

Research Paper

Investigating the occurrence of algae in the drinking water supply system of Harare, Zimbabwe

Pardon Dandadzi, Zvikomborero Hoko and Tamuka Nhiwatiwa

ABSTRACT

This study assessed the quality of drinking water in the water supply system for the City of Harare (Zimbabwe) by investigating the occurrence of algae and other water quality parameters that affect its growth. At Morton Jaffray Water Treatment Works (MJWTWs), samples were collected from the raw water inlet and treated water outlet points. In the distribution system, samples were collected from selected sites and grouped into four zones (1, 2, 3 and 4). The algal taxonomic groups that were found in both raw and treated water comprised of Cyanophyceae, Chlorophyceae, Bacillariophyceae, Euglenophyceae and Dinophyceae. It was found out that *Microcystis aeruginosa* followed by *Anabaena* were the most abundant species in both raw water and in the distribution system. All measured water quality parameters were within the Standards Association of Zimbabwe and WHO guideline values except for chlorine which had an average residual chlorine concentration that was lower than the WHO recommended lower value of 0.2 mg/L in parts of Zone 2. Morton Jaffray Water Treatment Works does not completely remove algae, and there is a carry-over of algae into the distribution system. Boosting of chlorine is recommended for Zone 2 that had residual chlorine less than the WHO minimum threshold of 0.2 mg/L.

Key words | algae, distribution system, *Microcystis aeruginosa*, Morton Jaffray Water Treatment Works, water quality

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INTRODUCTION

Globally, water bodies such as lakes, reservoirs, streams and estuaries are facing the problem of eutrophication (Toor *et al.* 2013). This eutrophication is conducive for cyanobacterial bloom formation (Merel *et al.* 2013). Some cyanobacteria species, such as *Microcystis*, *Anabaena*, *Nodularia*, *Nostoc* and *Oscillatoria*, produce toxins during algal bloom periods (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). Nevertheless, contaminated water is still used for potable uses due to the lack of better sources of water.

Lake Chivero in Zimbabwe has been reported to be eutrophic for quite some time, and this has caused the occurrence of dense blooms of bluegreen algae (Ndebele & Magadza 2006). Hoko & Makado (2011) highlighted that algae caused filter clogging at Morton Jaffray Water Treatment Works (MJWTWs), Harare's main water treatment plant, resulting in high frequencies of backwashing and the reduced plant output. Algae in the lake affect the quality of treated water as there is likely to be a carry-over of algae and toxins into the distribution system. There have

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been considerable concern on the drinking water supplied to residents in Harare due to the presence of algae that has resulted in unpleasant taste and odour problems. This has led to user rejection resulting in poor relations with customers and low willingness to pay for the service (Dandadzi *et al.* 2019). Public perceptions of water quality ranged from unsafe to highly contaminated (Chirenda *et al.* 2015).

The 2008/9 cholera outbreak in Zimbabwe and repeated cases of typhoid in some suburbs in the city have been attributed to poor drinking water quality (Chirisa *et al.* 2017). According to Fernández *et al.* (2011), the 2008/9 outbreak mainly affected Harare and resulted in about 4,300 deaths countrywide. The latest outbreak in 2018 resulted in 38 deaths, and the risk of another outbreak is still there (UNICEF 2018).

This study was carried out in Harare in the period from May to June 2017 and investigated the occurrence of algae in the raw and treated water at MJWTWs as well as at selected points in the distribution system. The study also assessed the levels of key parameters that affect growth of algae which included pH, turbidity, total nitrogen, total phosphorus and free residual chlorine.

STUDY AREA

Harare is the capital city of Zimbabwe. Greater Harare is situated on Zimbabwe's Highveld between latitudes 17°40'S and 18°06'S and between longitudes 30°37'E and 31°16'E (World Bank 2014). Harare is the industrial hub and the seat of government and the commercial centre of Zimbabwe (World Bank 2014). Figure 1 shows the location of Harare and the specific study areas.

The specific study areas were Kuwadzana 2, Kuwadzana 5, Lochinvar, Glen View, Waterfalls, Dzivarasekwa, Mabelreign and Belgravia.

Background on water supply for the city of Harare

Harare City Council supplies water to its residents and those of Chitungwiza, Norton, Ruwa and Epworth (Nhapi & Hoko 2004). Drinking water in Harare is produced from two water treatment plants, MJWTWs and Prince Edward

Water Works (Muisa *et al.* 2011). Figure 2 shows the water supply infrastructure for Harare. There are approximately 192,000 consumer connections in Harare (Chisango 2012). According to Ndunguru & Hoko (2016), the pipe age for Glen View is 34 and 47 years in Mabelreign. The age of all the other suburbs under study is estimated to be 40 years with some over 60 years. The pipe diameters in the Harare water distribution system range from 50 to 1,500 mm. The network has 6,000 km of water pipes (Chirenda *et al.* 2015). Pipe materials are steel, asbestos cement and unplasticised polyvinyl chloride (Ndunguru & Hoko 2016).

MATERIALS AND METHODS

Selection of study area and sampling points

Sampling was done at MJWTWs for both raw and treated water. In the distribution system, sampling sites were divided into zones depending on the pathway of flow of water from MJWTW and depending on whether they received water that passed through Warren Control Reservoirs (WCRs) where further chlorination is done or whether it did not pass through the WCR. Zone 1 consisted of areas that received water from the mains that do not pass through WCRs (Kuwadzana 2 and Kuwadzana 5). Zone 2 comprised of areas that received water without further chlorination but are further than Zone 1 (Glen View and Lochinvar). Zone 3 had areas that received water via WCRs and passing through other reservoirs (Waterfalls and Dzivarasekwa). Zone 4 comprised of areas that received water via WCRs but did not pass through any reservoir thereafter (Belgravia and Mabelreign). A schematic of the sampling zones is shown in Figure 3, while Figure 4 shows sampling points in the distribution system. Water samples were collected at eight sampling sites on the distribution system during six campaigns once every week from May to June 2017. Samples were collected using 500 mL sterile plastic bottles. Parameters studied included pH, turbidity, total nitrogen (TN), total phosphorus (TP), free residual chlorine and algae.

Samples were transported within 5 h of collection for analysis at the Civil Engineering Department and the

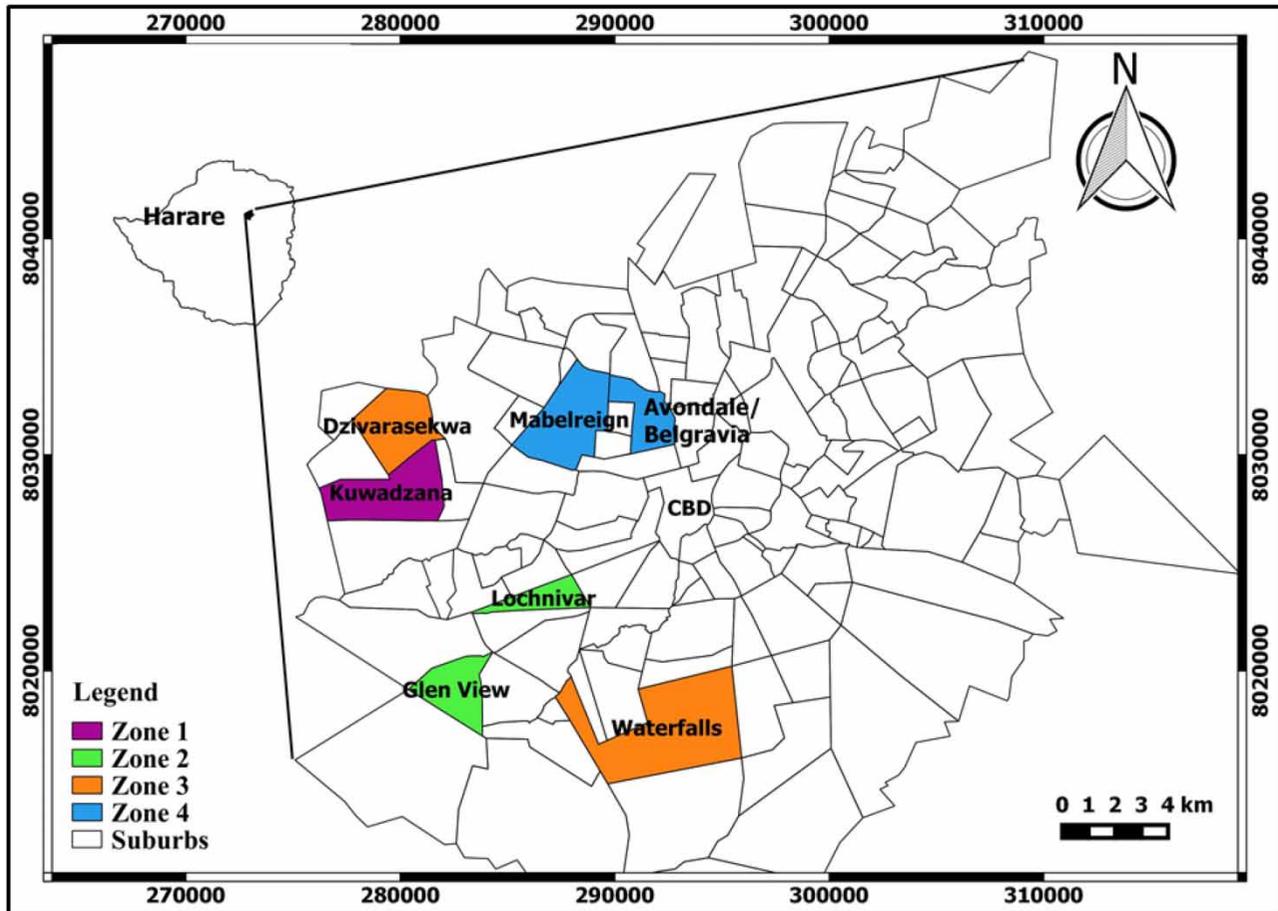


Figure 1 | Maps showing the location of the study area.

Biological Sciences Department laboratories of the University of Zimbabwe. Samples for algae analysis were preserved using Lugol's solution as suggested by APHA (2012). Phytoplankton guidelines by van Vuuren *et al.* (2006) and Bellinger & Sigeo (2010) were used for the identification of algae species. Analyses of pH, turbidity, TN, TP and free residual chlorine were carried out in accordance with APHA (2012).

RESULTS

The results for water quality analysis of Morton Jaffray Raw Water (MJRW), Morton Jaffray Treated Water (MJTW) and the distribution system are shown in Table 1.

Physical and chemical water quality parameters for raw water and in the distribution system

pH

The pH values for all study sites are shown in Figure 5. The pH value of MJRW was 7.30–8.20 (mean 7.52). The pH value of MJTW ranged from 6.98 to 7.02 (average 7.0).

In Zone 1 (Kuwadzana 2 and Kuwadzana 5), the pH values were 6.97–7.02 (average 6.99). In Zone 2 (Glen View and Lochinvar), it was 6.96–7.01 (average 6.98). In Zone 3 (Waterfalls and Dzivarasekwa), this was 7.00–7.04 (average 7.02). In Zone 4 (Belgravia and Mabelreign), the pH value ranged from 6.93 to 7.09 (average was 6.98). In most distribution networks, the pH value of final treated water is in the range of 6.5–8.5 (Aghaarabi *et al.* 2014). The

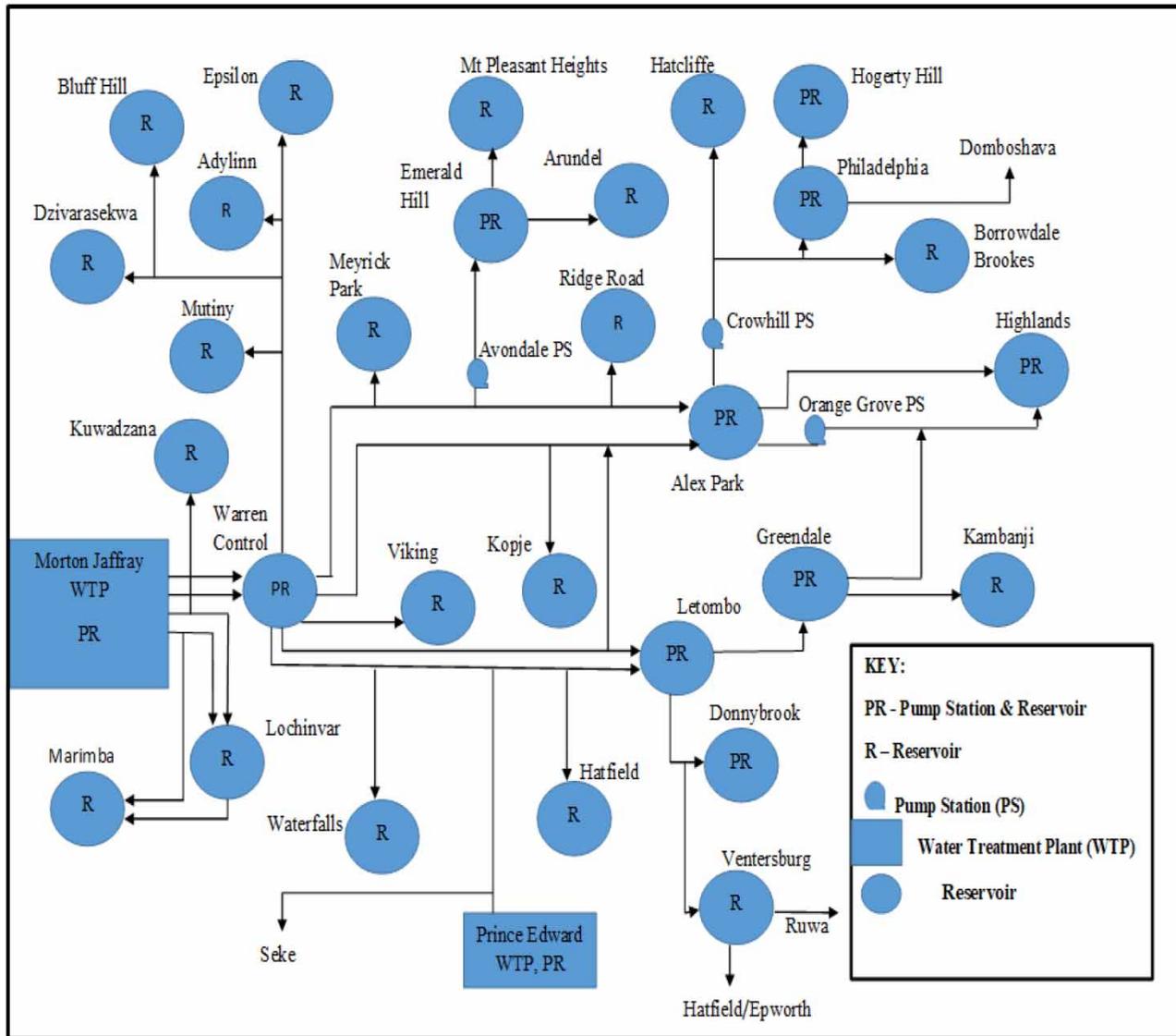


Figure 2 | Schematic of primary water supply infrastructure for Harare.

pH value in the Accra water distribution system ranged from 6.80 to 7.80 (Karikari & Ampofo 2013). The optimum pH value for algal growth is in the range of 6.5–8.5 (Giannuzzi et al. 2016), and thus, the pH value of the water was suitable for algal growth.

A Pearson correlation coefficient of 0.2 was found between pH and algal concentration, suggesting a weak relationship. There was no significant change in pH in the distribution system beyond the treatment plant. A one-way analysis of variance (ANOVA) at 5% confidence interval showed no significant differences ($p = 0.16$) in pH between

each zone and treated water for MJTW. It was found out that the value of pH of all treated water samples was within the SAZ (1997) and WHO (2011) pH limits of 6.5–8.5.

Turbidity

The variation of turbidity for all study sites is shown in Figure 6. Turbidity values of MJRW ranged from 2.14 to 5.30 NTU (average 3.39 NTU). MJTW values ranged from 0.81 to 1.18 NTU with an average value of 1.10 NTU. In Zone 1, turbidity value was 0.80–0.91 NTU

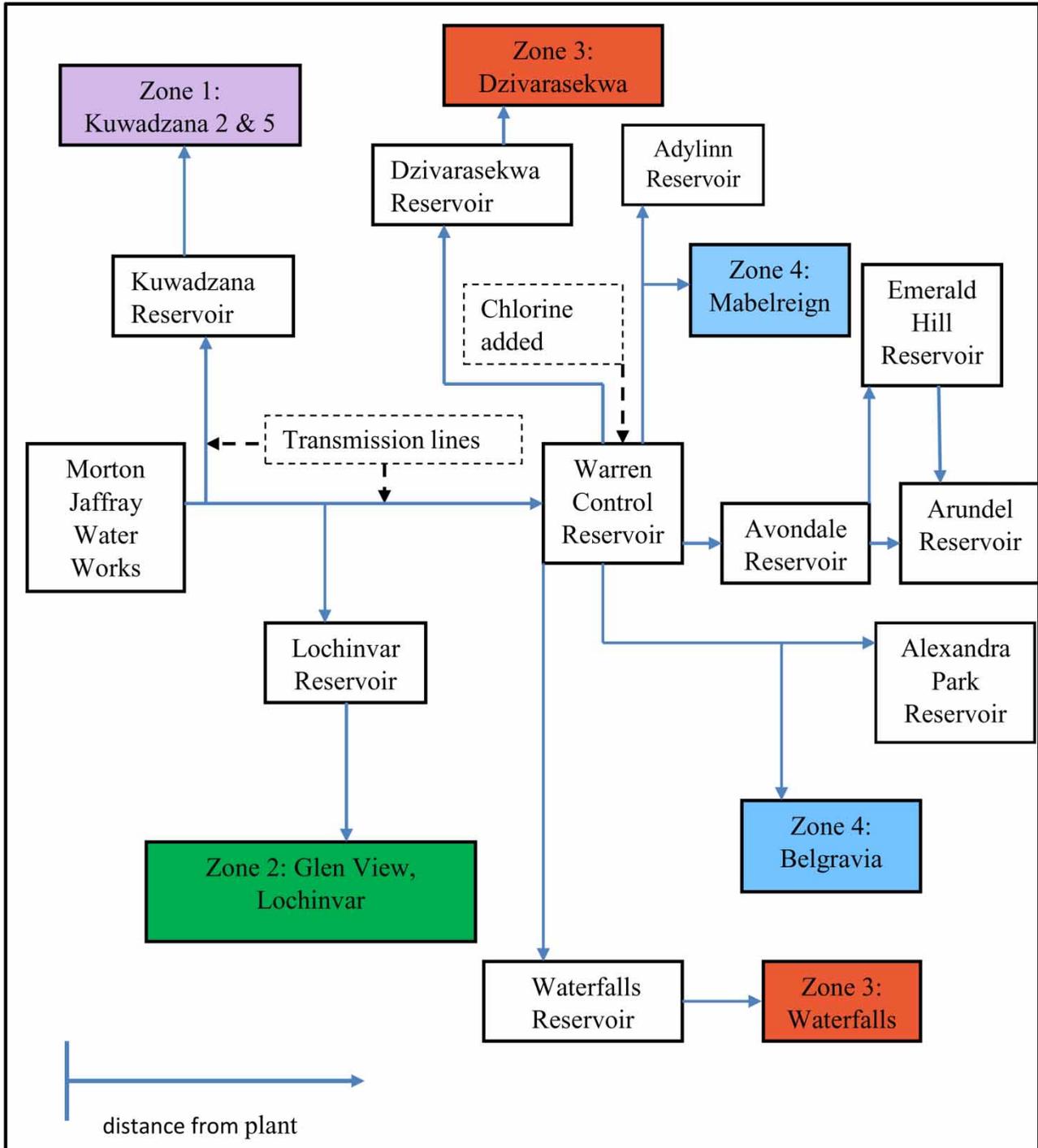


Figure 3 | Sampling zones on the Harare water distribution system.

(average 0.86 NTU). For Zone 2, turbidity value was 0.67–1.33 NTU (average 1.20 NTU). In Zone 3, the turbidity values ranged from 0.80 to 1.17 NTU (average 1.06 NTU). Zone 4 had values from 0.68 to 0.84 NTU (average

0.80 NTU). Turbidity decreased in all the four zones compared to MJTW possibly due to the sedimentation of the residual suspended material in the distribution reservoirs.

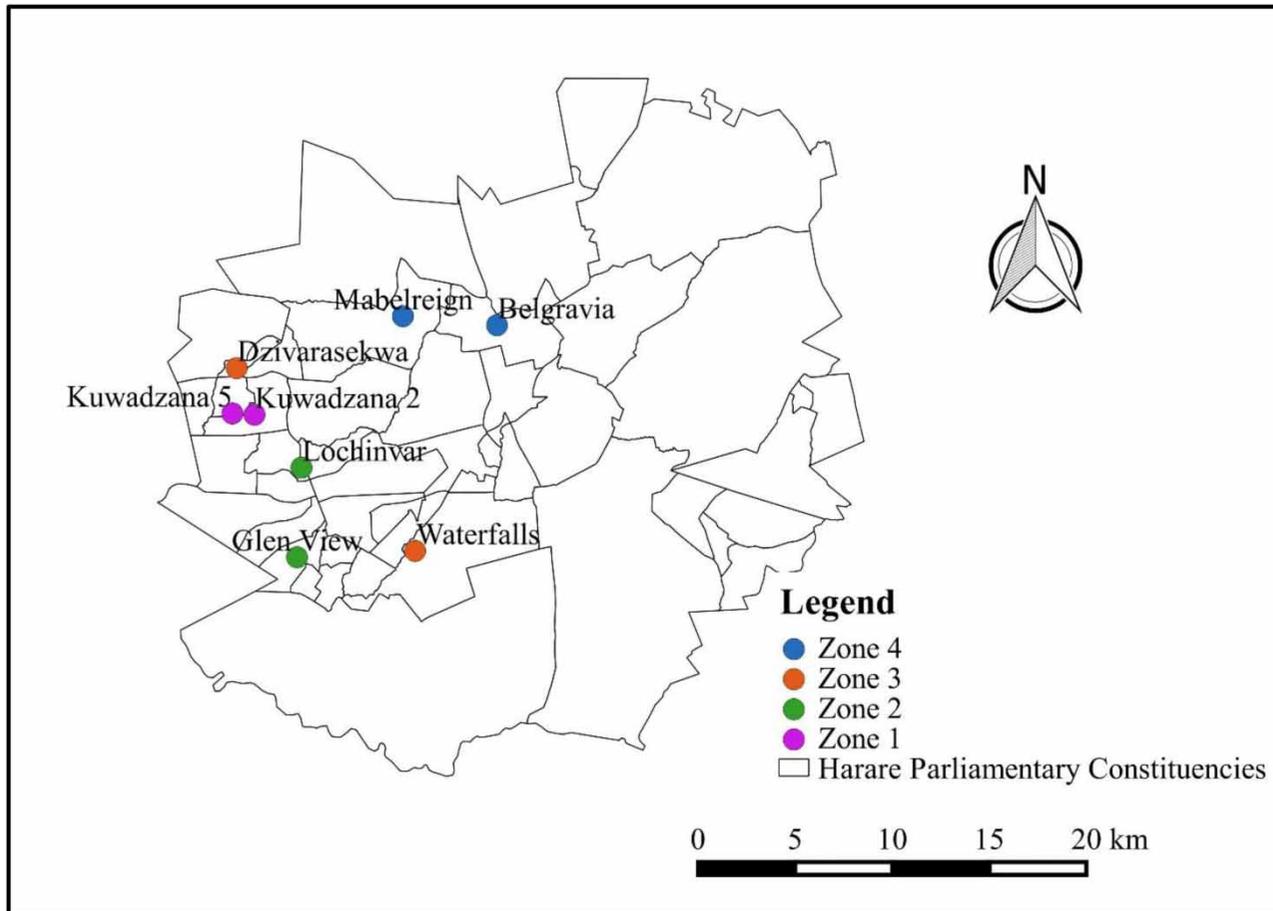


Figure 4 | Sampling points in the Harare water distribution system.

A Pearson correlation coefficient of 0.31 was found between turbidity and algal concentration. [Nhongo *et al.* \(2018\)](#) found an average turbidity value of 0.49–1.14 NTU in Kuwadzana (Zone 1 in this study).

There were no significant differences in turbidity between (MJTW) and all the zones except with Zone 4. Turbidity can indicate the presence of microbial contamination in the distribution network ([Aghaarabi *et al.* 2014](#)). The [WHO \(2011\)](#) and [SAZ \(1997\)](#) turbidity limit value for drinking water is 1 NTU, although an extreme value of 5 NTU is acceptable.

Total nitrogen

TN for all sampling sites are shown in [Figure 7](#).

TN values in MJRW ranged from 0.86 to 0.94 mg/L (average 0.89 mg/L). The TN value for MJTW was 0.29–0.41 mg/L (average 0.34 mg/L). In Zone 1, TN values

were 0.38–0.41 mg/L (average 0.40 mg/L). In Zone 2, TN values had 0.38–0.44 mg/L (average 0.41 mg/L). In Zone 3, the TN value was 0.35–0.42 mg/L (average 0.39 mg/L). For Zone 4, this was 0.40–0.44 mg/L (average 0.42 mg/L).

Water quality in the distribution system is affected by pipe maintenance works or breaks in pipes ([Ikonen *et al.* 2013](#)). Old systems allow ingress of contaminated groundwater, especially when there is an intermittent supply. A Pearson correlation coefficient of 0.37 was found between TN and algal concentration. Nitrogen is an essential component for algal growth ([Chen *et al.* 2009](#)). There was a significant difference in TN concentration between MJTW and all zones.

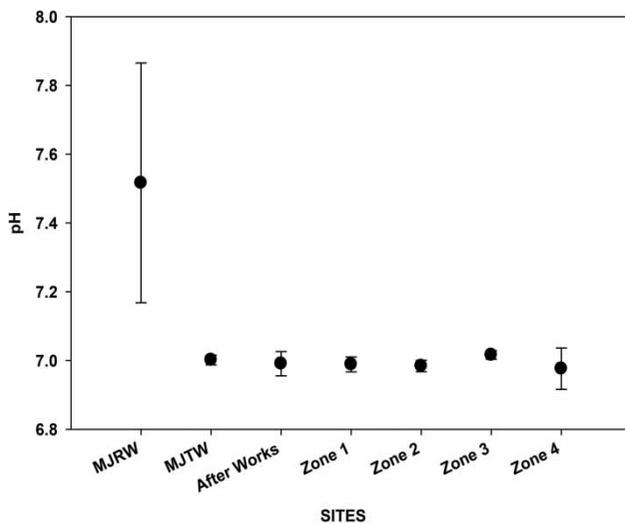
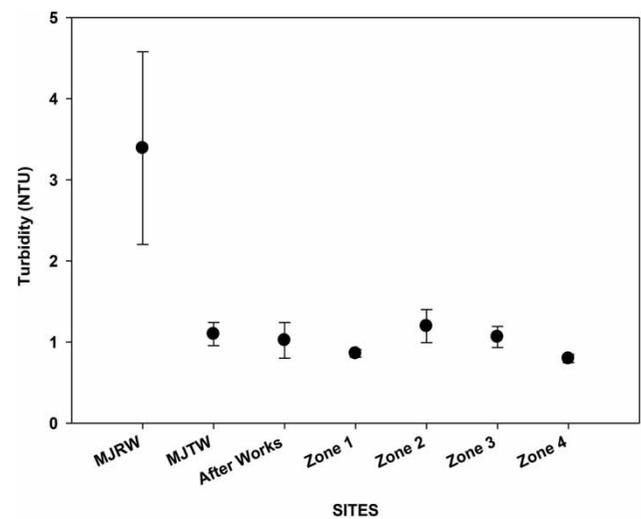
Total phosphorus

The variation in TP for all sampling points is presented in [Figure 8](#). The TP value of MJRW ranged from 0.16 to

Table 1 | Average values of water quality parameters for MJRW and MJTW and in the Harare distribution system, May–June 2017

Zone/sampling site	Site	pH	Turbidity (NTU)	TN (mg/L)	TP (mg/L)	Free residual chlorine (mg/L)	Algae (cells/mL)
MJRW	Morton Jaffray Raw Water	7.52	3.39	0.888	0.175	0.02	2,740
MJTW	Morton Jaffray Treated Water	7.00	1.10	0.337	0.031	0.59	50
1	Kuwadzana 5	7.00	0.88	0.392	0.041	0.43	50
1	Kuwadzana 2	6.98	0.84	0.405	0.043	0.49	45
2	Lochinvar	6.98	1.24	0.408	0.034	0.11	168
2	Glen View	6.99	1.16	0.411	0.052	0.05	232
3	Dzivarasekwa	7.02	1.12	0.379	0.046	0.21	135
3	Waterfalls	7.01	0.90	0.401	0.040	0.14	155
4	Belgravia	6.95	0.79	0.420	0.050	0.27	88
4	Mabelreign	7.07	0.83	0.423	0.059	0.13	215
	Min	6.95	0.79	0.379	0.034	0.05	45
	Max	7.07	1.24	0.423	0.059	0.49	232
	SD	0.04	0.18	0.01	0.01	0.16	136
	Mean	7.00	0.97	0.40	0.05	0.23	51.9
	CV	0.51	18.00	3.56	17.26	69.02	70.5
	WHO Guideline Value	6.5–8.5	5	–	–	0.2–0.5	–

Note: Calculations for SD, mean and CV do not include MJRW and MJTW.

**Figure 5** | pH variation for MJRW, MJTW and Harare water distribution system, May–June 2017.**Figure 6** | Turbidity variation of MJRW, MJTW and in the Harare water distribution system, May–June 2017.

0.19 mg/L (average 0.18 mg/L). *Nhapi et al. (2002)* found an average TP value of 0.60 mg/L in the lake, while *Ndebele & Magadza (2006)* reported TP values of 1.98–2.99 mg/L. These values were higher than those found in this study possibly due to different periods of sampling. The TP value of MJTW was 0.02–0.05 mg/L, with an average value of

0.03 mg/L. The TP value in Zone 1 ranged from 0.03 to 0.05 mg/L (average 0.04 mg/L). In Zone 2, it ranged from 0.01 to 0.07 mg/L (average 0.04 mg/L). The TP value in Zone 3 was 0.04–0.06 mg/L, with an average value of 0.04 mg/L. In Zone 4, it was 0.04–0.07 mg/L (average 0.05 mg/L).

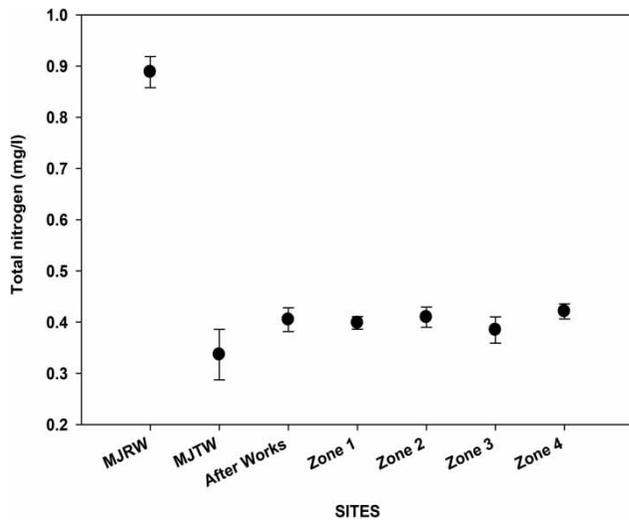


Figure 7 | Total nitrogen variation of MJRW, MJTW and in the Harare distribution system, May–June 2017.

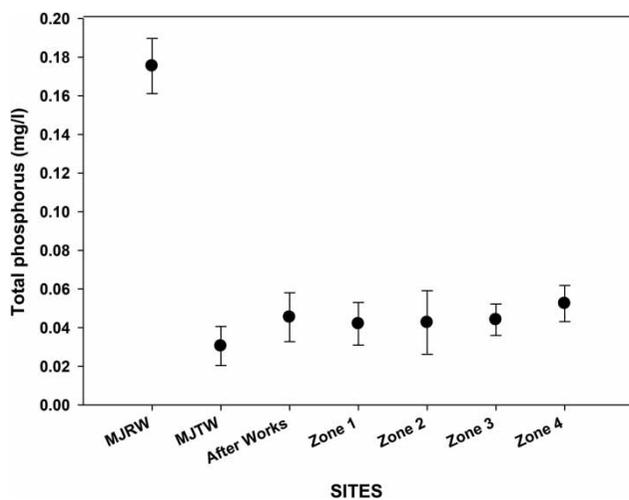


Figure 8 | Total phosphorus variation of MJRW, MJTW and in the Harare distribution system, May–June 2017.

TP in treated water at a water treatment plant in Belgium ranged from 0.3–0.5 $\mu\text{g/L}$ (Polanska et al. 2005), and this was lower than values found in this study. High TP content in water promotes algal growth (Tang et al. 2014). A Pearson correlation coefficient of 0.28 was found between TP and algal concentration. Phosphorus is critical for phytoplankton growth (Chen et al. 2009).

There were no significant differences in TP concentration between each zone and MJTW except Zone 4 ($p = 0.02$). The high levels found could be attributed to pollution

in the lake and intrusion of dirty water in the distribution system due to an ageing system.

Free residual chlorine

The trend of free residual chlorine for all study sites is shown in Figure 9. Free residual chlorine for MJRW was 0.00–0.03 mg/L (average 0.02 mg/L). According to Nhapi (2009), the wastewater treatment plants in the study area (which receive both domestic and industrial wastewater) are now overloaded and discharging partially treated wastewaters into main tributaries that feed into Lake Chivero, the potable raw water source for Harare. Thus, the traces of chlorine could be coming from wastewater effluent. MJTW had free residual chlorine of 0.55–0.62 mg/L (average 0.59 mg/L). Most waterwork operators in Zimbabwe target a residual chlorine of around 1 mg/L at the plant and slightly more for long transmission and distribution systems (Government of Zimbabwe 2012). Thus, the chlorine levels for MJTW appear on the low side, given the length of the distribution system. Chlorine boosting is needed at strategic positions of the network.

Free residual chlorine was 0.38–0.52 mg/L in Zone 1 (average 0.46 mg/L). In Zone 2, free residual chlorine values ranged from 0.04 to 0.16 mg/L, with an average value of 0.08 mg/L. In Zone 3, chlorine was 0.13–0.24 mg/L (average 0.19 mg/L). Free residual chlorine values ranged from 0.12 to 0.30 mg/L in Zone 4 (average

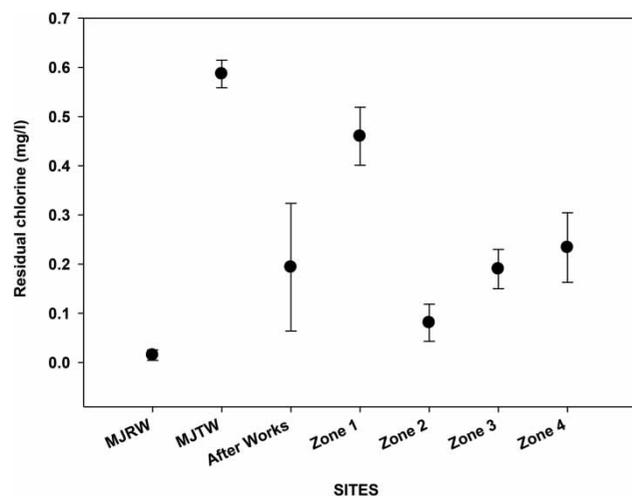


Figure 9 | Free residual chlorine variation of MJRW, MJTW and in the Harare distribution system, May–June 2017.

0.23 mg/L). The recommended guideline for residual chlorine is 0.2–0.5 mg/L (WHO 2011). All chlorine values for Zone 2 were below the minimum WHO requirement of 0.2 mg/L. Zone 2 receives water that does not get chlorine boosting and passes through reservoirs with a significant storage volume that increases the retention time and affects chlorine decay. The Harare water distribution system had free residual chlorine ranging from 0.05 to 0.7 mg/L (Nhongo et al. 2018). Chlorine decay in distribution networks is affected by the distance travelled by the water, water flow velocity, retention time, age and material of pipes and water pressure (Lee & Schwab 2005). As the distance from the water treatment plant increased, free residual chlorine concentration decreased. The approximate distances of Zones 1 and 2 from the water treatment plant are 16 and 19 km, respectively, while other zones are way beyond these distances. Zone 1 has only one reservoir, while Zone 2 has seven reservoirs. Thus, Zone 1 is likely to have a lower retention time than Zone 2.

A Pearson correlation coefficient of -0.77 was found between free residual chlorine and algal concentration and this was the strongest. Chlorine decreased with retention time in the system from MJTW to Zones 1 and 2. The boosting of chlorine at the WCR increased the chlorine in Zone 3, although the levels were lower than in Zone 1 but higher than in Zone 2.

A significant proportion of samples had residual chlorine levels below the recommended limit, suggesting a need for review of chlorine dosage at MJWTW and the identification of other points for chlorine boosting in Zones 2, 3 and 4. There were significant differences in free residual chlorine concentration between each zone and MJTW ($p = 0.00$).

Species and abundance of algae in raw water and the water distribution network

Species of algae

The algal community in both raw and treated water was composed of five taxonomic groups: Cyanophyceae (three species), Chlorophyceae (six species), Bacillariophyceae (two species), Euglenophyceae (two species) and Dinophyceae (two species) as presented in Table 2.

Mhlanga et al. (2006) found cyanobacteria, bacillariophytes, chlorophytes, cryptophytes and euglenophytes in Lake Chivero. There is evidence that some of the biofilms in water distribution components contain algae (Codony et al. 2003). Excessive growth of cyanobacteria in reservoirs that are used as potable water sources can result in severe problems during water treatment (Swanepoel et al. 2017).

Abundance of algae

The concentration of algae for the different species for all sampling sites is shown in Table 3, and the total algal concentration is shown in Figure 10. The algal concentration of MJRW was 1000–2740 cells/mL (average 1,533 cells/mL).

The total algal concentration of MJTW ranged from 10 to 130 cells/mL (average 50 cells/mL). The total removal efficiency for algae at MJTW was 94.0%, and this was comparable to the removal efficiency of 96.50% reported by Hoko & Makado (2011) for the same water works. For Damietta plant in Egypt, the removal efficiency of cyanobacteria of the plant was 99.7% (Mohamed et al. 2015). The total algal concentration in the distribution system ranged from 20 to 300 cells/mL, with an average value of 146 cells/mL. Compared to the levels of algae in the treated water, there was an increase in algal

Table 2 | Algae species for the Harare water supply system

Cyanophyceae	Chlorophyceae	Bacillariophyceae	Euglenophyceae	Dinophyceae
<i>Microcystis aeruginosa</i> , <i>Oscillatoria</i> sp. <i>Anabaena</i> sp.	<i>Scenedesmus quadricauda</i> , <i>Staurastrum gracile</i> , <i>S. polymorphum</i> , <i>Pediastrum simplex</i> , <i>P. duplex</i> , <i>P. gracillimum</i>	<i>Aulacoseira</i> sp. <i>Melosira</i> sp.	<i>Trachelomonas</i> sp. <i>Phacus</i> sp.	<i>Peridinium</i> sp. <i>Ceratium</i> sp.

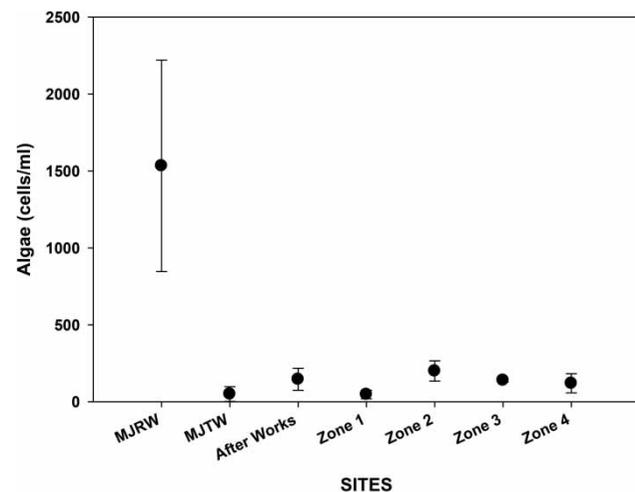
Table 3 | Algal concentrations for MJRW, MJTW and in the distribution system, May–June 2017

Sample		Cyanophyceae (cells/mL)	Chlorophyceae (cells/mL)	Bacillariophyceae (cells/mL)	Euglenophyceae (cells/mL)	Dinophyceae (cells/mL)
Morton Jaffray Raw Water	Minimum	640	100	70	40	0
	Maximum	850	950	300	60	30
	Mean	787	367	123	50	18
Morton Jaffray Treated Water	Minimum	0	0	0	0	0
	Maximum	100	20	10	10	10
	Mean	47	10	5	3	2
Zone 1	Minimum	0	10	0	0	0
	Maximum	50	20	10	10	10
	Mean	18	15	8	5	3
Zone 2	Minimum	10	10	0	0	0
	Maximum	240	50	50	30	10
	Mean	128	31	17	4	3
Zone 3	Minimum	30	10	0	0	0
	Maximum	120	30	10	10	10
	Mean	95	21	8	2	45
Zone 4	Minimum	50	10	0	0	0
	Maximum	180	50	10	10	10
	Mean	100	30	8	3	3

concentration in the distribution system, suggesting regrowth in the system. This could be due to the fact that free residual chlorine concentration in the distribution system was much lower than that at the treatment plant. Chlorine inhibits the growth of microorganisms (Aghaarabi *et al.* 2014).

Algae increased from the treatment plant to Zone 1. However, there was a larger increase in algal concentration from the plant to Zone 2. The concentration of algae in Zone 3 was lower than that in Zone 2, but Zone 4 had a higher concentration of algae than Zone 3.

Areas that had the highest concentration of free residual chlorine (Figure 9) had the least concentration of algae (Figure 10), while those that had the least free residual chlorine concentration (Figure 9) had the highest algal concentration (Figure 10). Cyanophyceae had the highest concentration in all the zones and in MJTW, while Dinophyceae had the lowest in all the zones. The concentration in all the zones was in the order Cyanophyceae > Chlorophyceae > Bacillariophyceae > Euglenophyceae > Dinophyceae. All the taxonomic groups showed regrowth in the distribution system. Algae have the ability to regrow in the dark when it uses organic matter as a source of carbon (Codony *et al.* 2003). Algal growth and microbial regrowth can also be promoted when water has a prolonged residence time in the

**Figure 10** | Algae variation of MJRW, MJTW and in the Harare distribution system, May–June 2017.

distribution system (El-Dars *et al.* 2015). There were significant differences in algal concentration between treated water and all zones except with Zone 4 ($p = 0.12$). There were no significant differences in algal concentration among all the zones. There is no limit for algae in the SAZ standards. Cyanobacterial cells in the treated water ranged from 2,200 to 14,200 cells/L at Damietta Plant in Egypt (Mohamed *et al.* 2015).

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the results of this study, the following conclusions were made:

1. Five algal taxonomic groups that were found in the raw water and also in the treated water at the plant and in the distribution system. Removal of algae at the treatment plant was high (90–97%).
2. The levels of algae in the distribution system showed regrowth for most of the algal groups and the concentration increased with an increase in retention time in the distribution system. Chlorine was found to be the parameter that affected the concentration of algae most in the distribution system.
3. All water quality parameters in the distribution system had average values that were within the SAZ and WHO guidelines, except for turbidity in Zone 2 that was higher than the SAZ guideline value. Residual chlorine in Zone 2 was lower than the WHO limit.

Recommendations

Boosting of chlorine for water that does not pass through the Warren Control Reservoir is recommended to reduce algal regrowth and also to ensure that the chlorine levels meet WHO recommended levels thus reducing public health risk.

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