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Investigating opportunities for use of alternative coagulants for drinking water treatment at Morton Jaffray Water Treatment works, Harare, Zimbabwe

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Abstract

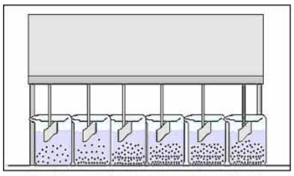
Drinking water treatment at Harare's main water works, Morton Jaffray Water Treatment Works (MJWTW), has been a challenge due to source (Lake Chivero) pollution, and the efficacy of some of the processes and chemicals including aluminium sulphate (alum) has been questioned. This study investigated the use of an alternative coagulant to the traditional use of alum at MJWTW. The effectiveness of five coagulants, namely Anhydrous Poly Aluminium Chloride (APAC), Poly Aluminium Chloride (PAC), Primco 100, Zetafloc 4030 and alum (control) was investigated by flocculation tests in a laboratory using Lake Chivero water. Parameters analysed included pH, turbidity, Electrical Conductivity (EC) and chlorophyll-a for raw water and treated water. Raw water mean pH was 7 ± 0.4, turbidity (3.3 ± 0.2 NTU), EC (337 ± 5.0 μS/cm) and chlorophyll-a concentration (2.28 μg/L). Primco 100 had the best performance with the lowest optimum dosage of 25 mg/L while alum had the highest dosage of 55 mg/L. APAC, PAC, Primco 100 and Zetafloc 4030 did not change the pH of water significantly but alum did. The study concluded that Primco 100 was the most suitable coagulant and could be an alternative to alum.

Key words: alternative coagulant, drinking water, Lake Chivero, Morton Jaffray Water Works, water treatment

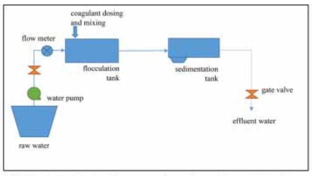
Highlights

- Provides insight on developing technology on coagulants for treatment plants.
- Closes research gap on use of alternative coagulants at water treatment plants in Zimbabwe.
- Provides practical guidelines on how to select a new coagulant, especially in developing countries.
- Provides insights on cost saving measures in water treatment process at MJWTW.
- Provides extensive methods of laboratory tests in assessing efficacy of coagulants.

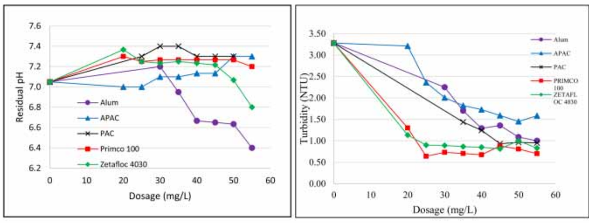
Graphical Abstract



Flocculation tests to determine best coagulant out of 5 options



Pilot plant setup to test performance under continuous flow conditions for best coagulant



Results of settled water after flocculation tests with treatment of each of the 5 coagulants

INTRODUCTION

Traditionally, metallic salts such as aluminium sulphate (alum) and ferric chloride have been widely used in drinking water treatment as coagulants (Gebbie 2006; Tzoupanos & Zouboulis 2008; Leopold & Freese 2009; Sahu & Chaudhari 2013). Limited documented studies have been carried out in Zimbabwe concerning the use of alternative coagulants to alum at water treatment plants. However, it has been investigated and shown elsewhere that there are other coagulants such as polymeric coagulants that can be used instead of alum and they have been reported to enhance water quality at a lower cost (Nozaic *et al.* 2001; Kurenkov *et al.* 2003; Momba *et al.* 2006, 2009; Tzoupanos & Zouboulis 2008; Selami *et al.* 2013).

Some 60–70% of the total chemical costs in treating drinking water are contributed by coagulants (McCool 2009). It has been concluded that the use of polymeric coagulants significantly enhances the drinking water quality and considerably decreases the treatment costs (Kurenkov *et al.* 2003; Tzoupanos & Zouboulis 2008). Moreover, the finest results are achieved in a narrow concentration range of the polymeric coagulant (Nozaic *et al.* 2001). Polymer blends (aluminium polyamines) and aluminium chlorohydrates ($\{Al_n(OH)_mCl_{3\,m\text{-}m}\}_n$) are typical polymeric coagulants being used at several water treatment plants (Gebbie 2006; Tzoupanos & Zouboulis 2008). Some of the chemicals that have been reported to be effective in treating heavily polluted water are Poly-Aluminium Chlorides (PACs), Primco and Zetafloc (Gebbie 2006). These, however, are only trade names used by manufacturers as most of these are aluminium polyamines or polymeric coagulants and different manufacturers formulate coagulant products according to their own design, particularly in this field of polyelectrolyte chemicals (EPA 2002).

Many water supply agencies have abandoned the use of alum and ferric chloride in favour of polymeric coagulants (Nozaic *et al.* 2001; Kurenkov *et al.* 2003; Gebbie 2006; Momba *et al.* 2006; Momba *et al.* 2009). Studies were conducted at water treatment plants to compare use of polymeric coagulants with traditional inorganic coagulants in treating water and the conclusion was that there was significant improvement in water quality and reduced water treatment costs (Gebbie 2006; Tzoupanos & Zouboulis 2008). It was also concluded that with polymeric coagulants, there is reduced need for pH control, decreased sludge production, improved sludge dewatering, reduced residual aluminium content in treated water and most importantly reduced chemical costs (Leopold & Freese 2009). Thus, good decision making is essential as to which type and concentration of coagulant to use. The best method of comparing coagulants is to assess coagulant performance and treatment cost (McCool 2009). It is against this background that the polymeric coagulants should be investigated.

The main raw water source for Morton Jaffray Water Treatment Works (MJWTW), Lake Chivero, has been heavily polluted (Nhapi *et al.* 2002; Nhapi & Hoko 2004; Hoko & Makado 2011). Poorly treated wastewater is being discharged into Lake Chivero (Nhapi & Hoko 2004). Sewage contributes 40% of nutrient input into the lake (Nhapi *et al.* 2002; Gumbo 2005). High phosphorus levels of about 5 mg/L have been reported for Lake Chivero (Magadza & Ndebele 2006). The proliferation of algae resulting from excessive pollution has become a major problem to water treatment at MJWTW (Hoko & Makado 2011). This has also led to an increase in the chemical demand, including alum. Moreover, this has resulted in deterioration of the drinking water quality in the distribution system of Harare (Dandadzi *et al.* 2020). The poor quality of potable water in Harare has led to loss of customer confidence in the City of Harare's water and low willingness to pay for the service (Dandadzi *et al.* 2019).

The City of Harare now uses up to nine water treatment chemicals (i.e. (i) powdered activated carbon, (ii) sulphuric acid, (iii) sodium silicate, (iv) aluminium sulphate, (v) white hydrated lime, (vi) chlorine gas, (vii) HTH, (viii) anhydrous ammonia and (ix) PAC) at high dosages, leading to a very high cost to treat Lake Chivero water (Hoko & Makado 2011). When the treatment units were constructed and commenced operations, in 1960, only chemicals such as alum, lime and chlorine were used in the treatment process and application was at relatively low dosages (Hoko & Makado 2011). The deterioration of raw water quality has led to continuous increase in alum doses at Morton Jaffray (Moyo 1997; Hoko & Makado 2011). In 1982, the dosage was 40 mg/L and it increased to 100 mg/L in 1995, a 150% increment in 13 years (Moyo 1997; Muisa *et al.* 2011).

Studies have reported algae as a problem in Harare's drinking water (Nhongo *et al.* 2018; Dandadzi *et al.* 2019). Magadza & Ndebele (2006) reported that microcystin concentration in Lake Chivero is about 19.89 μg/L against the guideline of 1 μg/l (WHO 2006). In a study conducted at Morton Jaffray, Hoko & Makado (2011) found out that high dosages of alum ranging from 90 mg/L and 110 mg/L were needed to improve algae removal. High algal concentrations in raw water have high cost implications due to the high chemical demand, particularly for coagulation and disinfection. When properly performed and optimised, coagulation, flocculation and sedimentation can result in efficient and significant removal of algae (Hoko & Makado 2011). High algae levels increase the organic load in water, which increases the chlorine demand and the risk of formation of carcinogenic trihalomethanes (THMs). Nhongo *et al.* (2018) reported THMs in the Harare Water Distribution System.

Alum quantitatively contributes to the bulk of the chemicals used at MJWTW and takes the largest fraction of the water treatment chemical costs (Hoko & Makado 2011). Furthermore, approximately 60–70 tonnes of alum were used per day at Morton Jaffray (Muisa *et al.* 2011), particularly during the rainy season. As such, this stage is where considerable cost savings are possible (Tzoupanos & Zouboulis 2008). There has not been detailed investigation on whether the use of alternative coagulants could reduce treatment cost, increase water output, enhance water quality and optimize the coagulation-flocculation process for algae removal at Morton Jaffray. Given this background, this study investigated opportunities for use of alternative coagulants for treating raw water from Lakes Chivero and Manyame at MJWTW. The study compared the performance of five coagulants on the market through flocculation tests in a laboratory. The coagulants tested included; alum, anhydrous poly aluminium chloride (APAC), poly aluminium chloride (PAC), Primco 100 and Zetafloc 4030. The raw water characterization and evaluation of performance of the coagulants was based on levels of pH, turbidity, electrical conductivity and chlorophyll-a concentration.

STUDY AREA

Morton Jaffray Water Treatment Works (MJWTW) is located at about 35 km to the south western side of Harare (Figure 1). According to Nhapi (2007), MJWTW supplies drinking water to Harare and the satellite towns of Ruwa, Chitungwiza, Norton and Epworth. Greater Harare had a population of

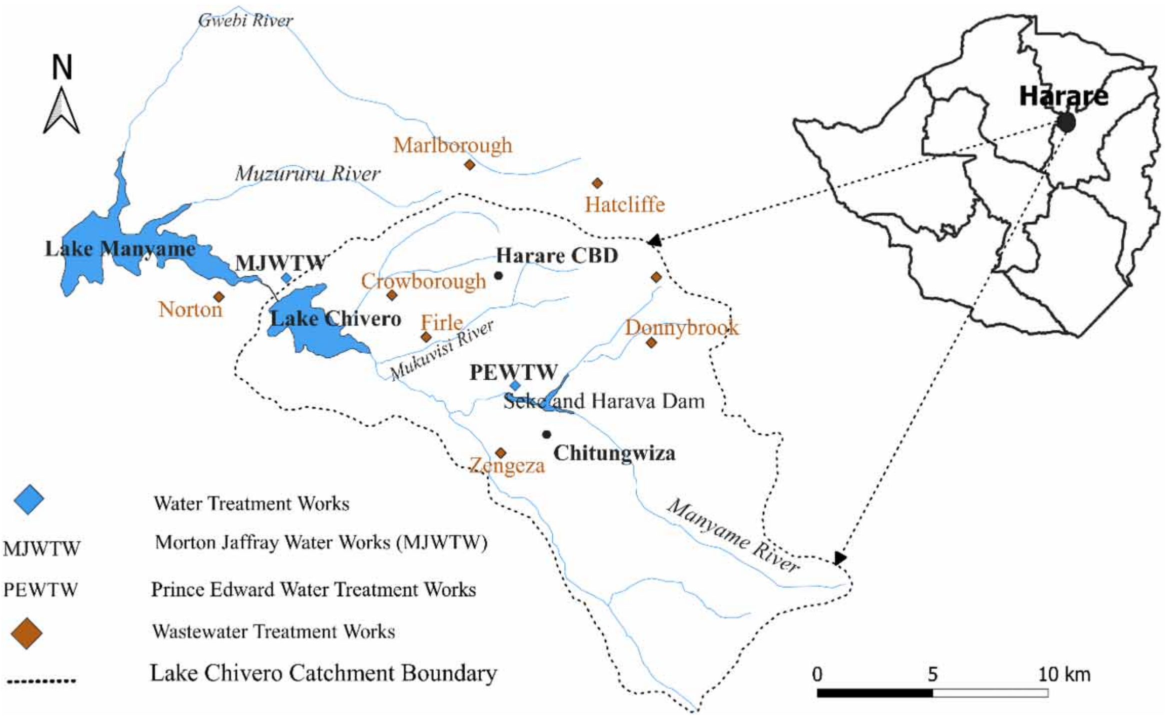


Figure 1 | Location of Morton Jaffray Water Treatment Works and Lake Chivero.

2,123,132 in 2012, which was 16.3% of the Zimbabwean population (ZimStat 2012) and was 1,973,906 in 2017 (ZimStat 2019). MJWTW treats raw water from two lakes, Chivero and Manyame, which is blended in the ratio 2:1 respectively (Hoko & Makado 2011).

Lake Chivero, which is the main source of raw water treated at MJWTW has been heavily polluted (Nhapi & Hoko 2004; Muisa *et al.* 2011). The poor water quality of the lakes, especially Lake Chivero, has complicated water treatment at MJWTW (Hoko & Makado 2011). The pollution is a result of pollution from point sources from municipal sewage works in Harare, Chitungwiza, Ruwa and Norton, which over the years have been malfunctioning due to poor maintenance and lack of investment. This has resulted in poor quality of treated water in the distribution system (Nhongo *et al.* 2018; Dandadzi *et al.* 2020). Recurrent cases of cholera outbreak that have been experienced in Harare have been linked to poor drinking water quality (Dandadzi *et al.* 2019).

Lake Chivero has a capacity of 247 $M{\cdot}m^3$ (Nhapi *et al.* 2002) and has a catchment area of 2,136 km^2 (JICA 1996). Morton Jaffray water treatment plant has three units. Unit 1, unit 2 and unit 3 have design capacities of 160,000 m^3/day, 227,000 m^3/day and 227,00 m^3/day respectively, making a total of 614,000 m^3/day when fully operational (Nhongo *et al.* 2018). Potable water treatment at MJWTW involves a combination of conventional treatment processes: aeration, coagulation, flocculation, sedimentation, filtration, stabilisation (through lime addition) and disinfection (Hoko & Makado 2011). A water treatement flow scheme adapted from Hoko & Makado (2011) is shown in Figure 2.

MATERIALS AND METHODS

Study design

Selection of study area

Harare is the capital city of Zimbabwe and accounts for about 14.3% of the national population (ZimStat 2019). Many studies report that Harare's water supply source, Lake Chivero, has become

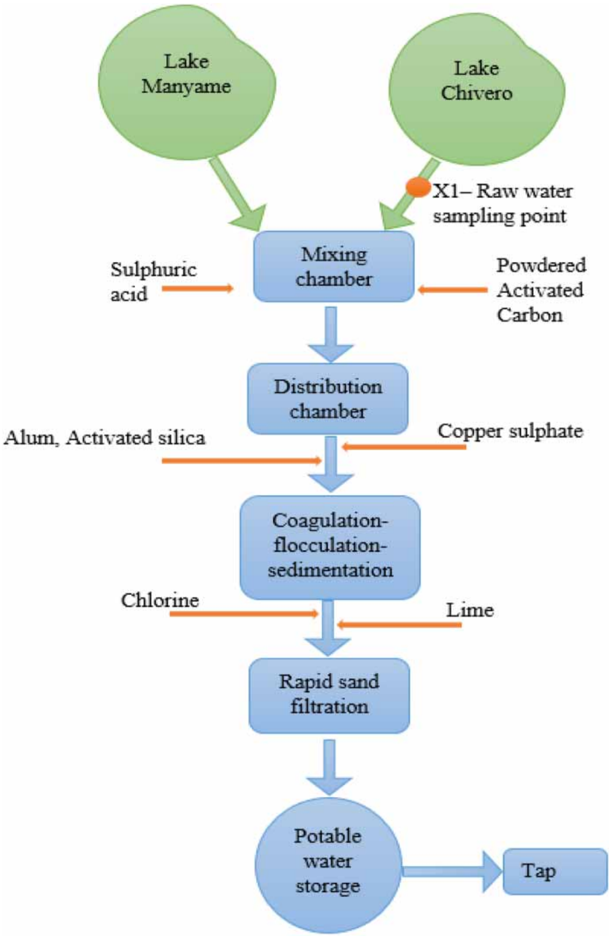


Figure 2 | Morton Jaffray Water Treatment Works flow scheme and sampling point. Adapted from Hoko & Makado (2011).

hypereutrophic (Thornton & Nduku 1982; Nhapi *et al.* 2002) This has affected water treatment at the main water works including increased chemical usage (Hoko & Makado 2011). There is evidence that the treatment system has been failing to treat water effectively resulting in poor quality water containing algae among other impurities (Dandadzi *et al.* 2019). To a very great extent this has contributed to water shortage and diseases outbreak, such as cholera and typhoid, as the residents of the City have been forced to look for water from unsafe sources such as unprotected shallow wells and boreholes (Chirisa *et al.* 2015; Nhongo *et al.* 2018; Dandadzi *et al.* 2019). It is for this background that Morton Jaffray Water Treatment Works was selected.

Selection of sampling points

A single raw water sample taken from the same sampling point is recommended to provide a better evaluation of different coagulants (EPA 2002; APHA 2005). The accuracy and usefulness of laboratory analysis results is largely dependent on the representative nature of the raw water samples. It is against these guidelines that the raw water samples were collected from the raiser shaft at Morton Jaffray Water Treatment Works feeding raw unblended water from Lake Chivero. The raw water sampling point is marked X1 on Figure 2.

Selection of study parameters

Laboratory analysis included water quality assessment where the critical parameters of pH, turbidity, electrical conductivity and chlorophyll-a concentration were analysed for the raw and treated water in order to determine the effluent quality. Literature suggest that the presence of chlorophyll-a infers the presence of algae (Dandadzi *et al.* 2019). These parameters are of paramount importance and significance and are critical in water quality assessment as described by EPA (2002); Sawyer *et al.* (2003) and WHO (2006), hence they were the main process monitoring requirements in this study. The pH of water affects coagulation and disinfection of water (Degremont 2007). Turbidity can increase the cost of water treatment for drinking. Turbidity and pH are the two key parameters considered in determination of optimum dosage (EPA 2002).

Growth of algae has become a problem due to pollution and there has been a carry-over of algae from Morton Jaffray Water Treatment Works into the distribution system including algae regrowth (Dandadzi *et al.* 2019). The presence of algae in drinking water has been a major concern for consumers (Dandadzi *et al.* 2019).

Raw water sample collection

Grab sampling was done in March, April and May of the year 2014 in six campaigns from point X1 (Figure 2). A 40 L grab sample was collected during each sampling campaign. This sampling approach guaranteed that the most representative sample of raw water treated at MJWTW was collected. Experiments were conducted for each campaign.

Determination of suitable coagulant

Selection of coagulants

Some of the common coagulants on the market that have been reported to be effective in treating polluted water were selected. These include mainly polymeric coagulants as recommended by (Momba *et al.* 2006; Tzoupanos & Zouboulis 2008; Leopold & Freese 2009) and included APAC, PAC, Primco 100 and Zetafloc 4030. Alum acted as the control. The characteristics of the coagulants are presented in Table 1. The strength of solutions was as recommended by Greville (1997).

Table 1 | Characteristics of coagulants used in the study

Item.	Coagulant (Trade name)	Type	Major Constituents	State	Strength (%)	Dosage range	Source
1.	Alum	Inorganic metal salt	– Aluminium – Sulphate	Solid/liquid	1	30–100	Gebbie (2006)
2.	APAC	Polymer	– Aluminium – Chloride	Liquid	0.1	20–50	Leopold & Freese (2009)
3.	PAC	Polymer	– Aluminium – Chloride	Liquid	0.1	20–50	Gebbie (2006)
4.	Primco 100	Polymer	– Aluminium – Chloride	Liquid	0.1	20–50	Leopold & Freese (2009)
5.	Zetafloc 4030	Polymer	– Aluminium – Polyamine	Liquid	0.1	20–50	Leopold & Freese (2009)

Flocculation test

In order to compare effectiveness of different coagulants, flocculation tests using a six-paddle Stuart Scientific flocculator SW1 (standard jar test equipment) were carried out in batch mode. The flocculation test is the most suitable and widely used method of determining the dosage required for a particular coagulant (Nozaic *et al.* 2001; EPA 2002; Tzoupanos & Zouboulis 2008; Leopold &

Freese 2009; Loua *et al.* 2013). The flocculation test simulates the coagulation, flocculation and sedimentation stages of water treatment (EPA 2002). The dosage range of alum being applied at Morton Jaffray water works at the time of the study was 40–60 mg/L, the average optimum dosage being 50 mg/l. This guided the range of dosages, which were selected as 0–55 mg/L. Thus, for comparison, the same dosage range was initially used in the flocculation test for each of the selected coagulants, after which adjustments were made. Preparation of solutions for each coagulant was adapted from Greville (1997). Alum acted as the control for the tests. The optimum dosage was selected as that which achieved acceptable and adequate removal of turbidity (WHO 2006). A jar test was conducted with each coagulant for the six campaigns and the optimum dosage determined.

Pilot plant design and operation

A pilot plant comprising a flocculation basin and sedimentation tank was designed, fabricated and set up in the University of Zimbabwe Civil Engineering Department Hydraulics laboratory to test the performance of selected alternative coagulants and alum (control) under flow through conditions to mimic the real situation. The pilot plant key components were designed based on design recommendations from literature. Key equations used are listed below with reference from Degremont (2007) and Bahadori *et al.* (2013).

Flocculation basin design

The volume and area of the flocculation basin was determined from the equations below. The design criteria and output are presented in Tables 2 and 3.

$$V = Q.t \tag{1}$$

where V = volume of basin (m^3), Q = inflow rate (m^3/hr), t = minimum detention time (hr)

$$A = \frac{V}{D} \tag{2}$$

Table 2 | Design criteria for flocculation basin

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

t = minimum detention time, Q = inflow rate, D = tank depth, A_s = surface area of basin.

Table 3 | Design output for flocculation basin

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

where $A =$ surface area of basin (m^2), $D =$ tank depth (m)

$$V = L.W.D \tag{3}$$

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

Mechanical mixing using a mixer with a power rating of 60 W was done to achieve rapid mixing.

Rectangular sedimentation tank design

The critical details of the sedimentation tank were determined as follows. The design criteria and output are presented in Tables 4 and 5.

$$A_s = \frac{Q}{\mathrm{v_s}} \tag{4}$$

where $\mathrm{v_s} =$ surface loading rate, $A_s =$ surface area of sedimentation tank.

$$D = \mathrm{v_s}.t \tag{5}$$

where $D =$ tank depth (m), $\mathrm{v_s} =$ surface loading rate.

Rectangular units have a length/width ratio of between 3 and 6 (Degremont 2007).

Table 4 | Design criteria for a rectangular sedimentation tank

Parameter	Unit	Design value	Literature ranges	Literature references
$\mathrm{v_s}$	m^3/m^2.hr	0.5	0.5–1 m^3/m^2.hr	Degremont (2007)
t	Hr	0.5	2–4 hrs	Bahadori *et al.* (2013)
D	m	0.25		

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

Table 5 | Design output for rectangular sedimentation tank

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

Operation of pilot plant

One campaign was conducted where a grab sample for raw water to feed the pilot was collected in the month of May 2014 from the point marked X1 on Figure 2. The efficacy of the alternative coagulant that had the best performance in jar tests was investigated under continuous flow conditions and compared with the control (alum). Three pilot plant test runs were conducted. The dosages applied in the pilot plant were selected as those with the highest turbidity removal efficiency as determined in jar tests. The flow schematic of the pilot plant is shown in Figure 3. A grab sample of the effluent was collected after 30 minutes of running the pilot plant for each test run and tested for pH, turbidity, electrical conductivity and algae, inferred from chlorophyll-a.

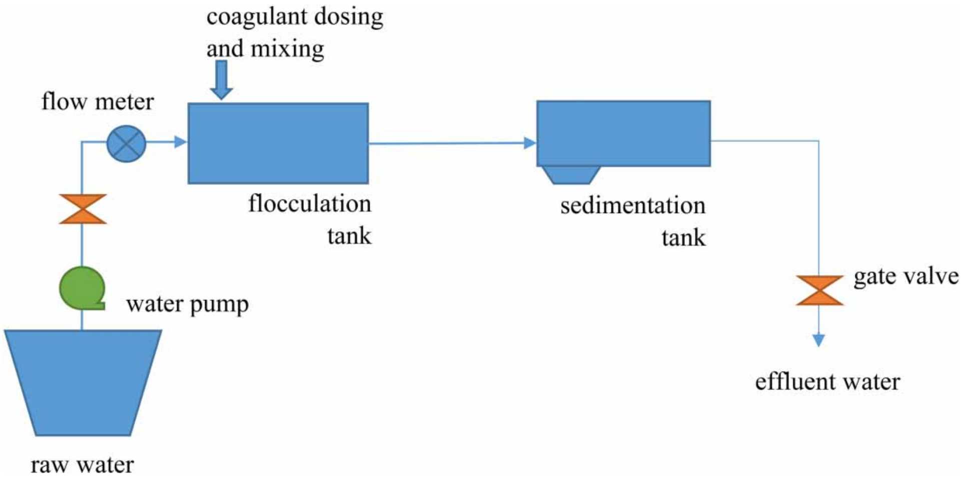


Figure 3 | Flow schematic of pilot plant.

Methods of water quality analysis

Raw water and treated water quality tests for pH, turbidity, electrical conductivity and chlorophyll-a concentration were conducted using standard procedures as prescribed by APHA (2005) and Bronmark & Hansson (2005). Table 6 shows the equipment and methods for all parameters.

Table 6 | Methods and equipment used for water quality analysis

Parameter	Analysis instrument	APHA method number	Equipment brand
pH	pH ion meter	4500-H^+	Hanna HI9103
Turbidity	Turbidity meter	2130 B	Hanna HI 9803
Electrical conductivity	Conductivity meter	–	Lasany Microprocessor 1-50
Chlorophyll-a	Acetone extraction	–	–

RESULTS AND DISCUSSION

Raw water characteristics

The raw water was characterised in six campaigns in order to determine the variability of the raw water quality. The results for raw water characterization are presented in Table 7.

Table 7 | Raw water characteristics for the period April – May 2014 ($n = 6$)

Campaign	1	2	3	4	5	6	Mean	Std deviation	CV [%]
pH	7.5	6.9	7.3	6.4	6.8	6.9	7.0	0.4	5.7
Turbidity (NTU)	3.6	3.2	3.3	3.4	3.5	3.0	3.3	0.2	6.1
EC (μS/cm)	345	339	331	333	332	334	337	5.0	1.5
Chlorophyll-a (μg/L)	–	–	–	–	–	2.28	2.28	0.0	0.0

pH

The lowest pH for raw water recorded was 6.4 and the highest was 7.5 with an average of 7.0 and a (coefficient of variation) CV of 5.7%. The low CV showed little variability of the pH. Water pH varies with time of day, which could be explained by the fact that photosynthetic aquatic plants such as algae remove carbon dioxide from water, thus significantly increasing pH (EPA 2006). This leads to polluted waters having pH values higher than 7. However, the slightly low pH in this study could be due to the intake position on the tower, which is well below the surface, and the fact that the water is conveyed from the lake via a pipe and as such anaerobic conditions may have resulted in lowering of the pH given the polluted state of the lake. However, a study by Dandadzi *et al.* (2019) had raw water pH values ranging between 7.30 and 8.20 (mean 7.52) in the period May to June 2017. The differences may be linked to intake points for raw water. The optimum pH for turbidity reduction when using alum is around 6.8, while precipitation of the organic matter present is best at a pH of around 5.0 (Freese *et al.* 2003). Optimum pH for coagulation-flocculation for alum is 6.0–7.4 (Degremont 2007). The raw water pH for Lake Chivero shows that there may have been no need for pH adjusting chemicals in order to optimise performance of coagulant in the case of alum. For effective disinfection with chlorine, the pH for raw water should preferably be less than 8.0 (WHO 2007). The raw water pH falls in the range suitable for coagulation by alum. From this background, no pH-adjusting chemicals were used in this study.

Turbidity

The raw water had a range of 3.0 to 3.6 NTU, a mean turbidity of 3.3 NTU and a CV of 6.1%. This indicates that there was a very small variation in water quality in terms of turbidity. This could be explained by the fact that lakes and reservoirs have a much higher capacity to self-cleanse (IHP 1982; Xiong *et al.* 2017). A report by Whiting (2017) revealed that turbidity for Graham Lake ranged between 2.2 and 7.5 NTU for samples collected bimonthly in 2013. Muchini *et al.* (2018) reported turbidity values in the range 3.2 to 5.8 NTU for Lake Chivero. These results of this study are in the range of findings by Hoko & Makado (2011) for raw water for the same point, which ranged from 2.5 to 6.3 NTU. Dandadzi *et al.* (2019) also obtained turbidity values of raw water ranging from 2.14 to 5.30 NTU (average 3.39 NTU), also for the same point. However, in this research, high values were not found. The low turbidity of Lake Chivero, which appears consistent with findings from other studies, is due to the size of the lake itself and the residence time of raw water in the lake. The raw water turbidity was comparable to levels found in previous studies and is likely not to cause complications in water treatment.

Electrical conductivity

Electrical conductivity (EC) had a range of 331 to 345 μS/cm and mean value of 337 μS/cm with a CV of 1.5%. The low CV is an indication that there was a small variation in water quality for raw water in terms of EC. An important factor influencing the effectiveness of water treatment is the consistency of the raw water quality (EPA 2002). A study by Momba *et al.* (2006) revealed that raw water at Chris Hani District Municipality water treatment plants in South Africa had an EC range of 0.02 to 410 μS/cm, which is wider than that of Chivero water. The consistency of values of EC for Chivero raw water may signify fewer complications in water treatment.

Chlorophyll-a

The chlorophyll-a concentration for raw water measured was 2.28 μg/L for one campaign. The presence of algae in Lake Chivero, a parameter linked to chlorophyll-a, is consistent with the findings by Hoko & Makado (2011) and Dandadzi *et al.* (2019). A pH range of 6.5–8.5 favours the growth of algae (Dandadzi *et al.* 2019) thus the pH of the raw water was suitable for algae growth. Studies have been conducted which identified algae related problems in water treatment (Hoko & Makado

2011; Dandadzi *et al.* 2019). The presence of chlorophyll-a inferred with algae in raw water indicate a high likelihood of complications in water treatment.

Assessment of performance of different coagulants

The results of this sub-section are based on the laboratory simulations of the coagulation, flocculation and sedimentation unit processes using a jar test equipment (flocculator). Raw water from the intake at MJWTW was used. The settled water quality after treatment with each of the coagulant types was characterized in terms of pH, turbidity, EC and chlorophyll-a. The performance of each of the coagulants in six campaigns based on the selected parameters is presented below.

pH

Results for pH after the flocculation test for each coagulant are shown in Figure 4. The initial pH of the raw water before the test was 7.1 and is plotted as the pH at coagulant dosage of zero.

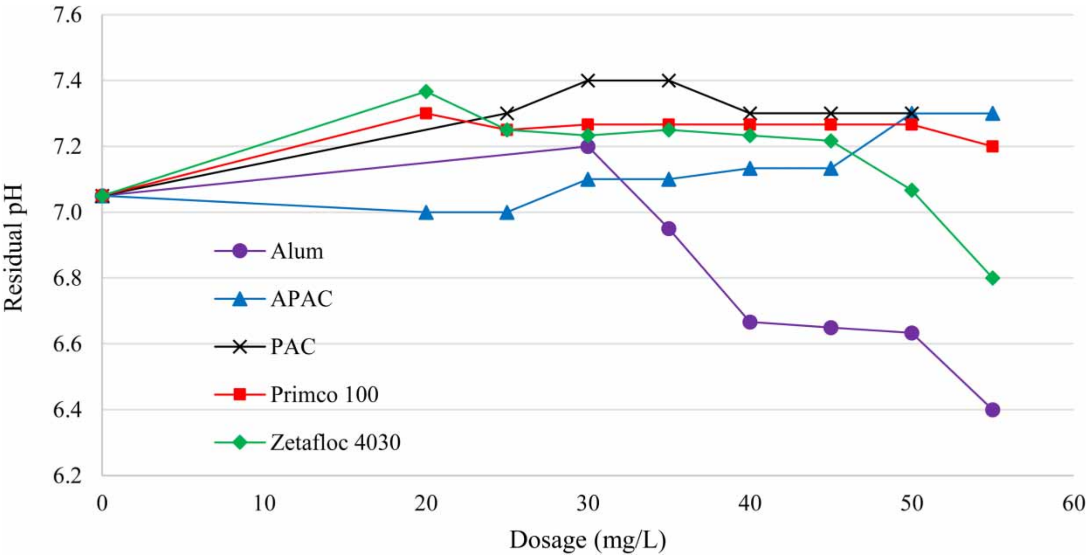


Figure 4 | Residual pH with varying dosages of coagulant for the period April – May 2014.

Reduced pH for samples treated with alum is consistent with findings by Tzoupanos & Zouboulis (2008). Gebbie (2006) reported that alum dissolves in water to produce aluminium hydroxide and as a by-product, sulphuric acid is also formed. The sulphuric acid produced reacts with alkalinity in raw water to produce carbon dioxide, thus depressing the pH. The pH of most drinking water lies within the range 6.5–8.5 (WHO 2006). Thus, the polymeric coagulants maintained the pH in this range (6.5–8.5) while alum lowered it, creating a need for pH correction at later stages of treatment thus creating a potential for increasing chemical requirements. The results obtained were in agreement with the results of pH sensitivity of the polymeric coagulants from other studies which concluded that polymeric coagulants do not considerably affect the pH of the water being treated at any dosage applied (Leopold & Freese 2009). This is beneficial in that the cost incurred in adjusting or correcting pH when using alum will be reduced since the addition of lime to correct the pH would have been eliminated. A one-way ANOVA test showed that pH values of raw water treated with the five coagulants were significantly ($p < 0.05$) different. Moreover, an independent sample t-test at 95% confidence interval at the final dosages for each coagulant showed that polymeric coagulants insignificantly ($p > 0.05$) affected the pH while raw water samples treated with alum had significantly

($p < 0.05$) lowered pH values. It was concluded that the use of APAC, PAC, Primco 100 and Zetafloc 4030 as coagulants does not significantly alter the pH of the raw water and this removes the need for other chemicals to adjust pH during treatment, thus reducing water treatment cost. On the other hand, alum lowered pH significantly, thus necessitating the need for use of other chemicals to adjust pH.

Turbidity

Results of mean settled turbidity against dosage for each of the coagulants are presented in Figure 5. The raw water sample used for these experiments had a mean turbidity of 3.3 NTU and this is plotted as the turbidity at 0 mg/L coagulant dosage.

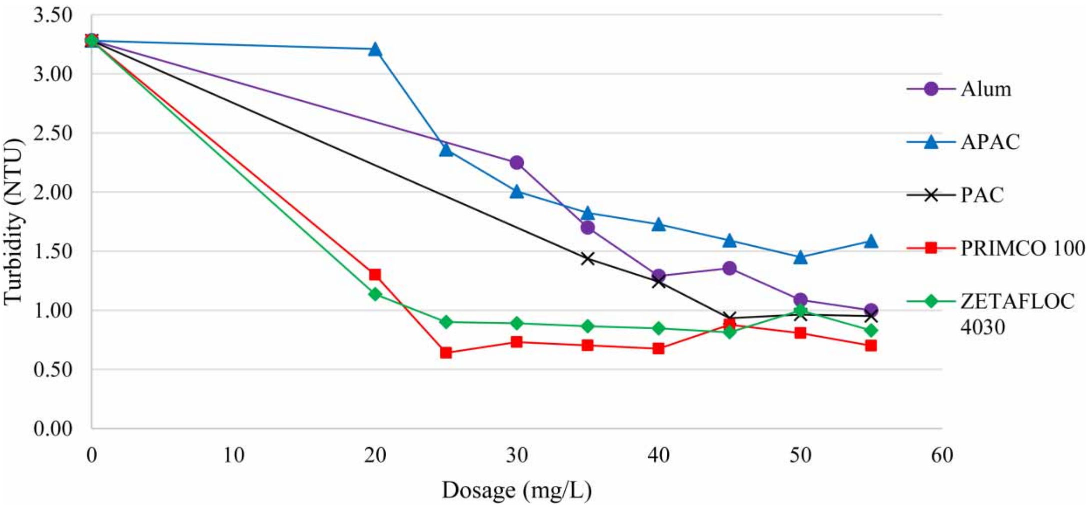


Figure 5 | Turbidity vs dosage for alum, APAC, PAC, Primco 100 and Zetafloc 4030 for the period April to May 2014.

Results showed that Primco 100 and Zetafloc 4030 could achieve the drinking water standard of turbidity of 1 NTU at relatively lower dosages of less than 25 mg/L compared to alum, APAC and PAC, which achieved 1 NTU at dosage values greater than 40 mg/L. Table 8 shows the minimum average values of dosages to achieve turbidity of 1 NTU. Primco 100 and Zetafloc 430 had the lowest average value of 25 mg/L while alum had the highest average value of 55 mg/L. APAC did not achieve the turbidity level of 1 NTU within the ranges of dosages used. At 25 mg/L, Primco 100 achieved the lowest turbidity level, suggesting that it was the most effective coagulant. Values of turbidity found by Hoko & Makado (2011) after flocculation test were in the range 0.5–1 NTU for alum dosages ranging from 60 to 120 mg/L. The general trend for the five coagulants was that residual turbidity reduced with increasing dosage, as was found by Hoko & Makado (2011).

Table 8 | Minimum values of applied coagulant dosages to achieve a turbidity of 1 NTU for the period April – May 2014

Coagulant	Mean dosage to achieve 1 NTU [mg/L]
Alum	55
APAC	–
PAC	45
Primco 100	25
Zetafloc 4030	25

Figure 6 shows turbidity average removal efficiency with increasing dosage for each of the coagulants. Primco 100 achieved the highest turbidity removal efficiency of 80% at a dosage of 40 mg/L while APAC had the lowest efficiency. APAC and PAC showed a reduction in efficiency beyond a dosage of 50 mg/L.

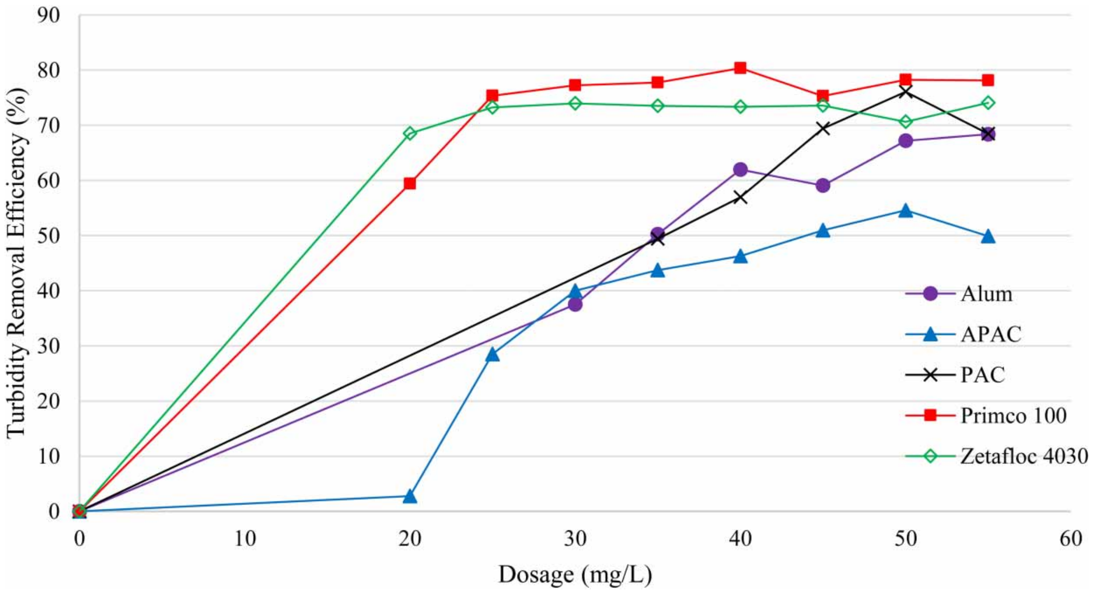


Figure 6 | Turbidity removal efficiency with increasing coagulant dosage for the period April – May 2014.

Based on a one-way ANOVA test, the difference in efficiency of turbidity removal among the five coagulants was statistically significant ($p < 0.05$). An independent t-test showed that turbidity values of raw water and treated water at the final dosage of 55 mg/L were significantly different ($p < 0.05$) for treatment with all coagulants. Amongst the five coagulants, Primco 100 and Zetafloc 4030 reduced the turbidity to 1 NTU earlier than the other coagulants. It was found that all coagulants significantly reduced turbidity. PAC, Primco 100 and Zetafloc performed better than alum. Lastly, Primco 100 had the best performance in reducing turbidity of raw water.

Electrical conductivity

Electrical conductivity (EC) results are as in Figure 7. The raw water EC was 334 μS/cm and this corresponds to the EC value at dosage of zero. EC had an increasing trend with increasing dosage of alum. However, there was a slight decreasing trend for APAC, PAC, Primco 100 and Zetafloc 4030 for EC.

From the results, Primco 100 had the lowest value of EC of 329 μS/cm, while alum had the highest EC value of 353 μS/cm. Increase in EC values means addition of dissolved ionic solids (EPA 2001). When alum dissolves in water it forms charged Al^{3+} ions (Bratby 1980). Residual aluminium in treated water could explain the increase in EC for aluminium sulphate. This finding concurs with the findings by Srinivasan *et al.* (1999) and Gebbie (2006) who reported that the use of aluminium sulphate as a coagulant often produces higher aluminium concentrations in the treated water than in raw water. Polymeric coagulants do not dissociate in water, thus the release of ions in the water phase is low (Leopold & Freese 2009). They actually have capacity to adsorb ions, thus reducing ions in water, leading to reduction in EC of the treated water (Leopold & Freese 2009). The standard for EC in potable water is 700 μS/cm and the recommended maximum value is 3,000 μS/cm (SAZ 1997). The raw water EC and EC values obtained after application of coagulants were all within

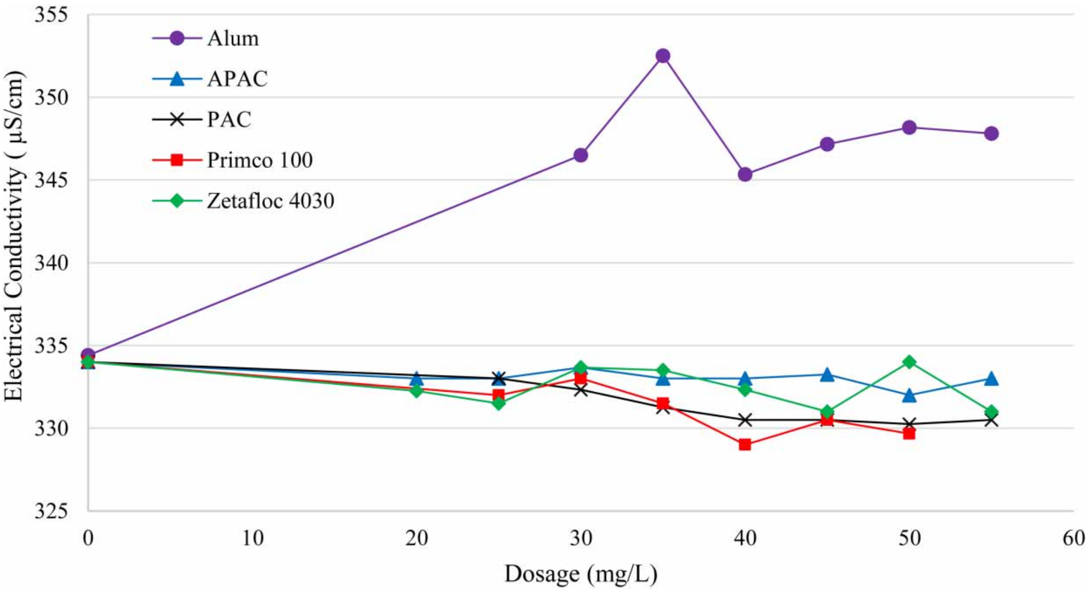


Figure 7 | Variation of residual electrical conductivity (EC) with dosage for the period April – May 2014.

the recommended range. However, the presence of dissolved ions in drinking water has an impact on taste of which the degree is dependent on the concentration of ions (Meride & Ayenew 2016; Ndoziya *et al.* 2019). It can therefore be concluded that the use of alum results in increased EC and aluminium content in the treated water compared to APAC, PAC Primco 100 and Zetafloc 4030. Thus, alum has potential to have an effect on the taste of water compared to polymeric coagulants. The difference in EC of water treated with the five coagulants was statistically significant ($p < 0.05$) based on a one-way ANOVA test. Independent t-tests showed that raw water treated with alum had significantly ($p < 0.05$) high EC values while polymeric coagulants insignificantly ($p > 0.05$) lowered the EC values at final dosages. It was also found that polymeric coagulants, including Primco 100, had the best performance when considering EC.

Chlorophyll-a removal

Results of performance of the five coagulants in removing chlorophyll-a are shown in Table 9 below. The raw water chlorophyll-a content was 2.28 μg/L and this corresponds to the chlorophyll-a value at coagulant dosage of zero. Initial pH of the raw water was 6.9. Results showed that chlorophyll-a removal increased with increasing dosage for all coagulants. This general trend was also found by Hoko & Makado (2011) where the removal of algae, a parameter linked with chlorophyll-a increased with increasing coagulant dosage, which could be explained by the fact that increase in coagulant dosage results in enhanced settlement (Sun *et al.* 2019).

Table 9 | Dosage of coagulant to remove 80% of chlorophyll-a concentration for the month of May 2014

Coagulant	Dosage for 80% chlorophyll-a removal (mg/L)
Alum	50
APAC	50
PAC	55
Primco 100	<25
Zetafloc 4030	25

A possible average cumulative algae removal efficiency of 80% is achievable in jar tests (Chorus & Bartram 1999; Henderson *et al.* 2008). Primco 100 achieved more than 80% chlorophyll-a concentration reduction at a relatively lower dosage of 25 mg/L in comparison to other coagulants while PAC achieved 80% removal at the highest dosage of 55 mg/L. Results showed that Primco 100 had the best performance in removing chlorophyll-a. The reduction in chlorophyll-a among the five coagulants was statistically significant ($p = 0.0116$) based on a one-way ANOVA test.

Performance of the continuous flow pilot plant

Results from the jar test showed that Primco 100 had the best performance in treating raw water in terms of the parameters: pH, turbidity, EC, and chlorophyll-a removal. Further experiments were then conducted on a laboratory pilot plant (prototype) comprising coagulation–flocculation and sedimentation processes to compare the performance of alum (control) to the best alternative coagulant from jar tests (Primco 100) under continuous flow conditions, as is the case in real life water treatment. Dosage of alum and Primco 100 applied was 55 mg/L and 40 mg/L respectively. These were selected as the dosages with highest turbidity removal efficiency (Figure 6). Water quality results for pilot tests after 0.5 hours of running the pilot are presented in Table 10.

Table 10 | Effluent water quality from pilot plant for the month of May 2014

Parameter	Unit	Influent water	Alum Effluent water	Primco 100 Effluent water	Alum Removal efficiency (%)	Primco 100 Removal efficiency (%)
pH		6.9	6.2	6.9	–	–
Turbidity	NTU	3.30	1.57	0.92	53	72
Electrical conductivity	μS/cm	334	351	327	−5.1	2.1
Chlorophyll-a	μg/L	2.28	1.09	0.68	52	70

pH

The pH of raw water used in the pilot ranged from 6.9 to 7.5 with a mean of 7.2. Alum lowered the pH to a mean of 6.2 while samples treated with Primco 100 had the same mean pH as that of the raw water (6.9). The pH results under continuous flow conditions had a similar pattern found from jar tests that showed that Primco 100 does not significantly alter the pH of water while alum reduces the pH of water (Leopold & Freese 2009). This reduction in pH after addition of alum, based on a paired sample t-test, was statistically significant ($p < 0.05$) while Primco 100 had a statistically insignificant ($p > 0.05$) effect on the pH. Based on an independent sample t-test, the mean pH of samples treated with alum was significantly ($p < 0.05$) different from that of Primco 100 treated samples. Thus, even under continuous flow conditions, Primco 100 performed better than alum and eliminated the need for other chemicals needed to adjust pH before and after coagulation.

Turbidity

The mean turbidity of the raw water was 3.30 NTU. Mean turbidity in the continuous flow pilot plant after addition of alum and Primco were 1.57 NTU and 0.92 NTU respectively. The use of alum as a coagulant reduced the turbidity by 53% which was relatively lower than that (72%) of Primco 100. Primco 100 achieved the standard turbidity value of 1 NTU suggested by WHO (2006) for conventional water treatment, whereas alum did not. Results under continuous flow conditions again showed that Primco 100 achieved turbidity of 1 NTU at a relatively lower dosage than that of alum. Based on an independent sample t-test, the efficiency of Primco 100 in turbidity removal was significantly

($p = 0.02$) better than that of alum. Thus Primco 100 performed better than alum in terms of reducing turbidity under continuous flow conditions.

Electrical conductivity

The mean electrical conductivity (EC) increased from an initial 334 μS/cm to 351 μS/cm for alum and decreased from 334 μS/cm to 327 μS/cm for Primco 100. Once again, the results show that the use of alum increases the ionic concentration of the treated water and could signify a greater potential of aluminium being present in the treated water (Gebbie 2006). Based on a paired sample t-test, this increase in EC caused by use of alum as a coagulant was statistically significant ($p < 0.05$). The decrease in EC for Primco 100 is explained by reduction in ionic concentration in treated water through adsorption (Leopold & Freese 2009). However, although Primco reduced the EC, this reduction in EC was statistically insignificant based on a paired sample t-test. The difference in mean EC of samples treated with the two coagulants was statistically significant ($p < 0.05$) based on an independent sample t-test at 95% confidence interval. Thus, even under continuous flow conditions, Primco 100 had a better performance compared to alum.

Chlorophyll-a removal

The raw water used in the pilot had a chlorophyll-a concentration of 2.28 μg/L. The reduction of chlorophyll-a concentration as a result of the addition of alum and Primco 100 was 1.09 μg/L and 0.68 μg/L, respectively. The results (Table 10) show that under continuous flow conditions, alum removed 52% of chlorophyll-a at a dosage of 55 mg/L while Primco 100 removed 70% of chlorophyll-a at a dosage of 40 mg/L. Based on paired sample t-tests, both coagulants significantly ($p < 0.05$) reduced chlorophyll-a concentration. However, Primco 100 was significantly ($p < 0.05$) better than alum based on an independent sample t-test. Henderson *et al.* (2008) deduced that a possible algal removal efficiency of 70–80% can be achieved after coagulation flocculation–sedimentation water treatment processes. Thus, the performance of alum was far below the expected range while that for Primco was within the range even at a lower dosage. Results show that Primco 100 had a better performance in the removal of chlorophyll-a compared to alum under flow through conditions.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the findings of this study, it was concluded that Primco 100 showed the best performance in treating Chivero water in terms of effect on pH, removal of turbidity, effect on electrical conductivity and chlorophyll-a removal compared to the other four selected coagulants. Primco 100 also required a relatively low coagulant dosage to meet drinking water standards in terms of key parameters. Primco 100 performed better than all other coagulants in jar tests (batch tests) and even under continuous flow conditions. It was concluded that the use of Primco 100 has potential for elimination of the addition of sulphuric acid and lime needed for pH adjustment when alum is used in conventional water treatment. Thus, the use of Primco 100 as an alternative coagulant at Morton Jaffray Water Works may lead to reduction of water treatment costs.

Recommendations

Based on the findings of this study, it is recommended that the City of Harare considers the use Primco 100 as an alternative coagulant to aluminium sulphate. While the results show that Primco removes up to 70% of chlorophyll-a, there is a need to use an oxidizing agent that does not create trihalomethanes (THMs), such as chlorine dioxide or potassium permanganate, to remove the remaining 30% of chlorophyll-a from the water.

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DATA AVAILABILITY STATEMENT

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

REFERENCES

APHA 2005 *Standard Methods for the Examination of Water and Wastewater*, 20th edn. APHA, AWWA, WEF, Washington, DC.

Bahadori, A., Clark, M. & Boyd, B. 2013 *Essentials of Water Systems Design in the Oil, Gas, and Chemical Processing Industries*. Springer, New York, NY.

Bratby, J. 1980 *Coagulation and Flocculation with an Emphasis on Water and Wastewater Treatment*. Uplands Press Ltd, UK.

Bronmark, C. & Hansson, L. A. 2005 *The Biology of Lakes and Ponds*, 2nd edn. Oxford University Press, Oxford, UK.

Chirisa, I., Nyamadzawo, L., Bandauko, E. & Mutsindikwa, N. 2015 The 2008/2009 cholera outbreak in Harare, Zimbabwe: case of failure in urban environmental health planning. *Environmental Health* **30**(2), 117–124.

Chorus, I. & Bartram, J. E. 1999 *Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring and Management*. Routledge, London.

Dandadzi, P., Hoko, Z. & Nhiwatiwa, T. 2019 Investigating the quality of drinking water in the water distribution system in Harare, Zimbabwe. *Water, Sanitation, and Hygiene for Development* **9**(1), 90–101.

Dandadzi, P., Hoko, Z. & Nhiwatiwa, T. 2020 Investigating the occurrence of algae in the drinking water supply system of Harare, Zimbabwe. *Water, Sanitation and Hygiene for Development* **10**(2), 179–190.

Degremont, O. 2007 *Water Treatment Handbook, Vol No. 2*, 7th edn. Lavoisier Publishing, Rueil-Malmaison Cedex, France.

DWD 1995 *Design and Training Manual for Piped Rural Water Supplies in Zimbabwe*. Ministry of Lands, Agriculture and Water Development, Department of Water Development (DWD), Harare, Zimbabwe.

EPA 2001 *Parameters of Water Quality: Interpretation and Standards*. EPA, Ireland.

EPA 2002 *Water Treatment Manuals Coagulation, Flocculation and Clarification*. Environmental Protection Agency, Ireland. Available from: https://www.epa.ie/pubs/advice/drinkingwater/EPA_water_treatment_mgt_coag_flocc_clar2.pdf (accessed 14 September 2020).

EPA 2006 *Volunteer Estuary Monitoring: A Methods Manual, Chapter 11: pH and Alkalinity*, 2nd edn. Available from: https://www.epa.gov/sites/production/files/2015-09/documents/2009_03_13_estuaries_monitor_chap11.pdf (accessed 23 September 2020).

Freese, S. D., Trollip, D. L. & Nozaic, D. J. 2003 *Manual for Testing of Water and Wastewater Treatment Chemicals*. Report no. 1184/1/04, Water Research Commission, Pretoria, South Africa.

Gebbie, P. 2006 31st Annual Water Industry Workshop – Operations Skills, University Central Queensland Campus, Rockhampton. In: *64th Annual Water Industry Engineers and Operators' Conference All Seasons International Hotel – Bendigo*. Available from: http://wioa.org.au/conference_papers/06_qld/documents/PeterGebbie.pdf (accessed 18 September 2020).

Greville, A. S. 1997 How to select a chemical coagulant and flocculant. In *Alberta Water & Wastewater Operators Association 22th Annual Seminar*, March 11–14, pp. 1–24. Available from: https://sswm.info/sites/default/files/reference_attachments/GREVILLE%201997%20%20How%20to%20Select%20a%20Chemical%20Coagulant%20and%20Flocculant.pdf/ (accessed 18 September 2020).

Gumbo, B. 2005 *Short-cutting the Phosphorus Cycle in Urban Ecosystems*. PhD thesis, Delft University of Technology and UNESCO-IHE, The Netherlands. Taylor and Francis Group, London, UK.

Henderson, R., Parsons, S. A. & Jefferson, B. 2008 The impact of algal properties and pre-oxidation on solid–liquid separation of algae. *Water Res.* **42**, 1827–1845.

Hoko, Z. & Makado, P. 2011 Optimization of algal removal process at Morton Jaffray water works, Harare, Zimbabwe. *Physics and Chemistry of the Earth* **36**, 1141–1150.

IHP (International Hydrological Programme) 1982 *Dispersion and Self – Purification of Pollutants in Surface Water Systems*. UNESCO, France, pp. 90.

JICA 1996 *The Study of Water Pollution Control in Upper Manyame River Basin in the Republic of Zimbabwe*. Nippon Jogeduido Sekkei Co. Ltd, Nippon Koei Co. Ltd, Ministry of Local Government and Public Construction, Zimbabwe.

Kurenkov, V. F., Gogolashvili, E. L., Molgacheva, I. V. & Gaisina, A. I. 2003 Cationic polymers as organic coagulants in water treatment at heat and electric power plants. *Russian Journal of Applied Chemistry* **76**, 1951–1954.

Leopold, P. & Freese, S. D. 2009 *A Simple Guide to the Chemistry, Selection and Use of Chemicals for Water And Wastewater Treatment*. Water Research Commission, Gezina, South Africa.

Loua, I., Gongb, S., Huangc, S., Liud, Y. & Moka, K. M. 2013 *Coagulation Optimization Using Ferric and Aluminum Salts for Treating High Algae and High Alkalinity Source Water in A Typical North-China Plant*. Desalination and Water Treatment, Taylor and Francis. http://dx.doi.org/10.1080/19443994.2012.751158 (accessed 18 August 2020).

Magadza, C. H. D. & Ndebele, M. R. 2006 The occurrence of microcystin-LR in Lake Chivero, Zimbabwe. *Lakes and Reservoirs: Research and Management* **1**(1), 57–62.

McCool, P. 2009 *The Use of Coagulants in Clarification Plants in Kansas*. The Kansas Lifeline, pp. 58–61. Available from: https://krwa.net/portals/krwa/lifeline/currentissue/0903_058.pdf/ (accessed 20 August 2020).

Meride, Y. & Ayenew, B. 2016 Drinking water quality assessment and its effects on resident's health in Wondo genet campus, Ethiopia. *Environ Syst Res* **5**(1), 1–7.

Momba, M. N. B., Tyafa, Z., Makala, N., Brouckaert, B. M. & Obi, C. L. 2006 Safe drinking water still a dream in rural areas of South Africa. Case study: the Eastern Cape province. *Water SA* **32**(5), 715–720.

Momba, M. N. B., Obi, C. L. & Thompson, P. 2009 Survey of disinfection efficiency of small drinking water treatment plants: challenges facing small water treatment plants in South Africa. *Water SA* **35**(4), 485–494.

Moyo, N. A. G. 1997 Causes of Massive Fish Deaths in Lake Chivero. In: *Lake Chivero: A Polluted Lake* (Moyo, ed.). University of Zimbabwe Publications, Harare.

Muchini, R., Gumindoga, W., Togarepi, S., Masarira, T. P. & Dube, T. 2018 Near real time water quality monitoring of Chivero and Manyame lakes of Zimbabwe, PIHS. *Copernicus Publications* **378**, 85–92.

Muisa, N., Hoko, Z. & Chifamba, P. 2011 Impacts of alum residues from Morton Jaffray Water Works on water quality and fish, Harare, Zimbabwe. *Physics and Chemistry of the Earth* **36**, 853–864.

Ndoziya, A. T., Hoko, Z. & Gumindoga, W. 2019 Assessment of the impact of pit latrines on groundwater contamination in Hopley Settlement, Harare, Zimbabwe. *Water, Sanitation and Hygiene for Development* **9**(3), 466.

Nhapi, I. 2007 Inventory of water management practices in Harare, Zimbabwe. *Water and Environmental Journal* **22**(2008), 54–63.

Nhapi, I. & Hoko, Z. 2004 A cleaner production approach to urban water management: potential for application in Harare, Zimbabwe. *Physics and Chemistry of the 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. *Physics and Chemistry of the Earth* **27**, 783–792.

Nhongo, K., Hoko, Z. & Kugara, J. 2018 Investigating disinfectant by-products in Harare potable water supply, Zimbabwe. *Water, Sanitation and Hygiene for Development* **8**(3), 415–428.

Nozaic, D. J., Freese, S. D. & Thompson, P. 2001 Long-term experience in the use of polymeric coagulants at Umgeni Water. *Water Science and Technology: Water Supply* **1**(1), 43–50.

Sahu, O. P. & Chaudhari, P. K. 2013 Review on chemical treatment of industrial waste water. *Applied Science and Environment Management* **17**(2), 241–257.

Sawyer, C. N., McCarty, P. L. & Parkin, G. F. 2003 *Chemistry for Environmental Engineering Science*, 5th edn. McGraw-Hill, New York, NY.

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

Selami, A. T., Takeda, F., Maruo, C., Fujibayashi, M. & Nishimura, O. 2013 Comparison of four kinds of coagulants for the removal of picophytoplankton. *Desalination and Water Treatment* **51**(16–18), 3547–3557.

Srinivasan, P. T., Viraraghavan, T. & Subramanian, K. S. 1999 Aluminium in drinking water: an overview. *Water SA* **25**(1), 47–55.

Sun, Y., Zhou, S., Chiang, P. & Shah, K. J. 2019 Evaluation and optimization of enhanced coagulation process. *Water and Energy Nexus* **2**(1), 25–36.

Thornton, J. A. & Nduku, W. K. 1982 Water chemistry and nutrient budgets. In: *Lake McIlwaine* (Thornton, J. A. & Nduku, W. K., eds). Springer, Dordrecht, The Netherlands, pp. 43–59.

Tzoupanos, N. D. & Zouboulis, A. I. 2008 Coagulation-Flocculation Processes in Water/Wastewater Treatment: The Application of New Generation of Chemical Reagents. In *6th IASME/WSEAS International Conference on Heat Transfer, Thermal Engineering and Environment (HTE'08)*, August 20–22, Rhodes, Greece, pp. 309–317. Available from: https://www.researchgate.net/publication/229039796 (accessed 23 September 2020).

Whiting, M. 2017 *A Turbidity Study for the Union River and A Discussion of Water Level Fluctuations in Graham Lake*. doi:10.13140/RG.2.2.32099.86568. Available from: https://www.researchgate.net/publication/324043134_A_Turbidity_Study_for_the_Union_River_and_a_Discussion_of_Water_Level_Fluctuations_in_Graham_Lake (accessed 10 October 2020).

WHO 2006 *Guidelines for Drinking Water Quality: A Framework for Safe Drinking Water*. World Health Organization, Geneva, Switzerland.

WHO 2007 *Guidelines for Drinking Water Quality: pH in Drinking Water*. World Health Organization, Geneva.

Xiong, G., Wang, G., Wang, D., Yang, W., Chen, Y. & Chen, Z. 2017 Spatio-temporal distribution of total nitrogen and phosphorus in Dianshan lake, China: the external loading and self-purification capability. *Sustainability* **9**(4), 500. http://dx.doi.org/10.3390/su9040500 (accessed 23 September 2020).

ZimStat 2012 *Zimbabwe Population Census*, Zimbabwe National Statistics Agency, Harare

ZimStat 2019 *Facts and Figures*, Zimbabwe National Statistics Agency, Harare.

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