of the main source of drinking water (Lake Chivero) which has resulted in the detection of toxins produced by algae (microcystins) in the treated water (Mhlanga *et al.* 2006). A study by Hoko & Makado (2011) showed carry over of algae in the final treated water at the treatment plant and there is a high possibility that the algae may be found in the drinking water distribution system. The presence of algae has resulted in unpleasant taste and odour problems (Mhlanga & Mhlanga 2013), as well as colouration of the water. This has reduced the confidence of the consumers leading to rejection of which some of the downstream impacts include poor relations with customers and low willingness to pay for the service. The 2008/2009 cholera outbreak in Harare, and repeated cases of typhoid in some suburbs in the city, have been attributed to poor drinking water quality caused by poor wastewater management (Chirisa *et al.* 2017).

The irregular supply of water in some parts of Harare creates a need for water storage at the household level. It has been established that the quality of drinking water deteriorates during storage (Khadse *et al.* 2012). When water is stored for days it may deteriorate in quality such that it may not be suitable for drinking (Douhri *et al.* 2015). The quality of water is also negatively affected by the residence time (Schafer & Mihelcic 2012). Given this background a study was carried out in Harare in the period June–July 2017. The main objective of the research was to examine the effects of storage conditions and time on the quality of water based on selected parameters.

STUDY AREA

Location of study area

Harare is the capital city of Zimbabwe and is the administrative, commercial, industrial and communications centre of the country. It is surrounded by satellite towns that include Chitungwiza, Epworth, Norton, and Ruwa. Figure 1 shows the location of Harare and the specific study areas.

According to a labour force survey that was conducted by the Zimbabwe Statistical Agency in 2014, about 445,300 people living in Harare were employed as either permanent or casual employees (ZimStat 2015). Zimbabwe has seen the sprouting of small and medium enterprises similar to many developing countries (Macheka *et al.* 2013). Increasingly more people in Harare are turning to street vending as a source of livelihood, the majority of whom are women (Gadaga *et al.* 2008). The study was carried out in Harare and mainly concentrated on the three suburbs of Kuwadzana, Glen View and Belgravia.

Water supply

Harare City supplies water to its residents as well as those of its neighbouring towns which are Chitungwiza, Epworth, Norton and Ruwa (Nhapi & Hoko 2004). Drinking water in Harare is produced from two water treatment plants, Morton Jaffray (MJ) Water Works (the main supplier)

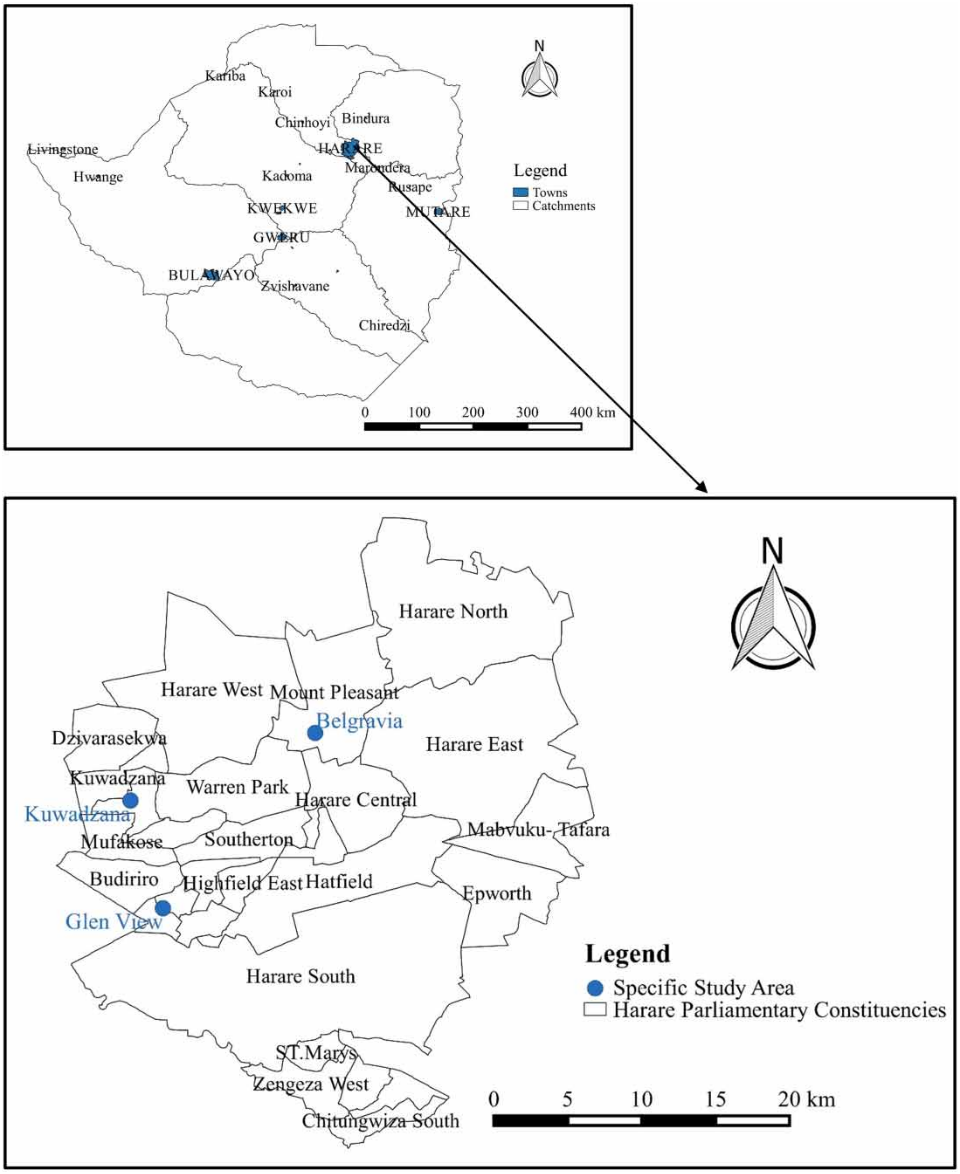

Figure 1 | Map showing the location of the study area.

which abstracts water from Lake Chivero and Lake Manyame and Prince Edward Water Works (PE) which abstracts water from Harava and Seke Dams (Muisa *et al.* 2011). Lake Chivero, which is the most polluted of the Harare water sources, supplies 416,000 m^3/day whilst Lake Manyame and Seke Dam supply 84,000 and 44,000 m^3/day respectively when operating under normal circumstances (Nhapi 2009; Muisa *et al.* 2011). However, during the study period, no water was being pumped from Lake Manyame as the pump house for Manyame has been down for years, only water from Lake Chivero was being treated at MJ.

MJ Water Works is about 35 km to the south-west of Harare. The water treatment process at MJ consists of coagulation, flocculation, filtration and disinfection (Muisa *et al.* 2011). According to HWD (2010), Harare has three modes of water supply and these include the pumping, the gravity supply and one which combines both pumping and gravity modes. Water from MJ takes three main routes, the first is that which goes direct to Kuwadzana Reservoir, the other one goes direct to Marimba and Lochinvar Reservoirs and the third goes through Warren Control Reservoirs and is then boosted to other reservoirs. Water pipe materials are steel, Asbestos Cement (AC) and Unplasticised Polyvinyl Chloride (uPVC) and most of the infrastructure is over 40 years old (Ndunguru & Hoko 2016). The old age of the distribution system has resulted in frequent pipe bursts and leakages in the city (Ndunguru & Hoko 2016). There have been reported cases of several complete shutdowns of the Harare water supply system (Fernández *et al.* 2011), resulting in failure by the city to supply water to its residents (Muserere *et al.* 2014). Non-revenue water of 57% was reported by Chisango (2012) and this was higher than the benchmark of 23% for developing countries (Tynan & Kingdom 2002). According to Mason (2009), the 2008/2009 cholera outbreak in Zimbabwe was attributed to poor drinking water quality. Harare was the main city affected by this outbreak which resulted in about 4,300 deaths (Fernández *et al.* 2011). Recurrent cases of typhoid and cholera in Harare have been reported.

MATERIALS AND METHODS

Study design

Harare was chosen as the study area because it has a large population that constitutes about 16% of the national population and any negative water supply effects would result in considerable public health consequences on its residents. According to Fernández *et al.* (2011), the 2008/2009 cholera outbreak in Zimbabwe mainly affected Harare. Eutrophication of Lake Chivero has become a problem for Zimbabwe (Nhapi *et al.* 2002), thus Harare has one of the worst qualities of raw water for drinking water treatment in the country. Furthermore, due to rapid population growth and being the capital city, it has serious problems in provision of water and sanitation services. As a result, the practice of storage of water fetched from the municipal system is very common as a coping strategy. It is therefore important to study how the quality of water changes when residents store water for later use. There have been reports of recurrent complaints on the drinking water quality of Harare over the years (Chirisa *et al.* 2017).

The study was carried out in the suburbs of Kuwadzana, Glen View and Belgravia. The sampling points are shown in Figure 2.

The suburbs were chosen because they represent the three main pathways of water supply in Harare. To exclude impacts of intermittent water supply on water quality and also on the sampling programme, areas that received regular water supply were selected. Zone 1 consists of areas that receive water from the mains before WCR and was represented by Kuwadzana. Zone 2 comprises of areas that receive water without further chlorination but were further than Zone 1 and was represented by Glen View. Zone 3 consists of areas that receive water via WCR and was represented by Belgravia. The schematic diagram of the sampling zones is shown in Figure 3. The chemistry of water is affected by pH. The pH of the water has an impact on metal pipe corrosion and disinfection efficiency (Aghaarabi *et al.* 2014). There are several factors that determine the microbiological quality of drinking water in the distribution systems of municipalities and residual chlorine is usually used to minimize the regrowth of these contaminants (Chowdhury 2012). Higher water temperatures contribute to the deterioration of water quality as several of the chemical reactions that occur in water are dependent on temperature (Blokker *et al.* 2014). Algae affect water quality because they produce odours and reduce the dissolved oxygen of the water when they die (Mbukwa *et al.* 2013).

Data collection

Samples were collected at selected sampling sites in the distribution system as was carried out by Qaiser *et al.* (2014). Water samples were collected from three zones in the distribution system. Kuwadzana, Glen View and Belgravia represented Zones 1, 2 and 3, respectively. Water samples were collected from customer taps in opaque 5 L plastic containers. The containers were first sterilised using 5% nitric acid and then rinsed with distilled water several times to remove contaminants (Bieranye *et al.* 2016). Three samples were collected from each zone from one tap. The three samples from each zone were then stored in the refrigerator, sunlight and the cupboard at the University of Zimbabwe to assess the effects of different storage conditions and time on the quality of water. The samples were

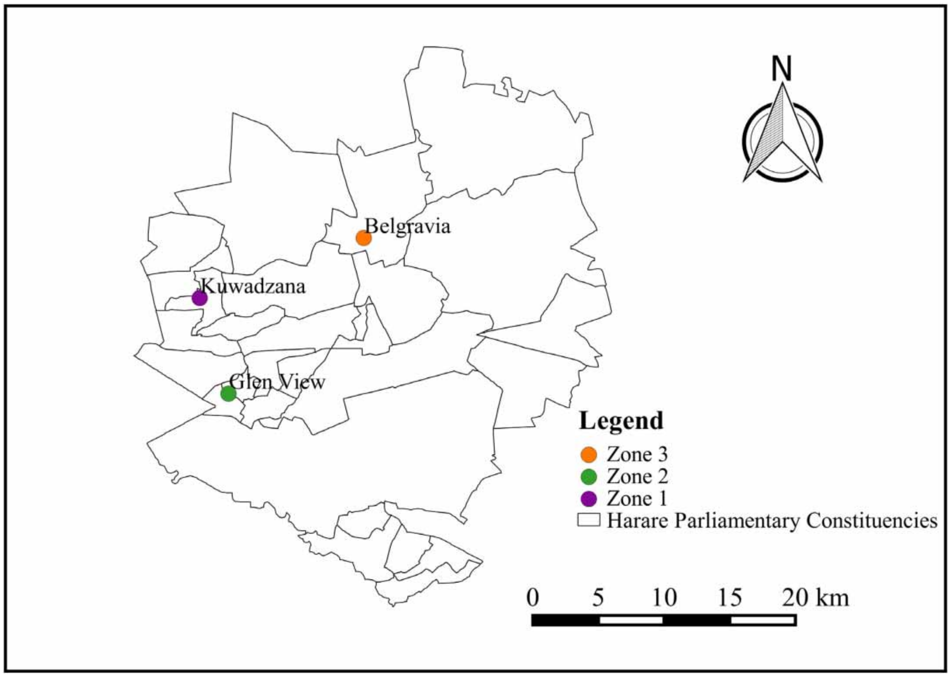

Figure 2 | Sampling points in Harare, 5 June–3 July 2017.

analysed for initial concentrations of the parameters of interest (pH, temperature, free residual chlorine, and chlorophyll-a). Samples (500 mL) were collected from the 5 L containers on a weekly basis for a month and analysed for the selected parameters. Table 1 presents details of the instruments that were used for water quality analysis.

RESULTS AND DISCUSSION

The results for each of the parameters are presented in the sections that follow.

pH

The pH variation with storage time for water samples from Zones 1, 2 and 3 is shown in Figure 4. In Zone 1, initially water had a pH of 6.95. For refrigerator storage, the pH gradually increased from the initial value to 7.34 by the end of the experimentation period (4 weeks). There was a slight increase in pH in the first week but thereafter the pH increased to 7.34. The pH of water in the cupboard increased considerably from the initial value to a final value of 7.60 after 4 weeks. There was a slight increase in the first week followed by a decrease in the second week and a gradual increase in weeks three and four. For sunlight storage, pH increased from an initial value of 6.95 to 8.04 after 4 weeks. In Zone 2, there was a gradual increase in pH of the water for refrigerator samples from an initial value of 7.00 to 7.45 at the end of the experimentation period. Water stored in the cupboard gradually increased from the initial value of 7.00 to 7.54 by the fourth week. Water stored in the sunlight reached a final value of 7.94 in four weeks. In Zone 3, the initial pH was 6.95. The pH of refrigerator, cupboard and sunlight samples all increased gradually to final values of 7.20, 7.25 and 7.25 respectively after 4 weeks of storage.

All the water samples stored under the three conditions remained within the SAZ (1997) and WHO (2011) pH guideline value of 6.5 to 8.5. In a study on the impact of storage tanks on drinking water quality in Jordan, the pH of the water stored in polyethylene containers increased from 7.5–7.8 to 7.8–8.2 during storage (Ziadat 2005).

All water samples from the three zones and under all storage conditions had an increase in pH with storage time. A one-way analysis of variance (ANOVA) showed

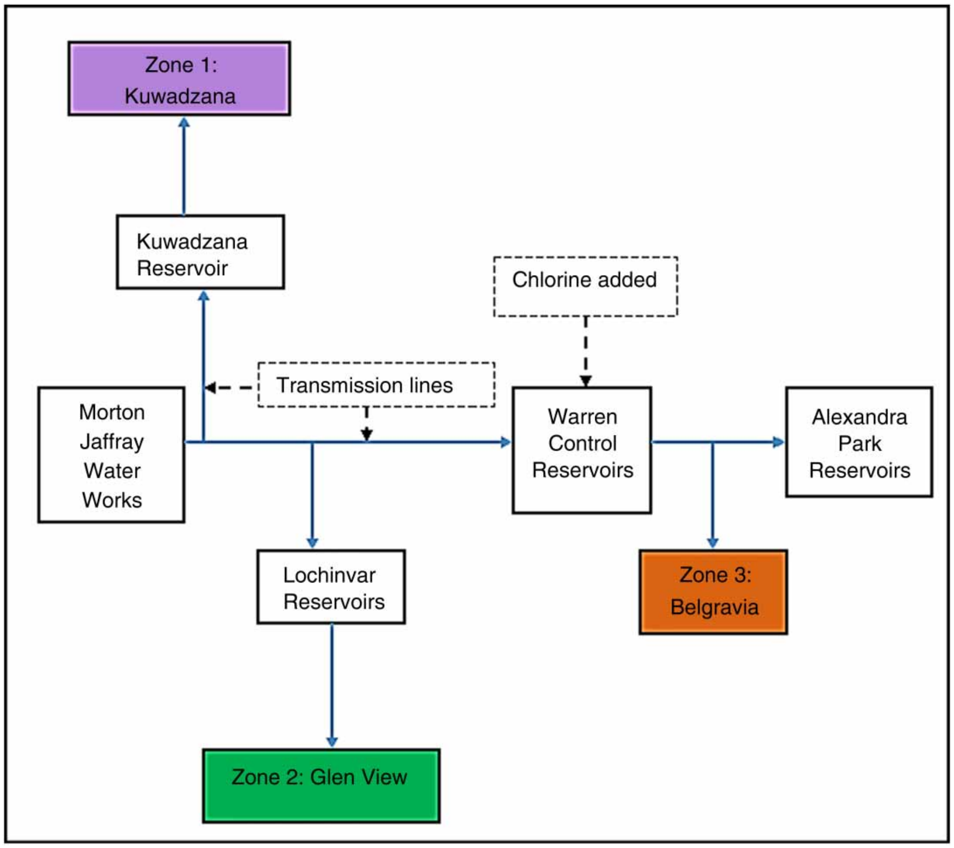

Figure 3 | Sampling zones on the Harare water distribution system.

Table 1 | Instruments used for water quality analysis

Parameter	Instrument/method	Instrument model
Temperature	Digital thermometer	KM3002
pH	pH ion meter	Hanna HI9103
Residual chlorine	Photometer	ELE Paqualab
Chlorophyll-a	Acetone extraction	

that there were no significant differences in pH among all the storage conditions. However, there were significant differences ($p < 0.05$) between the initial and final pH values under all the storage conditions with p values of 0.025, 0.013 and 0.00 for Zones 1, 2 and 3 respectively.

In all three zones the highest final pH value was recorded for water that was stored in sunlight and the least in water stored in the refrigerator, suggesting effect of temperature and sunlight. Sunlight increases photosynthesis (Çelik 2013) resulting in an increase in pH due to the uptake of carbon dioxide by phytoplankton. It has been established that low temperatures reduce photosynthesis (Allen & Ort 2001). Although chlorophyll-a generally decreased over time under all storage conditions due to many factors including depletion of nutrients and other elements required for phytoplankton growth, high temperatures and presence of sunlight for samples stored in sunlight promoted phytoplankton growth and photosynthesis resulted in elevated pH compared to samples under other storage conditions. It was found that the quality of water stored under all the storage conditions deteriorates with storage time as it became more alkaline as storage time increased. Sunlight stored samples had the highest pH change while refrigerated samples had the lowest change.

Temperature

Temperature variation with storage time for water samples from Zones 1, 2 and 3 is shown in Figure 5. Water samples from Zone 1 had an initial temperature of 22 °C. After 1

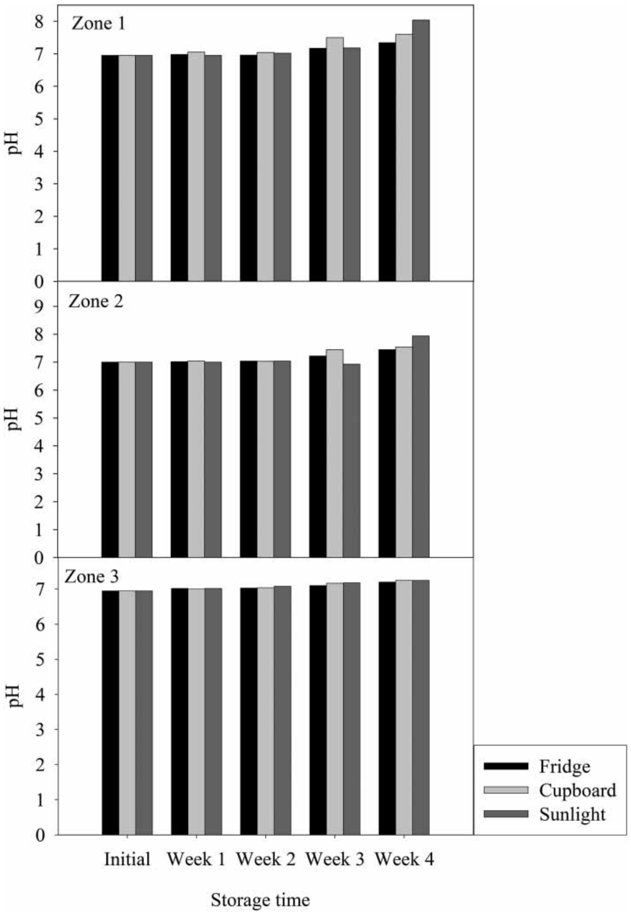

Figure 4 | pH variation with storage time in Zones 1, 2 and 3, 5 June–3 July 2017.

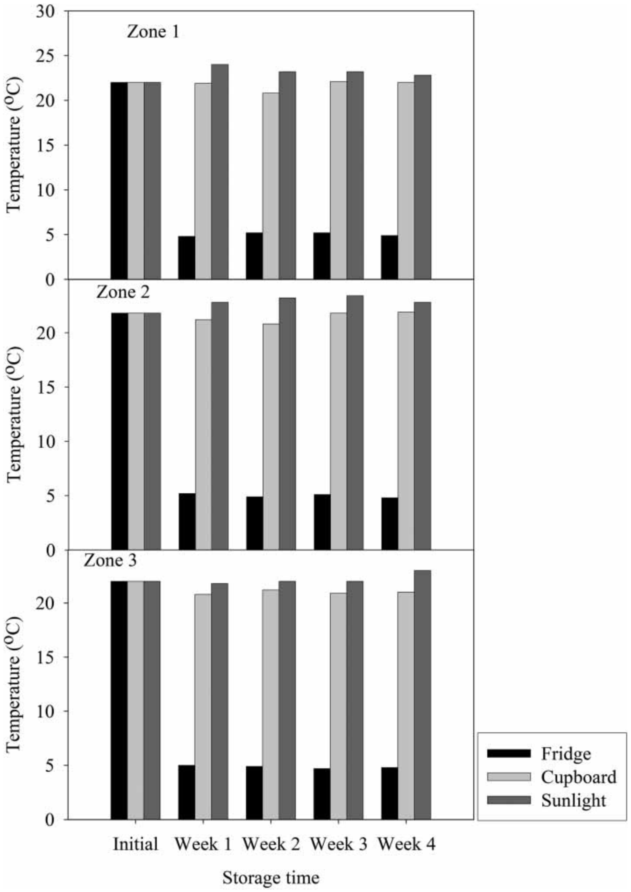

Figure 5 | Temperature variation with storage time in Zones 1, 2 and 3, 5 June–3 July 2017.

week of storage in the refrigerator, the temperature dropped to 4.8 °C and slightly increased to 4.9 °C in week four. For water stored in the cupboard, the temperature slightly decreased to 21.9 °C after 1 week of storage, finally reaching 22 °C in week four. Water stored in sunlight had an increase in temperature to 24 °C after 1 week of storage and after the 4 weeks of the experimentation period it was 22.8 °C. Water samples from Zone 2 had an initial temperature of 21.8 °C. After 1 week of storage in the refrigerator, the temperature dropped considerably to 5.2 °C and remained almost constant during the storage period, reaching 4.8 °C in week four. For cupboard storage, the temperature decreased to 21.2 °C after 1 week of storage, and remained almost constant with a final value of 21.9 °C in week four. Water stored in sunlight had an increase in temperature to 22.8 °C after 1 week of storage and had a final value of 22.8 °C after 4 weeks. Water samples from Zone 3 had an initial temperature of 22 °C. After 1 week of refrigerator storage the temperature dropped to 5 °C and was 4.8 °C in week four. For water stored in the cupboard the temperature slightly decreased to 20.8 °C after 1 week of storage and 21.0 °C in week four. Water stored in sunlight had a decrease in temperature to 21.8 °C after 1 week of storage and was 23.0 °C after 4 weeks. Temperature measurements were taken in mid-morning between 10:00 and 11:00 hrs. Cupboard temperature depended on the ambient temperature whilst the temperature in the fridge was independent and depended on the fridge setting. Temperature was highest for sunlight, followed by cupboard and least in the fridge. There was a significant difference ($p = 0.01$) in temperature between water stored in the refrigerator and in the cupboard and between water stored in the refrigerator and in sunlight ($p = 0.01$). However, there was no significant difference ($p = 0.89$) between storage in the cupboard and in the sunlight. There were no significant differences in the initial and final temperature under all storage conditions except for the refrigerator samples.

Free residual chlorine

Free residual chlorine variation with storage time for water samples from Zones 1, 2 and 3 is shown in Figure 6. Water from Zone 1 had an initial free residual chlorine concentration of 0.60 mg/L. The free residual chlorine concentration of refrigerator water decreased to 0.48 mg/L after 1 week of storage and decreased to 0.14 mg/L after 4 weeks. It went below the lower limit of 0.2 mg/L between the third and fourth week. The recommended WHO (2011) range for residual chlorine in drinking water is 0.2–0.5 mg/L. After 1 week of storage in the cupboard the free residual chlorine decreased to 0.40 mg/L and reached 0.12 mg/L after 4 weeks. The free residual chlorine decreased to 0.32 mg/L after 1 week of storage in the sunlight and further decreased to 0.08 mg/L after 4 weeks. Zone 2 had initial free residual chlorine concentration of 0.08 mg/L. This was already below the WHO limit of 0.2 mg/L. The free residual chlorine concentration of refrigerator water decreased to 0.04 mg/L after 1 week of storage and reached 0.01 mg/L after 4 weeks. After 1 week of storage in the cupboard, the free residual chlorine decreased to 0.06 mg/L and decreased to 0.01 mg/L after 4 weeks. The free residual chlorine decreased to 0.04 mg/L after 1 week for sunlight storage and reached 0.01 mg/L after 4 weeks. All storage conditions had the same value of chlorine after 4 weeks. Water from Zone 3 had an initial free residual chlorine concentration of 0.27 mg/L. The free residual chlorine concentration of refrigerator samples decreased to 0.17 mg/L after 1 week of storage and decreased further to 0.02 mg/L after 4 weeks. After 1 week of cupboard storage, the free residual chlorine concentration decreased to 0.17 mg/L with the trend continuing until it reached 0.01 mg/L after 4 weeks. For sunlight storage, the free residual chlorine decreased to 0.17 mg/L after 1 week and further decreased to 0.01 mg/L by the fourth week.

The free residual chlorine concentration of water from Zone 1 which was stored in both the refrigerator and the cupboard decreased to below the lower WHO (2011) guideline value after 4 weeks. However, it took 3 weeks for water stored in sunlight from the same zone to reach the same level. Thus, water from Zone 1 may generally be stored for 2–3 weeks with chlorine levels still being acceptable. Water from Zone 2 had an initial free residual chlorine that was lower than the WHO (2011) lower limit of 0.2 mg/L and by the end of the experimentation storage period it was practically zero. There were no significant differences in free residual chlorine among all the storage conditions. However, there were significant differences in the initial and final free residual chlorine concentration under all storage conditions. It took only 1 week for the free residual chlorine concentration of water from Zone 3 under all storage conditions to decrease to below the WHO (2011) lower limit. Thus, the initial level of chlorine is a major factor affecting the residual chlorine level during storage. Zone 1 had both an initial and final chlorine level higher than the other two zones under all storage conditions. Generally, the rate

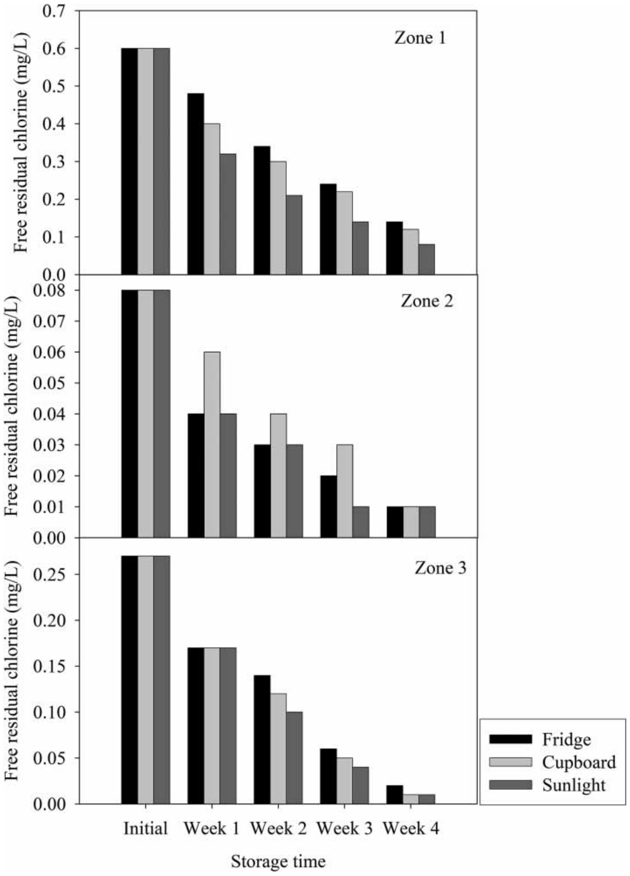

Figure 6 | Free residual chlorine variation with storage time in Zones 1, 2 and 3, 5 June–3 July 2017.

of decrease was of the order refrigerator, cupboard and sunlight in ascending order, suggesting a temperature effect on chlorine decay (Speight & Boxall 2015). It has been shown that chlorine decay is influenced by its initial concentration and that it decays more rapidly in the initial stages (Hua *et al.* 1999) and that it shows significant variation with temperature (Powell *et al.* 2000). Chlorine is also known to decay with an increase in residence time (Blokker *et al.* 2014) and to decay exponentially with time (Goyal & Patel 2015). Thus, water stored in sunlight is more prone to recontamination as compared to water stored in the refrigerator and in the cupboard. Generally, water stored under all the three conditions deteriorated in quality with time.

Chlorophyll-a

Chlorophyll-a variation with storage time for water samples from Zones 1, 2 and 3 is shown in Figure 7. Water from Zone 1 had an initial chlorophyll-a concentration of 0.13 μg/L. In Zone 1, the chlorophyll-a concentration for refrigerator samples decreased to 0.026 μg/L after 1 week of storage and decreased to zero after 2 weeks. After 1 week in the cupboard, the chlorophyll-a concentration decreased to 0.1 μg/L and to 0.03 μg/L after 2 weeks, reaching nil after 3 weeks. The chlorophyll-a decreased to 0.07 μg/L after 1 week of storage in sunlight and decreased to 0.04 μg/L after 2 weeks, reaching zero after 3 weeks.

Zone 2 had an initial chlorophyll-a concentration of 0.30 μg/L. The chlorophyll-a concentration for refrigerator samples decreased to 0.14 μg/L after 1 week, 0.01 μg/L after 2 weeks and to zero after 3 weeks. After 1 week of storage in the cupboard the chlorophyll-a decreased to 0.17 μg/L, 0.04 μg/L after 2 weeks and was zero by the third week. For sunlight storage, the chlorophyll-a concentration decreased to 0.20 μg/L after 1 week, 0.09 μg/L after 2 weeks, 0.02 μg/L after 3 weeks, and to zero after 4 weeks.

In Zone 3, initially chlorophyll-a concentration was 0.18 μg/L. The chlorophyll-a concentration of refrigerator storage decreased to 0.08 μg/L after 1 week and further to zero after 2 weeks. For the cupboard the concentration decreased to 0.10 μg/L after 1 week, 0.03 μg/L after 2 weeks and then to zero after 3 weeks. Under sunlight, the chlorophyll-a concentration decreased to 0.13 μg/L after 1 week, decreasing further to 0.06 μg/L after 2 weeks, 0.02 μg/L after 3 weeks and zero after 4 weeks. There were no significant differences in chlorophyll-a concentration under all storage conditions but there were significant differences between the initial and final chlorophyll-a concentration under all storage conditions.

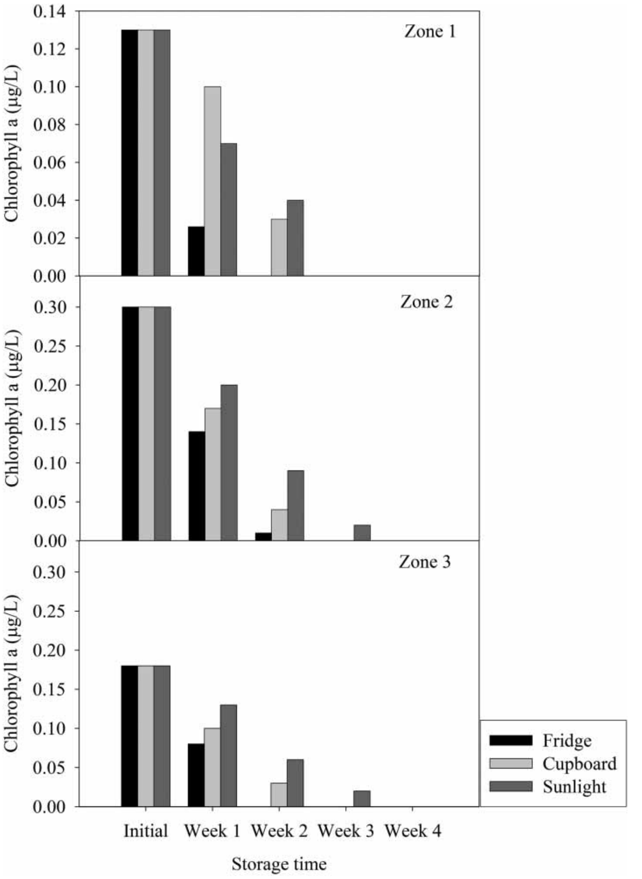

Figure 7 | Chlorophyll-a variation with storage time in Zones 1, 2 and 3, 5 June–3 July 2017.

Chlorophyll-a concentration is associated with different phytoplankton species that include *Microcystis aeruginosa* (Park *et al.* 2010). The concentration of cyanobacteria in water is directly proportional to the chlorophyll-a concentrations (Srinivasan & Sorial 2011). Although algae count and species identification was not carried out in this study, literature suggests that the detection of chlorophyll-a implies the presence of algae such as cyanobacteria. Some cyanobacteria species such as *Microcystis* and *Anabaena,* produce toxins (Krupadam *et al.* 2012). There are several health implications that are associated with algae toxins, for example neurotoxins cause tremors, convulsions, heavy breathing and dizziness (Piontek & Czyżewska 2012). Thus, the residents of Harare are at risk from the algae toxins. The initial chlorophyll-a concentrations of water samples from all the sampling zones in this study were above the WHO guideline alert level 1 and the virulent level for drinking water which are 0.001 and 0.0001 μg/L respectively (Park *et al.* 2010). Thus, the water in the distribution system exceeds the recommended limit for chlorophyll-a and present health risks. However, the final chlorophyll-a concentration in all zones after storage for 2–4 weeks was 0.00 μg/L which was within both the WHO guideline alert level 1 and the virulent level.

Highest initial chlorophyll-a was in Zone 2 (0.3 μg/L), then Zone 3 (0.18 μg/L) while Zone 1 had the least (0.13 μg/L). It can be seen that in terms of residual chlorine, Zone 1 had the highest initial residual chlorine (0.6 mg/L) then Zone 3 (0.27 mg/L) while Zone 2 had the least (0.08 mg/L). From the above there appears to be an inverse relationship between free residual chlorine and chlorophyll-a as the zone with the highest free residual chlorine (Zone 1) had the least initial chlorophyll-a, while that which had the least free residual chlorine (Zone 2) had the highest initial chlorophyll-a. A Pearson correlation test between the initial residual chlorine and initial chlorophyll-a gave a coefficient of –0.92 suggesting a strong inverse relationship. Generally, the reduction in chlorophyll-a was highest in the fridge compared to other storage conditions and reduction was highest in the zone with the highest initial residual chlorine (Zone 1) compared to other zones. The growth of phytoplankton has been shown to be affected by light (Magumba *et al.* 2013). Light intensity contributes to differences in chlorophyll-a concentrations in water and is the main driver of increases in chlorophyll-a concentration (Çelik 2013). Low temperatures (0–12 °C), which are typical in a refrigerator, disrupt all major components of photosynthesis (Allen & Ort 2001), hence the reduction in chlorophyll-a concentration at low temperatures.

Under all storage conditions, pH showed an increasing trend. This could be due to the reduction of chlorine concentration through decay of chlorine resulting in reduction of acidity in water. There is an inverse relationship between pH and the reduction of residual chlorine in water distribution networks (Nouri *et al.* 2015). The reduction of carbon dioxide due to photosynthesis also results in an increase in pH. In a study to investigate the effect of temperature and pH on chlorophyll-a degradation, it was found out that the chlorophyll-a concentration decreased with an increase in pH (Petrovi *et al.* 2014).

It was established that chlorophyll-a concentration showed an inverse relationship with chlorine. The zone with the highest initial chlorine concentration showed the highest reduction in chlorophyll-a. Water stored in the refrigerator had the sharpest decrease in chlorophyll-a concentration while that stored in sunlight had the least, suggesting temperature and sunlight effect. It took the least time for chlorophyll-a concentration to decrease to zero for refrigerator storage and longest for storage under sunlight.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

It was concluded that the quality of water stored under all the storage conditions deteriorated with storage time in terms of pH as it became more alkaline as storage time increased, but remained within both SAZ and WHO guideline values. Water stored in sunlight had the fastest decrease in free residual chlorine concentration, followed by that stored in the cupboard, and the least was water which was stored in the refrigerator. The free residual chlorine concentration decreased to below the WHO guideline within 4 weeks. Chlorophyll-a was initially above the limits set by WHO but dropped to zero over time. The fridge had the fastest reduction in chlorophyll-a while the chlorophyll-a persisted longer for sunlight storage. Temperature was found to affect all other parameters and water quality. There was an inverse relationship between chlorophyll-a and initial free residual chlorine.

Recommendations

It is recommended that Harare Water Department should carry out awareness campaigns to residents on disinfecting stored water which should be done at least a week after storage in areas that do not receive further chlorination and 3 weeks in areas that receive further chlorination. Boosting of residual chlorine in Zone 2 to reduce the risk of contamination when the water is stored, as well as to meet recommended levels, is necessary.

ACKNOWLEDGEMENTS

This paper presents part of the research results of an MSc study by Pardon Dandadzi at the University of Zimbabwe under the supervision team of Zvikomborero Hoko and Tamuka Nhiwatiwa. The Departments of Civil Engineering and Biological Sciences at the University of Zimbabwe are acknowledged for their support and assistance, especially on sample analysis.

REFERENCES

Abdelrahman, A. A. 2011 Bacteriological quality of drinking water in Nyala, South Darfur, Sudan. *Environ. Monit. Assess.* **175**, 37–43.

Aghaarabi, E., Aminravan, F., Sadiq, R., Hoorfar, M., Rodriguez, M. J. & Najjaran, H. 2014 Comparative study of fuzzy evidential reasoning and fuzzy rule-based approaches: an illustration for water quality assessment in distribution networks. *Stoch. Environ. Res. Risk Assess.* **28**, 655–679.

Allen, D. J. & Ort, D. R. 2001 Impacts of chilling temperatures on photosynthesis in warm-climate plants. *Trends Plant Sci.* **6** (1), 36–42.

Bieranye, S., Martin, B., Fosu, S. A., Sebiawu, G. E., Jackson, N. & Karikari, T. 2016 Assessment of the quality of groundwater for drinking purposes in the Upper West and Northern regions of Ghana. *Springer Int.* **5**, 1–15.

Blokker, M., Vreeburg, J. & Speight, V. 2014 Residual chlorine in the extremities of the drinking water distribution system: the influence of stochastic water demands. *Procedia Eng.* **70**, 172–180.

Çelik, K. 2013 The relationships between chlorophyll-a dynamics, certain physical and chemical variables in the temperate eutrophic reservoir, Çaygören Çelik, Kemal. *Iran. J. Fish. Sci.* **12** (4), 770–782.

Chalchisa, D., Megersa, M. & Beyene, A. 2017 Assessment of the quality of drinking water in storage tanks and its implication on the safety of urban water supply in developing countries. *Environ. Syst. Res.* **6** (12), 1–6.

Chirisa, I., Bandauko, E., Matamanda, A. & Mandisvika, G. 2017 Decentralized domestic wastewater systems in developing countries: the case study of Harare, Zimbabwe. *Appl. Water Sci.* **7**, 1069–1078.

Chisango, H. 2012 *Investigating Opportunities for Effective Water Demand Management in Harare's Residential Areas*. MSc Thesis, University of Zimbabwe, Unpublished.

Chowdhury, S. 2012 Heterotrophic bacteria in drinking water distribution system: a review. *Environ. Monit. Assess.* **184**, 6087–6137.

Douhri, H., Raissouni, I., Tazi, S. & Douhri, B. 2015 Effect of house storage on water's quality in rural areas of Tangier-Tetuan region (Morocco). *Larhyss J.* **24**, 301–314.

Fernández, M. Á. L., Mason, P. R., Gray, H., Bauernfeind, A., Fesselet, J. F. & Maes, P. 2011 Mapping recent built-up area changes in the city of Harare with high resolution satellite imagery. *Appl. Geogr.* **105**, 38–45.

Gadaga, T. H., Samende, B. K., Musuna, C. & Chibanda, D. 2008 The microbiological quality of informally vended foods in Harare, Zimbabwe. *Food Control* **19**, 829–832.

Goyal, R. V. & Patel, H. M. 2015 Analysis of residual chlorine in simple drinking water distribution system with intermittent water supply. *Appl. Water Sci.* **5**, 311–319.

Hoko, Z. & Makado, P. K. 2011 Optimization of algal removal process at Morton Jaffray water works. *Phys. Chem. Earth* **36** (14–15), 1141–1150.

Hsion-Wen, D. K. & Xagoraraki, I. 2008 Contaminants associated with drinking water. *Int. Encycl. Public Health* **6**, 539–550.

Hua, F., West, J. R., Barker, R. A. & Forster, C. F. 1999 Modelling of chlorine decay in municipal water supplies. *Water Res.* **33** (12), 2735–2746.

HWD (Harare Water Department) 2010 *Harare Water Annual Report 2010*. unpublished.

Khadse, G. K., Kalita, M. D. & Labhsetwar, P. K. 2012 Change in drinking water quality from source to point-of-use and storage: a case study from Guwahati, India. *Environ. Monit. Assess.* **184**, 5343–5361.

Krishna, M., Mudiam, R., Murthy, R. & Gopal, K. 2012 Studies on urban drinking water quality in a tropical zone. *Environ. Monit. Assess.* **184**, 461–469.

Krupadam, R. J., Patel, G. P. & Balasubramanian, R. 2012 Removal of cyanotoxins from surface water resources using reusable molecularly imprinted polymer adsorbents. *Environ. Sci. Pollut. Res.* **19**, 1841–1851.

Macheka, L., Angeline, F., Tambudzai, R., Mubaiwa, J. & Kuziwa, L. 2013 Barriers, benefits and motivation factors for the implementation of food safety management system in the food sector in Harare Province, Zimbabwe. *Food Control* **34**, 126–131.

Magumba, D. M., Aruyama, A. M., Akagaki, M. T., Ato, A. K. & Ikuchi, M. K. 2013 Relationships between chlorophyll-a, phosphorus and nitrogen as fundamentals for controlling phytoplankton biomass in lakes. *Environ. Control Biol.* **51** (4), 179–185.

Mason, P. R. 2009 Zimbabwe experiences the worst epidemic of cholera in Africa. *J. Infect. Dev. Ctries* **3** (2), 148–151.

Mbukwa, E. A., Boussiba, S., Wepener, V., Leu, S., Yuval, K., Msagati, T. A. M. & Mamba, B. B. 2013 Potential use of dissolved cyanobacterial DNA for monitoring toxic Microcystis cyanobacteria in filtered water. *Phys. Chem. Earth* **66**, 167–172.

Mhlanga, L. & Mhlanga, W. 2013 Dynamics of a cyanobacterial bloom in a hypereutrophic reservoir, Lake Chivero, Zimbabwe. *Afr. J. Aquat. Sci.* **38** (3), 313–321.

Mhlanga, L., Day, J., Cronberg, G., Chimbari, M., Siziba, N. & Annadotter, H. 2006 Cyanobacteria and cyanotoxins in the source water from Lake Chivero, Harare, Zimbabwe, and the presence of cyanotoxins in drinking water. *Afr. J. Aquat. Sci.* **31** (2), 166–173.

Muisa, N., Hoko, Z. & Chifamba, P. 2011 Impacts of alum residues from Morton Jaffray Water Works on water quality. *Phys. Chem. Earth* **36**, 853–864.

Muserere, S. T., Hoko, Z. & Nhapi, I. 2014 Characterisation of raw sewage and performance assessment of primary settling tanks at Firle Sewage Treatment Works, Harare, Zimbabwe. *Phys. Chem. Earth* **67–69**, 226–235.

Nabeela, F., Azizullah, A., Bibi, R., Uzma, S., Murad, W., Khan, S., Ullah, W., Qasin, M. & Hader, D. P. 2014 Microbial contamination of drinking water in Pakistan – a review. *Environ. Sci. Pollut. Res.* **21**, 13929–13942.

Ndunguru, M. G. & Hoko, Z. 2016 Assessment of water loss in Harare, Zimbabwe. *J. Water Sanit. Hyg. Dev.* **6** (4), 519–533.

Nhapi, I. 2009 The water situation in Harare, Zimbabwe: a policy and management problem. *Water Pol.* **11**, 221–235.

Nhapi, I. & Hoko, Z. 2004 A cleaner production approach to urban water management: potential for application in Harare, Zimbabwe. *Phys. Chem. Earth* **29**, 1281–1289.

Nhapi, I., Hoko, Z., Siebel, M. A. & Gijzen, H. J. 2002 Assessment of the major water and nutrient flows in the Chivero catchment area, Zimbabwe. *Phys. Chem. Earth* **27**, 783–792.

Nhongo, K., Hoko, Z. & Kugara, J. 2018 Investigating disinfectant by-products in the Harare potable water supply system, Zimbabwe. *J. Water Sanit. Hyg. Dev.* **8** (3), 415–428.

Nouri, A., Shahmoradi, B., Dehestani, S. & Maleki, A. 2015 Effect of temperature on pH, turbidity, and residual free chlorine in Sanandaj water distribution network, Iran. *J. Adv. Environ. Health Res.* **3** (3), 183–195.

Park, B. K., Soon-jin, H., Myung-hwan, P. & Kim, Y. 2010 Relationship between cyanobacterial biomass and total microcystin-LR levels in drinking and recreational water. *Bull. Environ. Contam. Toxicol.* **85**, 457–462.

Petrovi, S. M., Savi, S. R., Markovi, D. Z. & Petronijevi, ŽB. 2014 In vitro studies of temperature and pH influence on chlorophyll degradation by horseradish peroxidase: spectroscopic and HPLC studies. *Hem. Ind.* **68** (2), 233–239.

Piontek, M. & Czyżewska, W. 2012 Efficiency of drinking water treatment processes: removal of phytoplankton with special consideration for cyanobacteria and improving physical and chemical parameters. *Pol. J. Environ. Stud.* **21** (6), 1797–1805.

Powell, J. C., Hallam, N. B., West, J. R., Forster, C. F. & Simms, J. 2000 Factors which control bulk chlorine decay rates. *Water Res.* **34** (1), 117–126.

Proto, A., Zarrella, I., Capacchione, C. & Motta, O. 2014 One-year surveillance of the chemical and microbial quality of drinking water shuttled to the Eolian Islands. *Water* **6**, 139–149.

Qaiser, S., Hashmi, I. & Nasir, H. 2014 Chlorination at treatment plant and drinking water quality : a case study of different sectors of Islamabad, Pakistan. *Arab. J. Sci. Eng.* **39**, 5665–5675.

Savage, N. & Diallo, M. S. 2005 Nanomaterials and water purification: opportunities and challenges. *J. Nanopart. Res.* **7**, 331–342.

SAZ 1997 *Zimbabwe Standards Specification for Water for Domestic Supplies: Zimbabwe Standard No. 560: 1997*. Standards Association of Zimbabwe, Harare.

Schafer, C. A. & Mihelcic, J. R. 2012 Effect of storage tank material and maintenance on household water quality. *Am. Water Works Assoc.* **104** (9), 521–529.

Sharma, S. & Bhattacharya, A. 2016 Drinking water contamination and treatment techniques: review article. *Appl. Water Sci.* **3**, 1–14.

Speight, V. & Boxall, J. 2015 Current perspectives on disinfectant modelling. *Procedia Eng.* **119**, 434–441.

Srinivasan, R. & Sorial, G. A. 2011 Treatment of taste and odor causing compounds 2-methyl isoborneol and geosmin in drinking water: a critical review. *J. Environ. Sci.* **23** (1), 1–13.

Tynan, N. & Kingdom, B. 2002 *A Water Scorecard. Setting Performance Targets for Water Utilities*. Public Policy for the Private Sector, Note number 242, The World Bank, Washington, DC.

WHO 2011 *Guidelines for Drinking Water Quality*, Vol. 2. World Health Organization, Geneva, Switzerland.

Ziadat, A. 2005 Impact of storage tanks on drinking water quality in Al-Karak Province, Jordan. *J. Appl. Sci.* **5** (4), 634–638.

Zimbabwe Statistical Agency (ZimStat) 2015 *Labour Force Survey 2014*. Government Printers, Harare, Zimbabwe.

First received 24 July 2018; accepted in revised form 9 November 2018. Available online 27 December 2018