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Feasibility of dissolved air flotation for drinking water treatment for Harare

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ABSTRACT

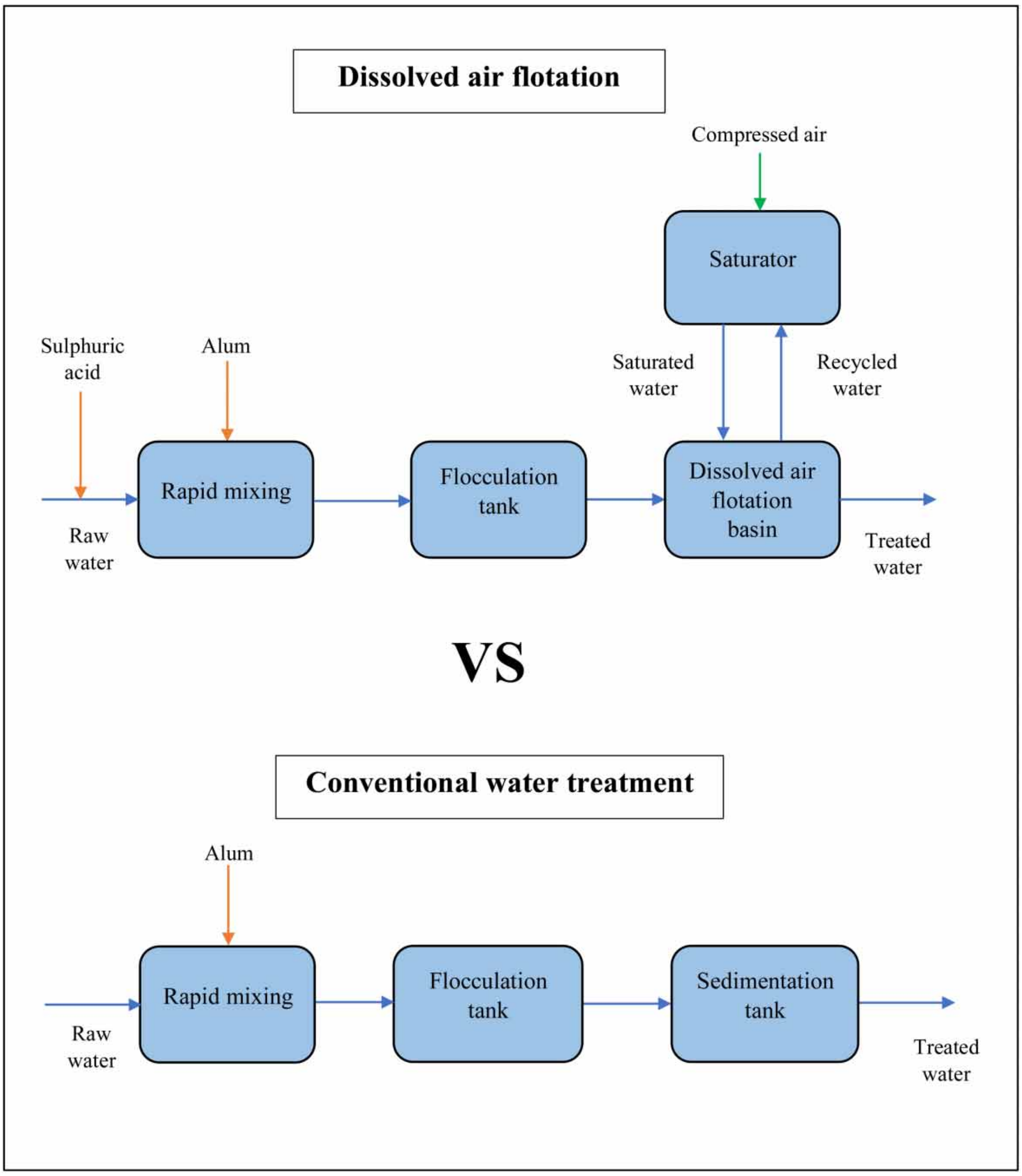
Lake Chivero, Harare's major raw water source, is eutrophic and algae-infested. Consequently, the conventional water treatment processes (CWTPs) that are used at Harare's main water treatment works, Morton Jaffray Water Treatment Works (MJWTW), have been ineffective in algae removal. This study was carried out to investigate the feasibility of using dissolved air flotation (DAF) to remove algae at MJWTW. Experiments were carried out using a 60-L DAF pilot system with a hydraulic loading rate of 7 m/h. Raw and treated water was characterised in terms of turbidity, pH and electrical conductivity (EC), and chlorophyll-a. Results showed reductions in turbidity, pH, and chlorophyll-a of 64, 27, and 95%, respectively. However, EC increased by 42% due to the addition of alum and acid. The DAF performed better than the CWTP currently used at MJWTW based on a comparison to a study carried out in the same period simulating conventional treatment of the same raw water and values reported in the literature for the CWTP. The adoption of DAF at MJWTW could potentially result in more efficient water treatment and better algae removal too. Further tests on optimum acid dosing for DAF are recommended while using alum as a coagulant.

Key words: algae, chlorophyll-a, dissolved air floatation, Lake Chivero, turbidity

HIGHLIGHTS

- Lake Chivero is eutrophic and algae-infested.
- The current conventional water treatment process (CWTP) being used are ineffective in algae removal.
- As such, water treatment costs at Morton Jaffray Water Treatment Works (MJWTW) have increased.
- Thus, algae have been observed in Harare's water distribution system.
- Dissolved air flotation (DAF) was considered an alternative to the CWTP as it is more effective in algae removal.

GRAPHICAL ABSTRACT



INTRODUCTION

Globally, the pollution of water resources has led to a decrease in water quality and rapid algae growth, which is associated with numerous health problems in humans (Czyżewska & Piontek 2019). As such, algae must be removed during the water treatment process. Algae can be removed by microstraining (physical), algaecides (chemical), and the application of coagulation, flocculation, sedimentation, filtration, and disinfection (conventional) respectively (Czyżewska & Piontek 2019; Shen *et al.* 2019). Although conventional methods are the most widely used techniques in algae removal in developing countries, they are now failing to deal with high levels of algae pollution (Hoko *et al.* 2021b). Conventional water treatment processes (CWTPs) fail to adequately remove algae since several algae species can regulate their buoyancy when alive and thus can avoid settling as stated by Hoko & Makado (2011). This presents a challenge when the CWTP is used to remove algae. Consequently, high doses of coagulant need to be applied for the effective removal of algae (Ghernaout *et al.* 2010). Therefore, dissolved air flotation (DAF), which takes advantage of the natural buoyancy of algae, can be applied to treat algae-infested water (Edzwald 2006).

DAF is a process that uses microbubbles to remove suspended matter dispersed in a liquid (Crittenden *et al.* 2012). DAF is the most suitable method for low-density particles and flocs (Edzwald 2006). The bubbles formed rise to the surface of the water with flocs attached to them due to their low density and are later skimmed off at the top (Edzwald 2011). After the water has been treated by DAF, clarified water (subnatant or floated water) is removed from the bottom while the accumulated sludge (float) is removed from the top (Brandt *et al.* 2017). The DAF process floats particles using microscopic bubbles that are produced by saturating recycled water with air at high pressure and subsequently releasing it at atmospheric pressure (Henderson *et al.* 2009). This makes DAF efficient for algae removal as the sludge with algae is raised to the surface. The sludge is removed by mechanical or hydraulic means (Crittenden *et al.* 2012). The most commonly applied mechanical sludge removal methods are scrappers which consist of rubber blades that push sludge into the collection channel and beach scrapers which scrap sludge from the sludge beach (Zabel 1985). DAF results in a 30% reduction in the amount of coagulant used compared to the CWTP for algae removal (Khiadani *et al.* 2014).

DAF has a cost–benefit extremely advantageous when compared to most algae removal techniques including centrifugation, filtration, flocculation, sedimentation, and flotation, demanding just 0.015 kW/m³ (Torres *et al.* 2017). DAF has been widely used to remove algae from water and has often proven more efficient than sedimentation for algae–water separation (Zhang *et al.* 2014). Teixera & Rosa (2007) concluded that DAF had better results as compared to clarifiers which resulted in reduced algal load on the filters consequently leading to a more efficient filtration process for the treatment of raw water from Thames River in the United Kingdom. Therefore, DAF is cost-effective and efficient for algae removal. However, the advantages of algae removal using DAF have not been fully exploited in southern Africa, where CWTPs are commonly used although the technology has been used in South Africa as stated by Muñoz-Alegría *et al.* (2021). An example of an algae-infested raw water source for drinking water is Lake Chivero in Zimbabwe (Dandadzi *et al.* 2020).

Lake Chivero has been reported to be highly eutrophic since the 1960s and its water quality has been getting worse with time (Nhongo *et al.* 2018). Consequently, Lake Chivero's water is now algae-infested, resulting in water treatment problems at Harare's main water treatment works, Morton Jaffray Water Treatment Works (MJWTW), as stated by Hoko *et al.* (2021b). The presence of algae in Lake Chivero has caused unpleasant taste and odour problems in drinking water in Harare and has also led to the detection of algae in Harare's water distribution system (Dandadzi *et al.* 2019). This implies that the CWTPs currently applied at MJWTW are ineffective in algae removal. Consequently, this has led to multiple challenges, including a low willingness to pay for water by the City of Harare's customers. It is for this reason that this study investigated the feasibility of the application of the DAF at MJWTW for algae removal, through laboratory experiments. The study was carried out in the period from April to May 2014. Physical (turbidity), chemical [pH and electrical conductivity (EC)], and biological (chlorophyll-a) parameters were used to assess the performance of the DAF pilot system.

MATERIALS AND METHODS

Study area

Location of study site

The study was carried out in a laboratory at the University of Zimbabwe using raw water from Lake Chivero, MJWTW's main raw water source. MJWTW is Harare's main water treatment plant and the City of Harare is responsible for the supply of water to Harare residents, the capital of Zimbabwe (Dandadzi *et al.* 2020). Figure 1 shows the location of Harare and MJWTW.

Background on MJWTW

MJWTW has a capacity of 614,000 m^3/day and it abstracts water from Lake Chivero and Lake Manyame (Hoko & Makado 2011). The treatment processes at MJWTW include coagulation–flocculation, sedimentation, filtration, disinfection, and stabilisation through the addition of lime (Hoko *et al.* 2021a). Figure 2 shows the water treatment processes at MJWTW.

Lake Chivero has become very eutrophic, thus algae have become one of the main problems affecting treatment of potable water at MJWTW (Hoko *et al.* 2021b). As such, the filter backwashing frequency has been between 4 and 8 h against the recommended 24–36 h and this has resulted in inefficient turbidity removal and low plant output (Hoko & Makado 2011). Consequently, there are recurring problems related to the quality and quantity of drinking water in Harare that have been linked to repeated outbreaks of cholera (WHO 2018).

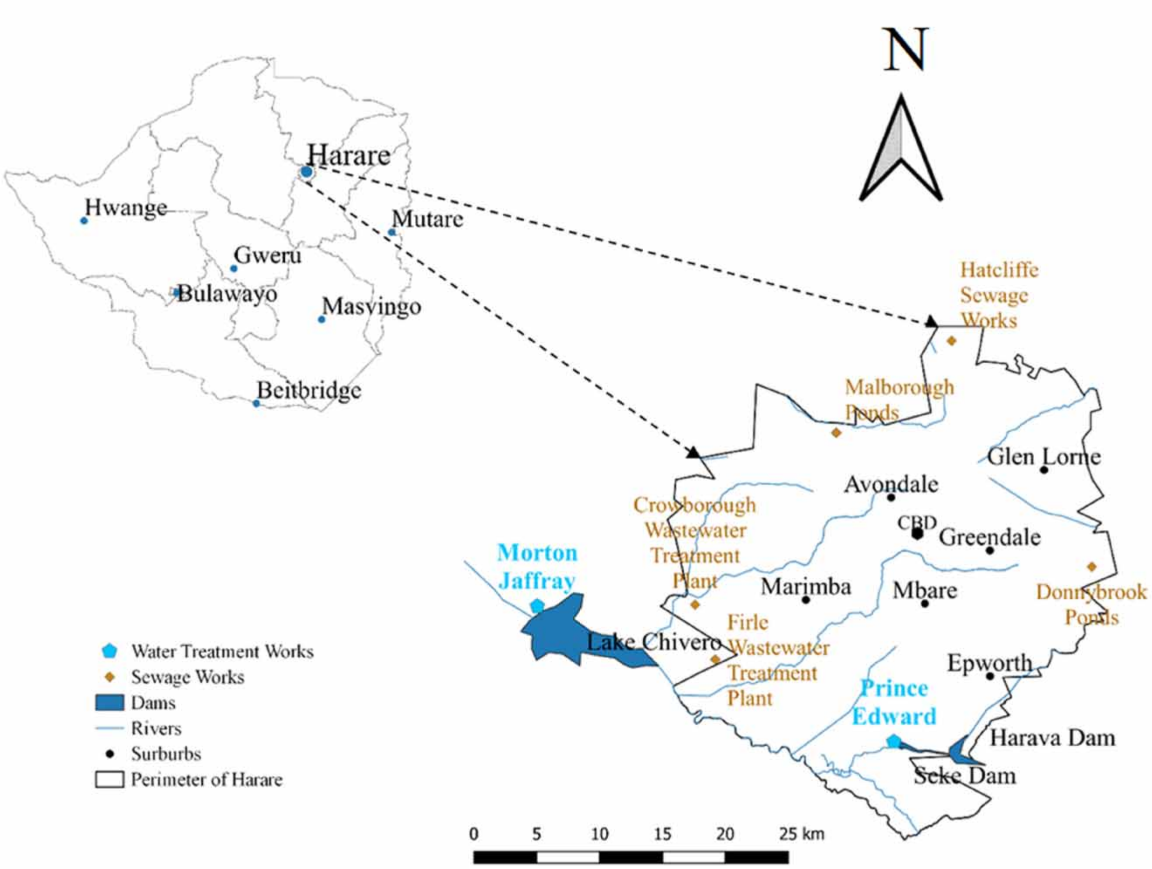


Figure 1 | City of Harare and the location of MJWTW (adapted from Hoko *et al.* 2021b).

Study design

Selection of study site

Harare, the capital city of Zimbabwe, faces drinking water quality problems because Lake Chivero is eutrophic (Hoko *et al.* 2021b). Consequently, MJWTW has been failing to produce acceptable-quality water (Dandadzi *et al.* 2019). There has been evidence of poor water quality in Harare's distribution system, including algae regrowth (Dandadzi *et al.* 2020). Thus, an effective algae removal process needs to be adopted at MJWTW.

Selection of study parameters

Physical (turbidity), chemical [pH and EC], and biological (chlorophyll-a) parameters were considered for this study. Turbidity is one of the key parameters for monitoring water and affects aesthetics (Sawyer *et al.* 2003). The pH of water affects the disinfection process, especially when chlorine is used, as is the case at MJWTW (Hoko & Makado 2011). EC is used to monitor the performance of water treatment (Sawyer *et al.* 2003). The presence of chlorophyll-a in water implies the presence of algae (EPA 2022).

Experimental design

A laboratory DAF pilot system was designed and set up in a laboratory at the University of Zimbabwe to assess the feasibility of the application of DAF for water treatment at MJWTW. The fabrication of the DAF pilot plant was followed by experiments using raw water obtained from the inlet at MJWTW. To compare DAF with the CWTP, the results of the DAF system were compared with those of a study by Hoko *et al.* (2021a) carried out during the same period using raw water from MJWTW. The study by Hoko *et al.* (2021a) investigated the use of alternative coagulants applied to the CWTP.

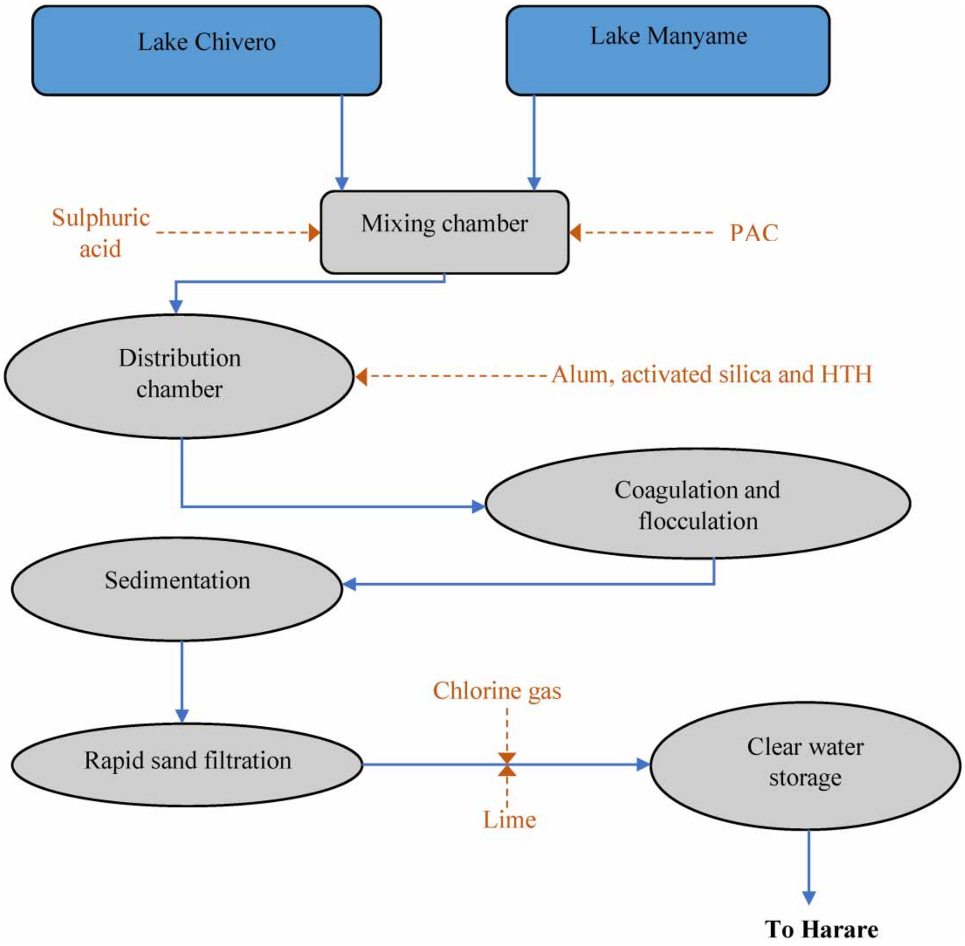


Figure 2 | MJWTW schematic (adapted from Hoko *et al.* 2021b).

Design and layout of the DAF pilot plant

Figure 3 shows the layout of the DAF pilot system.

The surface area, volume, and retention time of the DAF pilot system were calculated using Equations (1)–(3), respectively.

$$A_s = \frac{Q}{HLR} \tag{1}$$

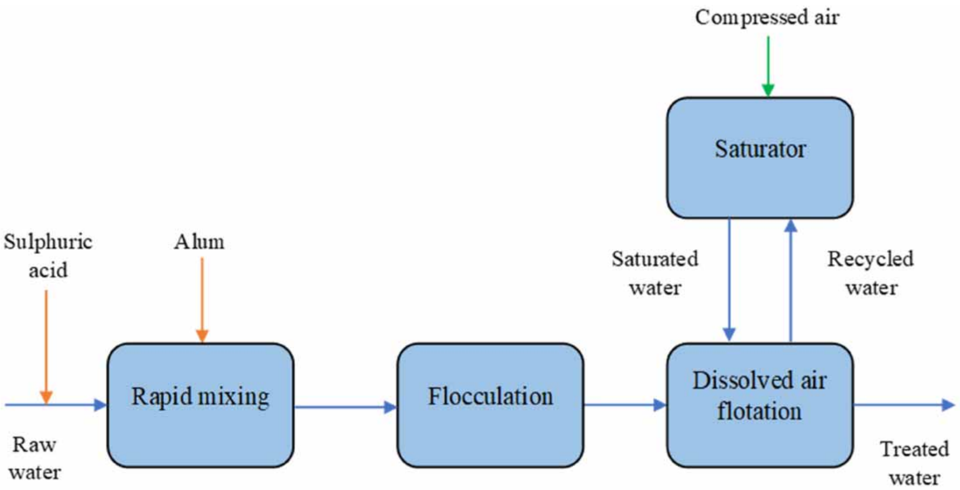


Figure 3 | Schematic of the laboratory-scale DAF system (Edzwald 2006).

where A_s is the surface area which includes contact and separation zone (m^2); Q is the process flow rate (m^3/s); HLR is the hydraulic loading rate (m/h).

$$V_{DAF} = A_s \times D_{DAF} \tag{2}$$

where V_{DAF} is the volume of the DAF pilot system (m^3); D_{DAF} is the depth of the DAF pilot system (m).

$$HRT = \frac{V_{DAF}}{Q} \tag{3}$$

where HRT is the hydraulic retention time (h).

Layout of the DAF basin

The DAF pilot system was fabricated using 5-mm thick perspex. The working volume of the DAF pilot system was 60 L while the HLR was 7 m/h. It consisted of a contact and the separation zone divided by an inclined baffle (Figure 4) to encourage re-circulation in the attachment zone and to prevent the back feed of air bubbles into the flocculation basin as suggested by Edzwald (2011).

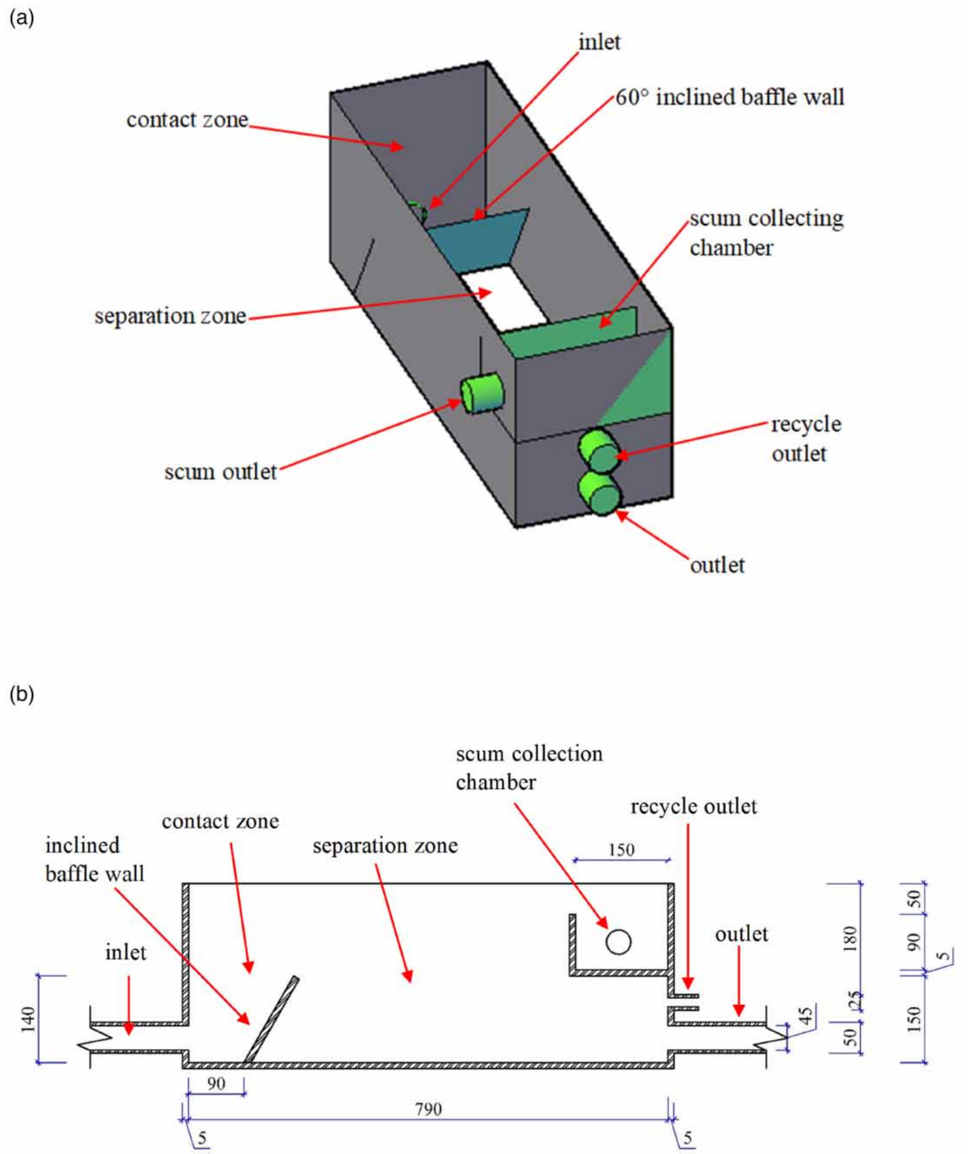


Figure 4 | (a): Three-dimensional view of the dissolved air floatation system and (b) section view of the dissolved air floatation system (all dimensions in mm).

DAF pilot system design and operational parameters

Table 1 shows the DAF pilot system design parameters which were adopted for this study.

Table 1 | Design parameters of the DAF pilot system

Parameter	Range in the literature	Selected value	Remark
Hydraulic loading rate (HLR) (m/h)	5–15[a]	5–10	Based on the available pump
Recycle rate (%)	5–12[b]	5–10	–
Pressure (kPa)	300–600	300	–
Process inflow rate (L/s)	–	0.2	Based on the available pump
Surface area (m^2)	–	0.2	Based on HLR
Retention time (min)	5–15[c]	5	Based on the volume

[a] Adapted from Crittenden *et al.* (2012).

[b] Adapted from AWWA (2011).

[c] Adapted from Edzwald (2006).

Design of the flocculation basin

The flocculation basin was fabricated using 5-mm thick Perspex. It consisted of four separate baffles (Figure 5) to ensure adequate mixing. Rapid mixing of the coagulant was carried out using a mechanical mixer with a maximum power rating of 120 W.

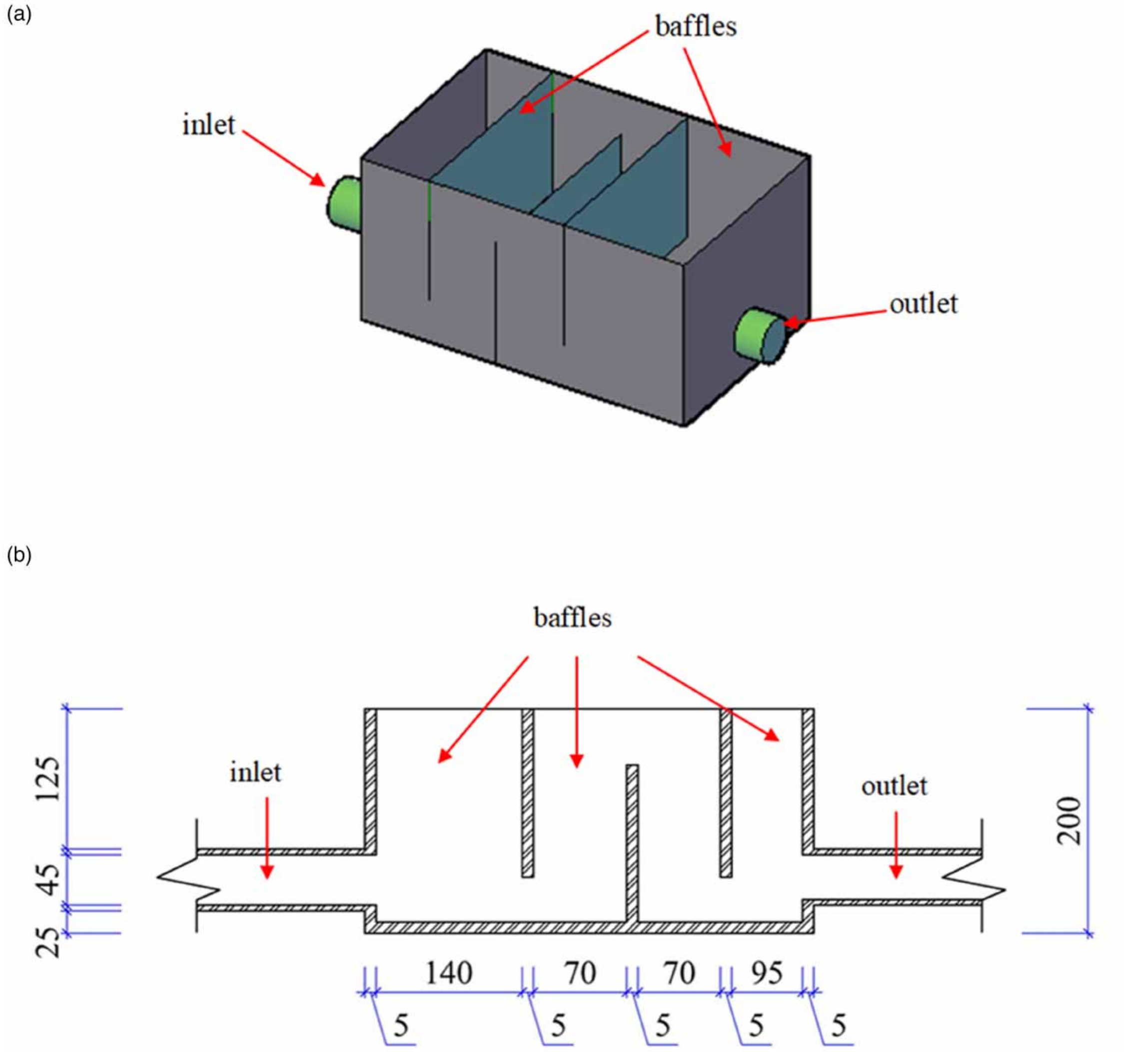


Figure 5 | (a) Three-dimensional view of the flocculation basin and (b) section view of the flocculation basin (all dimensions in mm).

The intensity of mixing in flocculation basins is based on the G value according to AWWA (2011). The G value and the number of baffles required were calculated using Equations (4) and (5), respectively:

$$G = \sqrt{\frac{P}{\mu V}} \tag{4}$$

where G is the velocity gradient (s^{-1}); P is the power transmitted (W); Q is the volumetric flow rate (m^3/s); μ is the dynamic viscosity (kg/ms); V is the volume of water in the basin (m^3).

$$n = \left[\frac{2\mu t}{p(1.44 + k)}\left(\frac{HLG}{Q}\right)^2\right]^{\frac{1}{3}} \tag{5}$$

where n is the number of baffles; H is the depth of water (m); L is the length of the basin (m); G is the velocity gradient (/s); Q is the flow rate (m^3/s); t is the time of flocculation (s); μ is the dynamic viscosity (kg/ms); ρ is the density of water (kg/m^3); k is the coefficient of friction of the baffles.

Determination of the coagulant dosage

Jar tests were carried out to determine the optimum alum dosage as recommended by Langlais & Degremont (2010). Alum was used because it is the coagulant currently used at MJWTW (Hoko & Makado 2011). Before the jar tests were carried out, the pH was lowered using sulphuric acid as is the practice at MJWTW to ensure that the pH falls within the optimum pH range for alum (Hoko *et al.* 2021b).

Operation of the DAF pilot system

The operation of the DAF system involved turning on the inflow pump and setting the inflow to the flocculation basin to the desired flow. The coagulant dosing was performed in the flocculation basin and a mechanical mixer was used for the rapid mixing process. The pH of the raw water was lowered using sulphuric acid to the recommended range for alum of around 6–7 (EPA 2017). An alum dosage of 12.46 mL/s was derived based on the dose (70 mg/L) determined from the jar tests, the process flow rate, and the percentage of aluminium oxide (Al_2O_3) in the alum. Rapid and slow mixing occurred for 5 min (alum reaction) and 2 min (flocculation) respectively in the flocculation basin before the water being fed to the DAF pilot system as recommended by Edzwald (1995). A saturator, which was elevated above the DAF basin to prevent backflow of water, was used to promote the formation of small bubbles. Air was blown into the system using a compressor through 1-mm nozzles as soon as the water was in the contact zone of the DAF basin. The sizes of the air bubbles were altered by adjusting the air inlet valve on the saturator. An air control valve and a pressure gauge were incorporated to allow regulation of air and measurement of the pressure. Recycling was initiated at the instance when the water level in the DAF basin was above the recycle pump suction level. The pressure in the saturation tank was controlled using a pressure regulator with a pressure of around 300–400 kPa as recommended by Liu *et al.* (2007). The recycling rate was also adjusted to balance the incoming air and the recycled water in the saturator using a calibrated valve on the saturator. The scum was removed by raising the water level in the flotation tank by throttling the outlet valve to allow the sludge to flow into the scum collection chamber. A pump was connected to recycle the water into the saturation vessel. The recycling rate was maintained between the recommended range of 6 and 12% (Edzwald 2011). The treated water samples were collected at the outlet for characterisation. The experiments were carried out to determine optimum pressure, coagulant dosage, and recycle ratio. Seven experiments were carried out for 30 min each (after adjustment of all operational parameters to ensure a steady state performance of the system) over 5 weeks, i.e. five campaigns.

The CWTP design and operation

This section describes the CWTP design and operation outlined in the reference study by Hoko *et al.* (2021a). The study was a parallel study carried out at the same time using the same raw water source in the same laboratory. The text below is extracted from Hoko *et al.* (2021a). The CWTP pilot plant comprised of a flocculation basin and sedimentation tank which were setup and fabricated in the University of Zimbabwe Construction and Civil Engineering Department Hydraulics laboratory. The setup was to test the performance of selected alternative coagulants having alum as the control, under flow through conditions to mimic the process at MJWTW.

Flocculation basin design

The volume and area of the flocculation basin was determined from Equations (6) and (7).

$$V = Q \times t \tag{6}$$

where V is the volume of the basin (m^3), Q is the inflow rate (m^3/h), t is the minimum detention time (h).

$$A = \frac{V}{D} \tag{7}$$

where A is the surface area of the basin (m^2); D is the tank depth (m).

Tables 2 and 3 show the design criteria and output for the CWTP pilot plant. Rapid mixing was achieved using a mechanical mixer with a power rating of 60 W.

$$V = L \times W \times D \tag{8}$$

where V is the volume of the basin (m^3), L is the length (m), W is the width (m), D is the depth (m).

Table 2 | Criteria for the design of the flocculation basin

Parameter	Unit	Design value	Literature ranges	Literature reference
t	min	15	10–20	DWD (1995); Degremont (2007)
Q	m^3/h	0.1	–	
D	m	0.2	–	
As	m^2	0.0125	–	

Table 3 | Output for the design of the flocculation basin

Parameter	Unit	Value
Length	m	0.6
Width	m	0.15
Depth	m	0.2
Area	m^2	0.0125

Rectangular sedimentation tank design

The design criteria and output of the sedimentation tank are presented in Tables 4 and 5. Degremont (2007) highlighted that sedimentation tanks have a length/width ratio of between 3 and 6. Equations (9) and (10) show the surface loading rate and tank depth were calculated.

$$A_s = \frac{Q}{v_s} \tag{9}$$

where v_s is the surface loading rate (m/h)

Table 4 | Design criteria for a rectangular sedimentation tank

Parameter	Unit	Design	Literature ranges	Literature references
v_s	$m^3/m^2 \cdot h$	0.5	0.5–1	Degremont (2007)
t	h	0.5	2–4	Bahadori *et al.* (2013)
D	m	0.25	–	–

SLR, surface loading rate; t, hydraulic detention time; A_s, surface area of basin; D, tank depth.

Table 5 | Design output for a rectangular sedimentation tank

Parameter	Unit	Value
Length	m	0.90
Width	m	0.20
Depth	m	0.25
A_s	m^2	0.2

A_s, surface area of basin.

where A_s is the surface area of sedimentation tank (m^2), v_s is the surface loading rate ($m^3/m^2{\cdot}h$).

$$D = v_s \times t \tag{10}$$

where D is the tank depth (m).

Operation of the CWTP plant

A grab sample of raw water was collected in May 2014, during one campaign to feed the CWTP pilot plant. The efficacy of alum was investigated under continuous flow conditions. Three pilot plant test runs were conducted. The flow schematic of the pilot plant is shown in Figure 6. A grab sample of the effluent was collected after 30 min of running the pilot plant for each test run. The effluent was tested for pH, turbidity, EC, and chlorophyll-a concentration.

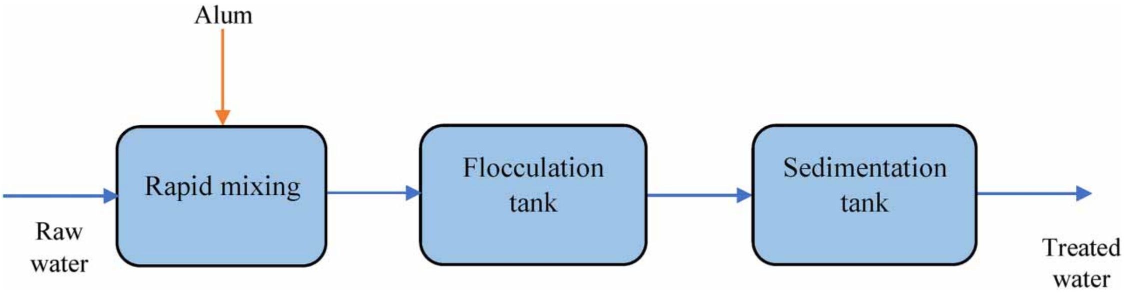


Figure 6 | Flow schematic of the CWTP pilot plant.

Raw and treated water sampling

Seven composite raw water samples were obtained from Lake Chivero on different days and treated in the DAF system each time samples were collected. They were transported to the laboratory in 20-L plastic containers. From these containers, the water was taken and fed into the DAF pilot system. Grab samples for treated water were collected on the lower outlet of the DAF system.

Methods of water quality analysis

Raw and treated water was characterised in terms of turbidity, pH, EC and chlorophyll-a concentration. The characterisation was carried out at the Department of Construction and Civil Engineering and the Department of Biological Sciences laboratories of the University of Zimbabwe. EC, pH and turbidity were analysed according to the procedures outlined in Standard Methods for the Examination of Water and Wastewater (APHA 2012). Chlorophyll-a concentration was determined using the method described by Brönmark & Hansson (2005). Table 6 shows the equipment and methods used for water quality testing.

Methods of data analysis

Statistical analysis that included the coefficient of variation (CV) and *t*-test were used to determine the variation of the water quality parameters and also the efficiency of water treatment by DAF.

Table 6 | Methods and equipment of water quality testing

Parameter	Analytical instrument	APHA method number	Equipment brand
Turbidity	Turbidity meter	2130B	Hanna (HI 9803)
pH	pH ion meter	4500-H^+	Hanna
Electrical conductivity	Conductivity meter	–	Lasany Microprocessor 1–50
Chlorophyll-a	Acetone extraction	–	–

RESULTS AND DISCUSSION

Raw water characteristics

Table 7 shows the results for raw water characterisation of the Lake Chivero water which was collected at MJWTW inlet works.

Table 7 | Summary of Lake Chivero raw water quality from April 2014 to May 2014 ($n = 7$)

Campaign number	1	2	3	4	5	6	7	Mean	Std deviation	CV (%)
Turbidity (NTU)	4.04	4.04	3.72	3.72	3.14	3.26	3.26	3.60	0.38	10.5
pH	8.0	8.4	7.3	7.7	8.0	7.2	7.5	7.73	0.43	5.6
EC (μS/cm)	483	483	328	328	339	339	339	377	72.6	19.3
Chlorophyll-a (μg/L)	2.12	2.12	1.92	1.92	0.36	0.36	0.36	1.31	0.89	68.1

The turbidity of the raw water ranged from 3.14 to 4.04 NTU with a mean of 3.60 NTU and a low CV of 10.8%. The range of raw water turbidity was comparable to the range of 3.0–3.6 NTU that Hoko *et al.* (2021a) obtained for the same raw water source during a study carried out around the same time as the current one. This was expected as both studies were carried out around the same time. The turbidity for Lake Chivero raw water was in the lower band for typical surface water sources which normally range from 1 to 200 NTU as highlighted by Sharma & Bhattacharya (2017). Thus, the turbidity of raw water found in this study was in the suggested range for lakes.

The raw water pH ranged from 7.2 to 8.4 with a mean of 7.7. The low CV (5.6%) implied that the pH did not vary much during the study period. The pH range of raw water obtained for this study was comparable to 7.3–8.2 found by Dandadzi *et al.* (2019) for the same water source. The pH was in the 5.0–9.0 range suggested by EPA (2001) for surface water sources. According to EPA (2017), the optimum pH range for coagulation and flocculation when alum is used as the coagulant is 6–7. Thus, the pH was higher than that required for the coagulant (alum) used for the experiments. Therefore, a pH adjustment was necessary for the effective use of alum.

The raw water EC ranged from 328 to 483 μS/cm with a mean of 377 μS/cm and moderate CV of 19.3% suggesting a moderate variation in the EC of raw water during the study period. The range of EC obtained in this study for raw water was comparable to the range 440–528 μS/cm obtained by Hoko *et al.* (2021b) for the same water source. The EC obtained in this study was below the 1,000 μS/cm limit highlighted by EPA (2001) for surface water sources. Therefore, the raw water EC was moderate during the study period.

The raw water chlorophyll-a concentration ranged from 0.36 to 2.12 μg/L with a mean of 1.31 μg/L and a high variability (CV = 67.9%). The mean chlorophyll-a concentration in raw water was comparable to 2.28 μg/L obtained by a study by Hoko *et al.* (2021a) for the same raw water source. The chlorophyll-a concentration in the raw water was lower than the 33.89 μg/L obtained by Mogakabe & Van Ginkel (2008) for Bospoort Dam in South Africa. In addition, the chlorophyll-a concentration was below the 5 μg/L highlighted by ANZECC & ARMCANZ (2000) for freshwater reservoirs and lakes. Dandadzi *et al.* (2019) stated that the detection of chlorophyll-a infers the presence of algae. According to EPA (2022), one of the symptoms of degraded water quality condition is the increase of algae biomass as measured by the concentration of chlorophyll-a. Therefore, the long-term concentration of chlorophyll-a in the raw water signifies that the raw water is eutrophic. Thus, it can be concluded that there were algae in the raw water from Lake Chivero.

Raw water from Lake Chivero was characterised by moderate turbidity, slightly alkaline pH, high EC and high chlorophyll-a concentration. This indicates that the raw water from Lake Chivero was polluted which could render conventional water treatment ineffective to treat the water. Due to the slightly alkaline pH, it was necessary to adjust the pH of the raw water by adding sulphuric acid for effective coagulation.

Determination of alum dose

Figure 7 shows the results of the determination of the alum dose for the raw water from Lake Chivero. The pH and turbidity values of the settled water were used to determine the optimum dose of alum. The optimum alum dose was found to be around 70 mg/L as beyond this, turbidity increased, and pH decreased. The 70 mg/L corresponds to a turbidity of 1.61 NTU and a pH of 7.2. The settled water pH was higher than the 6.40 and 6.65 that were obtained by Hoko *et al.* (2021a) and Hoko *et al.* (2021b) after the jar test for the same raw water source. The optimum alum dose was comparable to 60 mg/L after pH correction obtained by Hoko *et al.* (2021b), but less than the 55 mg/L obtained by Hoko *et al.* (2021a) without pH correction for the same raw water source. The alum dosage required for the treatment of Lake Chivero raw water was higher than the typical doses applied in most treatment plants, which are in the range of 15–50 mg/L (Smethurst 1988). Therefore, the alum doses applied to the Lake Chivero raw water are high and imply increased water treatment costs.

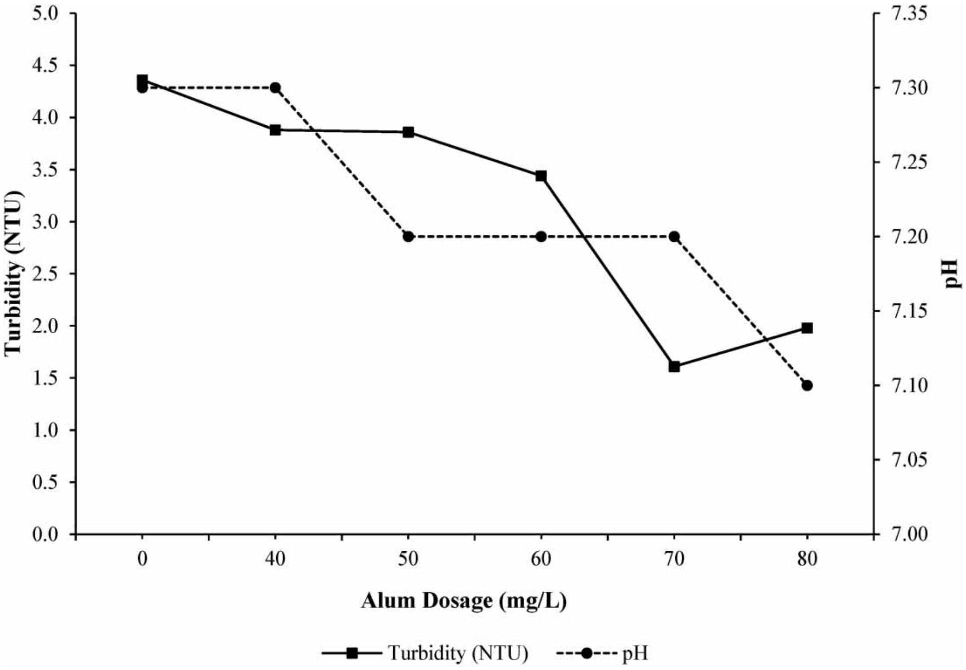


Figure 7 | Determination of the optimum dosage for alum (April 2014).

Performance of the dissolved air floatation system

Results from the experiments carried out on the treatment of raw water from Lake Chivero using the DAF pilot system are presented in this section. The results are based on the analysis of composite samples of raw water fed into the DAF pilot system and effluent from the system for each of the seven campaigns. The performance of the DAF pilot system for the parameters selected (turbidity, pH, EC, and chlorophyll-a concentration) is presented in the sections that follow. The performance of the DAF pilot system which simulated the processes of coagulation, flocculation, and DAF (termed DAF in this paper) were compared to a similar study carried out during the same period using the Lake Chivero raw water which simulated CWTPs of coagulation, flocculation, and sedimentation. Thus, essentially, the DAF basin should be compared to the sedimentation basin.

Turbidity

The turbidity results of raw water and the treated effluent from the DAF pilot system are shown in Figure 8. The raw water turbidity ranged from 3.14 to 4.04 NTU with a mean of 3.60 NTU and a low CV of 10.8%, while the treated

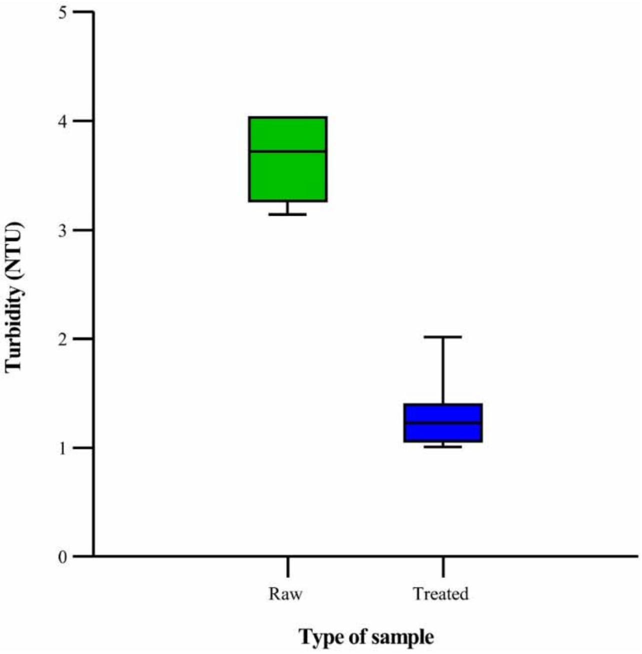


Figure 8 | Variation of raw water (after adding acid) and treated water turbidity from the period April 2014 to May 2014.

water turbidity ranged from 1.01 to 2.02 NTU with a mean of 1.31 NTU and a moderate CV of 29.8%. A paired *t*-test at a 95% confidence interval showed that the reduction in turbidity as a result of treatment by DAF was statistically significant ($p < 0.05$). However, both the raw and treated water turbidity were below the maximum recommended value of 5 NTU by WHO (2011) although they were both above the 1 NTU recommended by SAZ (1997).

The treatment of raw water by the DAF system reduced turbidity by 64%, which was lower than the 82.8% obtained by Teixeira & Rosa (2007) for DAF. This was higher than the 53% found by Hoko *et al.* (2021a) when the CWTP (across the sedimentation unit) was simulated for the same water source around the same period. However, Officer *et al.* (2001) obtained a much higher turbidity removal efficiency of 97% when DAF was used at Farmoor Water Treatment Works in the United Kingdom where the raw water from the Thames River was used. To increase the turbidity removal efficiency for the raw water from Lake Chivero, the use of alternative coagulants as suggested by Hoko *et al.* (2021a) together with DAF could be adopted. It can be concluded that DAF has a higher turbidity removal efficiency for the treatment of raw water from Lake Chivero compared to the CWTP. As such, the City of Harare should consider incorporating DAF in the water treatment process at MJWTW to replace the current sedimentation process being used. This could potentially result in longer filter runs and reduction in the coagulant dose applied during water treatment.

pH

Figure 9 shows the results of the variation of pH for both raw (after adding acid) and treated water. The addition of acid was done to attain the target operating range for alum which ranges from 6 to 7 (EPA 2017). Consequently, the pH decreased slightly to below neutral after the addition of sulphuric acid. The raw water pH before the addition of acid ranged from 7.2 to 8.4 with a mean of 7.7 and a low CV of 5.6% while the raw water pH range after the addition of sulphuric acid was 6.5–6.9 with a mean of 6.7 and a low CV of 2.99%. The addition of sulphuric acid reduced the mean pH by 17.3% and resulted in the pH being in the optimal range for coagulation (6–7) for alum. Treated effluent pH ranged between 4.8 and 5.1 with a mean of 4.9 and a low CV of 2.04%. The pH of treated water was lower as compared to that of raw water (both before and after adding the acid) as a result of the H^+ ions formed during the hydrolysis reaction of the metal ion in the alum. A paired *t*-test at a 95% confidence interval showed that the reduction in pH as a result of treatment by DAF was statistically significant ($p < 0.05$). According to Qasim *et al.* (2000), the pH for effective chlorination should be less than 8.5. However, the treated water was outside the recommended pH range by WHO (2011) of 6.5–8.5. Therefore, there will be a need to correct the pH at the end of the treatment process by the addition of lime as is the current practice at MJWTW.

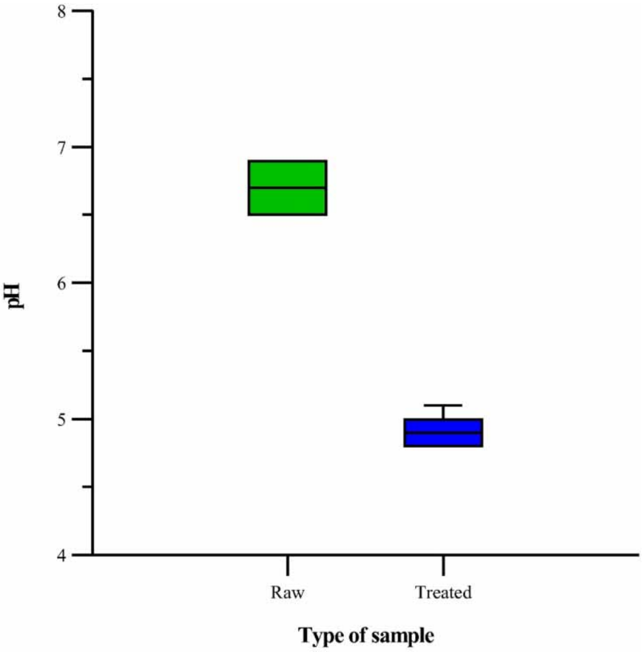


Figure 9 | Variation of pH for raw water (after adding acid) and treated water pH from the period April 2014 to May 2014.

The treatment of water with DAF further reduced the pH by 27% after the pH had initially been reduced due to the addition of sulphuric acid, which is higher than the 10% reduction in pH obtained by Hoko *et al.* (2021a) where the CWTP was simulated. The pH of water affects the effectiveness of chlorine disinfection, and according to WHO (2011), chlorine disinfection is more effective at low pH values of less than 8. Thus, further tests on determining the optimum acid dosing while using DAF should be carried out using raw water from Lake Chivero.

Electrical conductivity

Figure 10 shows the EC results of raw water and treated effluent from the DAF pilot system. The raw water EC before acid addition ranged from 328 to 483 μS/cm with a mean of 377 μS/cm and a moderate CV of 19.3% while

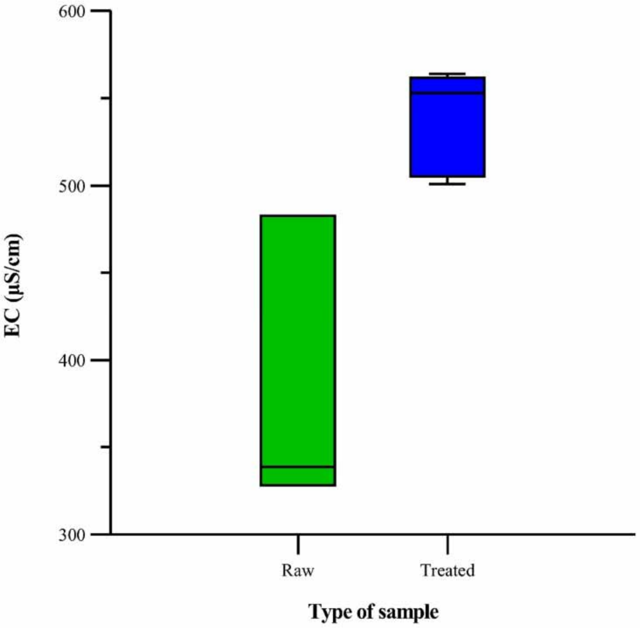


Figure 10 | Variation of raw water (after adding acid) and treated water EC from the period April 2014 to May 2014.

the EC before the addition of sulphuric acid ranged from 501 to 564 μS/cm with a mean of 537 μS/cm and a low CV of 5.48%. A paired *t*-test at a 95% confidence interval showed that the increase in EC after treatment by DAF was statistically significant ($p < 0.05$). According to SAZ (1997), the standard EC value for potable water is 700 μS/cm and the recommended maximum is 3,000 μS/cm therefore, both the raw water and treated water EC were all within the recommended range.

The treatment of water by DAF increased the EC by 42%. This was higher than the 5% increase obtained by Hoko *et al.* (2021a) where the CWTP was simulated. The EC increment was likely to have been caused by the addition of the coagulant (alum) for turbidity removal as mentioned by Hoko *et al.* (2021a). The increase in EC was also likely to have been caused by the addition of sulphuric acid as metals tend to be more soluble when the pH decreases as highlighted by Zhang *et al.* (2018). Therefore, the adoption of DAF at MJWTW could result in an increase in the EC of the treated water.

Chlorophyll-a concentration

Figure 11 shows the chlorophyll-a concentration results of raw water and the treated effluent from the DAF pilot system. The chlorophyll-a concentration in raw water ranged from 0.36 to 2.12 μg/L with a mean of 1.31 μg/L and a high CV of 67.9%, while the chlorophyll-a concentration for treated water ranged from 0 to 0.36 μg/L with a mean of 0.07 μg/L and high CV of 190%. A paired t-test at a 95% confidence interval showed that the reduction in chlorophyll-a concentration after treatment by DAF was statistically significant ($p < 0.05$). In this study, no algae counts and algal species characterisation was carried out. However, the detection of chlorophyll-a infers the presence of algae (Srinivasan & Sorial 2011). Therefore, it can be concluded that the algae in raw water was significantly reduced after treatment with the DAF pilot system. Although there was significant removal of chlorophyll-a, treated water at this stage was outside the recommended WHO Guideline alert level 1 of 0.001 μg/L.

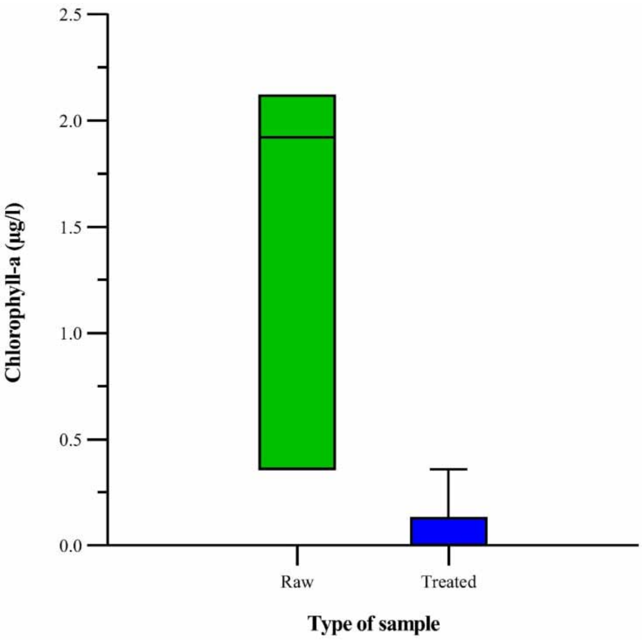


Figure 11 | Variation of chlorophyll-a in raw water (after adding acid) and treated water a from the period April 2014 to May 2014.

Treatment with DAF resulted in a chlorophyll-a removal efficiency of 95%, similar to the chlorophyll-a removal efficiency of 91.8% obtained by Teixeira & Rosa (2007) when DAF was used to treat water. The chlorophyll-a removal efficiency by the CWTP in a study carried out by Hoko *et al.* (2021a) using the same source of water was 52%. Dandadzi *et al.* (2020) established algae regrowth in the water supplied by the City of Harare to its residents. Therefore, it was concluded that DAF had a higher chlorophyll-a removal efficiency compared to the CWTP. The adoption of DAF in the water treatment process as MJWTW could significantly reduce or eliminate algae in treated water.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

It was concluded that the DAF system performed better for Lake Chivero raw water treatment in terms of turbidity and chlorophyll-a compared to CWTPs. However, the adoption of DAF is likely to result in an increase in EC and a pH reduction. Nevertheless, it is feasible to adopt DAF for efficient algae removal and longer filter runs leading to higher output at MJWTW.

Recommendations

Further tests to be carried on determining the optimum acid dosage for DAF while using alum as a coagulant.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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