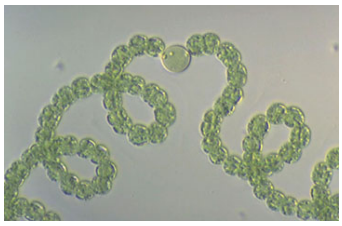
UNIVERSITY OF ZIMBABWE

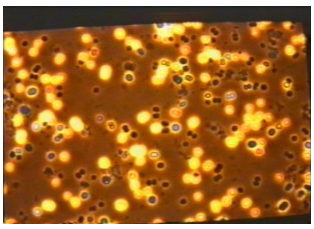
Masters in Integrated Water Resources Management

Optimisation of the algal control process at Morton Jaffray water works, Harare

By

Patience K. Makado





A thesis submitted in partial fulfilment of the requirements of the Masters degree in Integrated Water Resources Management

Department of Civil Engineering

Faculty of Engineering

JUNE 2007

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Supervised By

Eng. Z. Hoko
Mr. L. Chipfunde

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DECLARATION

I declare that this thesis is my own work. It has not been submitted before, for any degree or examination of any University.

Name: **Patience Kanganwiro Makado**

Signed……..…day of……2007

DEDICATION.

To the aces of my heart,
The pilots of my dreams,
The joys of my life.

And to my lovely daughter Tinotenda Annesha, you are truly the reason I wake up everyday. Everything I do, I do for you.

ABSTRACT

Water quality deterioration in Harare is an urgent problem and some of the causes of this deterioration have been the regular inflows of poorly treated sewage effluents into the major source of drinking water, Lake Chivero, and the proliferation of algae (blue-green algae). The occurrence of algae in raw water from Lake Chivero has caused problems in water purification at Morton Jaffray (MJ) water works, Harare's major water treatment works. At the plant, the filtration process has been the most affected as evidenced by frequent filter clogging and frequent backwashing now reported to be once every 4-8 hours compared to the acceptable frequency of once every 24-36 hours. The increased backwashing frequency has also resulted in reduced plant output and consequently water shortages in Harare. The high levels of algae have resulted in increased water treatment costs as more chemicals at high dosages are required for algae removal. Algae has also been detected in the treated water hence posing a health hazard for consumers.

The study was carried out at MJ water works from January to May 2007.The objectives of this study were to assess the effects of algae on water treatment processes, identify factors contributing to effective removal of algae and determine the optimum values of contact time, coagulant dose, and algaecide dose for removal of algae. Methods of study included literature research and water treatment process monitoring. Jar tests, simulating coagulation, flocculation and sedimentation, to determine the optimum conditions for removal of algal cells, were done. Simulations of dosing different doses of algaecide at Lake Chivero intake tower were also carried out using jar test.

Results showed that the water treatment works was hydraulically overloaded by 20 to 35%. The most abundant algae were found to be blue-green algae, particularly *Anabaena*, *Microcystis* and *Chlamydomonas*. The presence of algae was related to filter clogging, and the potential of causing taste and odours, as well as possibilities of toxin production in the final treated water. The concentration of algae in the raw water ranged from 875-6000 cells/ml. Algae removal by coagulation, flocculation and sedimentation ranged from 50-94%. Removal of algae by the filtration process ranged from -93 to 50%. Jar simulations showed that at algaecide dose of 0.8mg/l, applied 30 minutes before coagulation, in combination with coagulant dose ranging from 80 to 110mg/l, at pH 7, algae removal reached 99%. Lethal doses, for algae, of copper as copper sulphate was found to be in the range of 0.8 and 1mg/l if the algaecide was added at coagulation

It was concluded that there is a considerable variation in the effect of the algaecide at different contact times. It was shown that the filter clogging *Anabaena* was more susceptible to the algaecide when the contact time between the *Anabaena* and the algaecide was increased, and when the algaecide was dosed before addition of GAC and alum. Chemical doses and their application should be optimized; under-dosing results in poor removal of algae in clarification and problematic filtration, with the risk of breakthrough of algal cells containing toxins. Overdosing could also have a negative impact on the final water quality.

ACKNOWLEDGEMENTS

Firstly giving honour and glory to God almighty, in His mighty name, I am blessed.

My sincere gratitude to my supervisor, Eng. Z. Hoko, who gave me invaluable guidance and crystallized my hopes even in the darkest hours of the research. Thank you for the inspiration, the resources and the constructive criticism. Your criticism cultivated courage, patience and perseverance in me.

I would also like to thank Detlef Knappe, Department of Civil Engineering, North Carolina State University, the AWWA report you sent to me guided me so much. Though I may not have met you, I appreciate your help.

Knowledge acquired in life comes from 1001 sources. Special thanks and appreciation to:

Mr. L. Chipfunde, for your help, even through your busy schedule. The entire ZINWA staff at the city laboratory and Morton Jaffray, for the resources, the support and the help provided during the research.

The Civil Engineering water section staff, for the knowledge I acquired from them during the entire study period. Appreciation is also expressed for the support and assistance received from Mr. S. Mudzviti and Mr. Chawira, I could not have managed the laboratory work without your assistance.

Mr. Ashley and all the technicians at Biological Sciences, thank you for always willing to help me.

My Masters colleagues whom we toiled together in the journey of knowledge searching, Annatoria Chinyama and Lazarus Phiri, your help will be remembered always. Thank you.

Waternet, for the financial assistance. Thank you for affording me the chance to study for the Masters Degree.

Raphael Mwangobola, for the encouragement you always gave me. Thank you for friendship beyond compare.

Lastly, but not least, greatest thanks to my mum and dad, for always being there for me, through thick and thin. And to my lovely angel Tino-Ann, thank you for understanding my absence, as young as you are. Words could never express how much I love my daughter!

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CHAPTER 1

1.0 Introduction

Due to the continuing eutrophication of surface waters, algae-related problems in water treatment have gained worldwide attention. The major algae-related problems in such waters are unpleasant tastes and odours and filter clogging. Increased disinfection by-product (DBP) concentrations and microbial re-growth in distribution systems are other algae-related problems, and the production of toxins by some algae species is an emerging concern in the drinking water industry (Hang-Bae *et al*., 2001). Algae related water treatment and quality problems have been reported from different countries. In Argentine, mechanical problems at water purification plants, bad taste and odd flavour of drinking water caused by cyanobacterial blooms, were detected and reported in San Roque Reservoir since 1971, and in Paso de Piedras and Cruz de Piedra Reservoirs. Filter clogging *Synedra* has been the dominant filter-cloggers at the CheongJu water treatment plant (South Korea) in recent years (Hang-Bae *et al.,* 2001). Harmful algae has also been reported in Hartbeespoort Dam (South Africa), Alexandria Dam (Austria), Haimen City, Jian-Su Province, Guangxi Province (China) and Whitewater Lake (Canada) (Lepistö *et al.,* 1992; Murphy *et al*., 2002; Moyo and Mtetwa, 2002).

From the 1960s, the eutrophication of Lake Chivero, which is the major source of water for Harare, the capital city of Zimbabwe, has been evidenced by the proliferation of dense algae, principally *Microcystis aeruginosa and Anabaena* species (Munro, 1966; Thornton, 1982). Other species, such as *Asterionella* and *Ulothrix variabilis*, have also been detected (Johansson and Olsson, 1998). According to Magadza and Ndebele (2006), the algal toxin levels in Lake Chivero in 2003 exceed the recommended level of 1.0µg/l recommended by WHO (2001). The high algal toxins concentration was correlated to the presence of toxin producing algae in the lake.

Lake Chivero was built in 1952 on the Manyame River to supply water to the city of Harare. It has a full supply capacity of 250Mm^3 (Gumbo, 2005), a mean depth of 9m (max 27m at the dam wall) and is 10km long, (Magadza and Ndebele, 2006). As of studies carried out in 2002, the lake received sewage effluents from Harare, in excess of 120 000 m^3/day, via Firle and Crowborough sewage works (Nhapi *et al*., 2002), and this figure has increased over the years. The lake has become increasingly eutrophic and nutrient flows into the lake have increased.

The most serious consequence of the eutrophication has been the dense blooms of blue-green algae (*Cyanobacteria*), that causes problems, such as filter clogging, in water purification (Moyo and Mtetwa, 1999). Excessive amounts of algae have seriously impacted on the raw water abstraction and water treatment (Moyo and Mtetwa, 1999) at Morton Jaffray (MJ) water works, especially the filtration process as evidenced by the frequent backwashing now reported to be 4-8 hourly a day. The increased backwashing frequency has resulted in reduced plant output and consequently water shortages in Harare and its satellite towns. The high level of algae also has a cost implication, that is increased treatment costs due to a high chemical demand in the different stages of treatment, for example increased chlorine demand.

1.1 Background

As a result of the continuing eutrophication of surface waters, algae-related problems in water treatment are gaining worldwide attention. The major algae-related problems in such waters are unpleasant tastes and odours and filter clogging. Increased disinfection by-product (DBP) concentrations and microbial re-growth in distribution systems are other algae-related problems, and the production of toxins by some algae species is an emerging concern in the drinking water industry (Hang-Bae et al., 2001). Common filter-clogging algae include *Asterionella, Fragillaria, Anabaena* and *Synedra* (Montgomery 1985). *Synedra spp*. has caused filter clogging at CheongJu water treatment plant (Hang-Bae *et al.,* 2001). Knappe *et al.,* 2004, also reported that several water treatment plants experienced filter clogging and odour problems due to the presence on *Anabaena*, *Microcystis*, *Volvox*, *Chlamydomonas* and other types of algae.

Various studies have shown that algae in raw water may produce toxins which are harmful to humans and animals (Lam *et al.,* 1995; Hart *et al.,* 1998; Hall *et al.,* 2000). Algal toxins such as microcystins, produced by the *Microcystis* species are a threat to human health as they are hepatotoxic, carcinogenic and teratotoxic (Palmer, 1962; Lawton *et al.,* 1994) For Hartbeesport Dam (South Africa), Alexandria Dam (Austria), Haimen City, Jian-Su Province, Guangxi Province (China) and Whitewater Lake (Canada), cattle, sheep and bird kills, as well as increased incidences of liver cancer, have been linked to algal toxin contact, which usually coincides with algal blooms (Lepistö *et al.,* 1992.; Murphy *et al*., 2002; Moyo and Mtetwa, 2002). High microcystin concentrations of about 19.89 micrograms per litre have been detected in the raw water from Lake Chivero to the treatment works (Magadza and Ndebele, 2006). It is against this background that it was found worth carrying out this research.

One of the major consequences of the blue-green algae (*Cyanobacteria*) has been the problems in water purification at Morton Jaffray (MJ) water works which has adversely affected drinking water quality. Discussions with personnel responsible for the water treatment revealed that the filtration process has been the mostly affected as evidenced by the frequent clogging and backwashing (approximately backwashing every 4-8 hours). The high level of algae also has a cost implication, that is, increased treatment costs due to a high chemical demand in the different stages of treatment, for example increased chlorine demand (Moyo and Mtetwa, 1999).

The most effective means of eliminating algae, microcystins and other toxins would be to control the algal blooms in the lake, through reduction of the nutrient supply to the lake (Chorus *et al.,* 1993). This would require a major capital investment in sewage treatment works and in the disposal of sewage effluent. An example of such an investment is the estimate by Bulawayo City Council which shows that an investment of about US$575 000 for upgrading Aisleby Works, one of its major waste water treatment plants (www.queensu.ca/msp/pages/In_The_News). This may not be possible with the current economic situation in Zimbabwe. The reduction of pollution and eutrophication would ensure reduced, and possibly relatively safe, levels of algal blooms.

Algae may also be removed during potable water treatment through a combination of coagulation, clarification, filtration and disinfection. Chemical control may also be used

as an emergency measure of the control of algae, usually by use of algaecides (Chorus and Bartram, 1999). Compounds that have been used as algaecides include cooper sulphate, potassium permanganate, chlorine, ferric sulphate and copper citrate (Holden, 1970; McKnight *et al*., 1983; Raman, 1988; Hart *et al.* 1997).

A copper sulphate algaecide, Algaekill 2500, is being used at MJ treatment works. The algaecide is dosed at the distribution chamber, just before alum is dosed, but after dosing of Granular Activated Carbon (GAC) and sulphuric acid (H_2SO_4). Due to the high water demand the treatment units are being overloaded thereby reducing the contact time between the algae and the algaecide. A contact time of about 30 minutes is required before sedimentation (Hall *et al*., 2000). The toxicity of the copper algaecide could also be affected by the presence of activated carbon in the water. It has been widely recognized that metal can be removed from water by activated carbon adsorption. This is due to the surface complex formation between the metal ions and the acidic surface functional groups. Presence of acids also modify carbon surfaces by increasing their acidic surface functional groups.

Mostafa (1997) studied the adsorption of mercury, lead and cadmium on activated carbon modified with sulphuric acid and observed a significant increase in metal ion adsorption. He proposed that sulphuric acid might introduce acidic surface oxides on the carbon surface. Toles *et al.*, (1999) reported that air oxidation of phosphoric acid activated carbons yielded carbons with greater copper uptake. Copper adsorption showed good correlation with surface functional groups.

Algae is growing in all the treatment units, from the mixing chamber, flocculation channels, clarifiers and even in the filters, hence the need to determine the optimal conditions for the control of algae.

1.2 Objectives

1.2.1 Main Objective

The main objective of this study was to determine the impacts of algae on water treatment processes and the conditions suitable for optimizing control of the algae.

1.2.2 Specific Objectives

The following specific objectives were considered:

- To assess the effects of algae on water treatment processes and water quality.
- To determine the effective coagulation conditions for algae removal
- To identify factors contributing to effective removal of algae and determine the impacts of contact time and algaecide dose on removal of algae.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

As a result of the continuing eutrophication of surface waters, algae-related problems in water treatment are gaining worldwide attention. The major algae-related problems in such waters are unpleasant tastes and odours and filter clogging. Increased disinfection by-product (DBP) concentrations and microbial re-growth in distribution systems are other algae-related problems, and the production of toxins by some algae species is an emerging concern in the drinking water industry (Hang-Bae *et al.,* 2001; Knappe *et al.,* 2004).

Algae are aquatic, eukaryotic one-celled or multicellular plants without true stems, roots and leaves, that are typically autotrophic, photosynthetic, and contain chlorophyll (Bartram, 2004; www.nsc.org, 2007). Several of the large groups of algae are recognized by their common names such as the diatoms, blue-greens, greens and the yellow-greens. A brief explanation of the factors affecting growth of algae are discussed below.

2.1.1 Factors affecting growth of algae

Many complex factors operate in combination to cause algal blooms. Generally, algae thrive on nitrogen and phosphorus, which may enter surface water system in large amounts following their discharges in industrial effluent, domestic and municipal wastewater and agricultural runoff (Warren, 1971; Schreurs, 1992). Nutrients released from sediments also provide nourishment for algae (Feachem *et al.,* 1977).

Warm temperatures of about 20 °C and light saturation experienced in summer provide favourable conditions for growth (Reynolds, 1997). Other factors such as micronutrients (iron, molybdenum), pH and alkalinity, buoyancy, hydrologic and meteorological conditions have all been implicated to promote the growth of algae (Chorus and Bartram, 1999). Within a given water body, the factors listed above may progress in a routine seasonal cycle pattern as shown in Figure 1 (Horne and Goldman, 1994).

From figure 1, it can therefore be deduced that green algae and diatoms often dominate during summer conditions but blue-green algae can produce summer and winter blooms. Again, the most common nuisance forming blooms are associated with summer conditions when water temperatures and light availability are at a seasonal peak.

In Lake Okeechobee Florida USA, algal blooms that developed in the 1980s were attributed to high nutrient loading. Blooms in the Parano Lake in Brazil in the 1970s were attributed to the high nutrient levels as well as summer stratification of water which results in higher temperatures in the upper levels of the Lake (Cooke, 1993). In Zimbabwe, algal blooms in Lake Chivero have been due to eutrophication and thermal stratification of the lake (Nduku, 1978; Thornton, 1982; Magadza and Ndebele, 2006). High phosphorous levels of about 5 mg L^{-1} have been reported for Lake Chivero (Magadza and Ndebele, 2006).

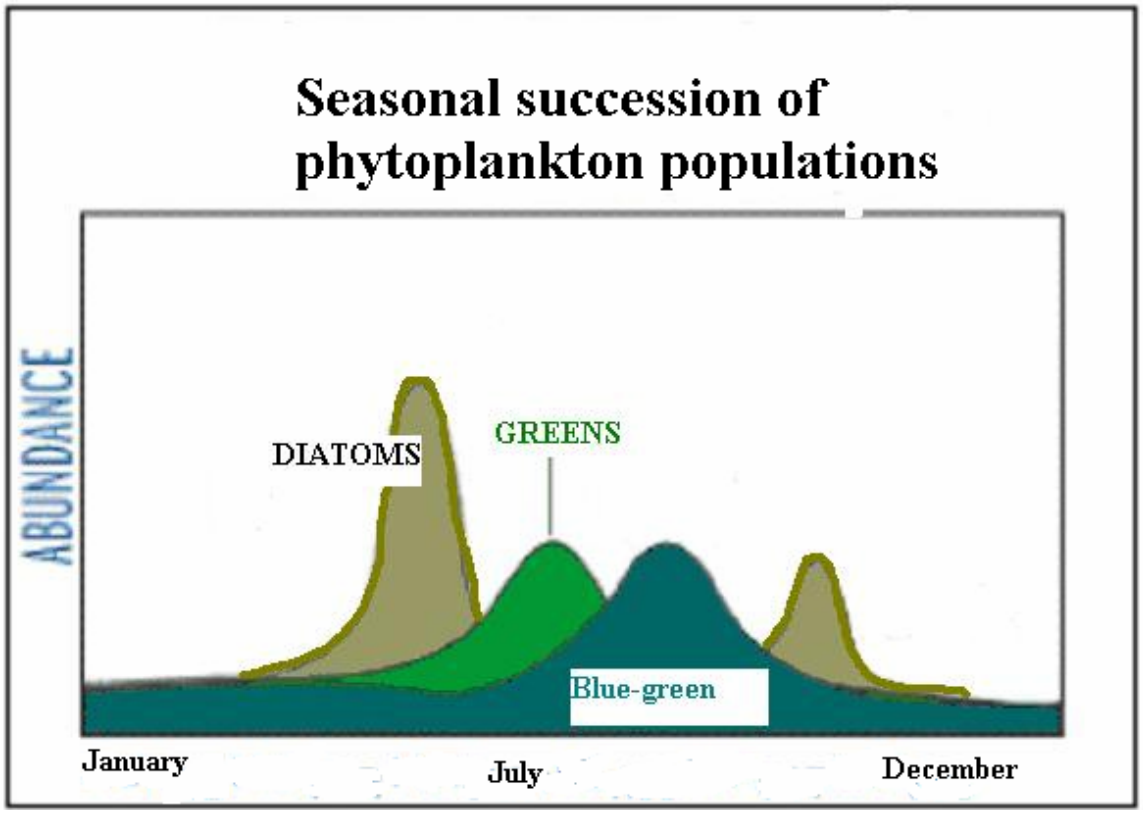

Figure 1 Typical periods of dominance of different algal species (Adapted from Horne and Goldman, 1994)

From a drinking water perspective, members of the blue-green algae are among the most problematic because many common blue-green algae adversely affect taste and odour, produce powerful toxins and cause clogging of filters. The principal types of algae which cause common problems in water treatment are (blue-green algae) are briefly described below. The health effects of the toxins produced by the blue-greens are also discussed.

2.2 Types of algae

2.2.1 Blue-green algae

The scientific name for blue-green algae is *Cyanobacteria* (Horne and Goldman, 1994). The first recognized species of algae were blue-green in colour, which is how cynobacteria got their name. About 150 genera and 2000 species of blue green-algae are known (van den Hoek et *al.,* 1995). Typical genera include *Anabaena, Microcystis* and *Oscillatoria* (Knappe *et al*., 2004). Blue-green algae are made up of cells, which can house poisons called cyanobacterial toxins (Viessman and Hammer, 2005). These toxins fall into various categories; some are known to attack the liver (hepatotoxins) or the nervous system (neurotoxins) and others simply irritate the skin (Palmer, 1962; Viessman and Hammer, 2005). *Microcystins,* produced by cyanobacterium called *Microcystis aeruginosa,* are the most common cyanobacterial toxins found in water, as well as being the ones most often responsible for poisoning animals and humans (Viessman and Hammer, 2005).

2.2.2 Microsystis aeruginosa

Microcystis aeruginosa is a noxious, bloom-forming cyanobacterium which is frequently associated with thermally stratified water bodies (Ganf, 1974: Robarts and Zohary, 1984). The ability of *M. aeruginosa* to exploit thermally stratified conditions can be attributed to gas vesicles, which provide buoyancy, reduce sedimentation losses (Reynolds and Walsby, 1975) and maintain colonies in a favourable light climate during periods of low turbulence (Humphries and Lyne, 1988)

Microcystis aeruginosa blooms are made up of small cells embedded in a gelatinous matrix and cells range from 3µm to 4.5µm in diameter (Presscott, 1951). Figure 2 shows a microsystis bloom. Some strains of *Microcystis* produce toxins that have been reported to result in health problems to animals that drink the water, minor skin irritation and gastrointestinal discomfort in humans that come in contact with toxic blooms (Chorus and Batram, 1999).

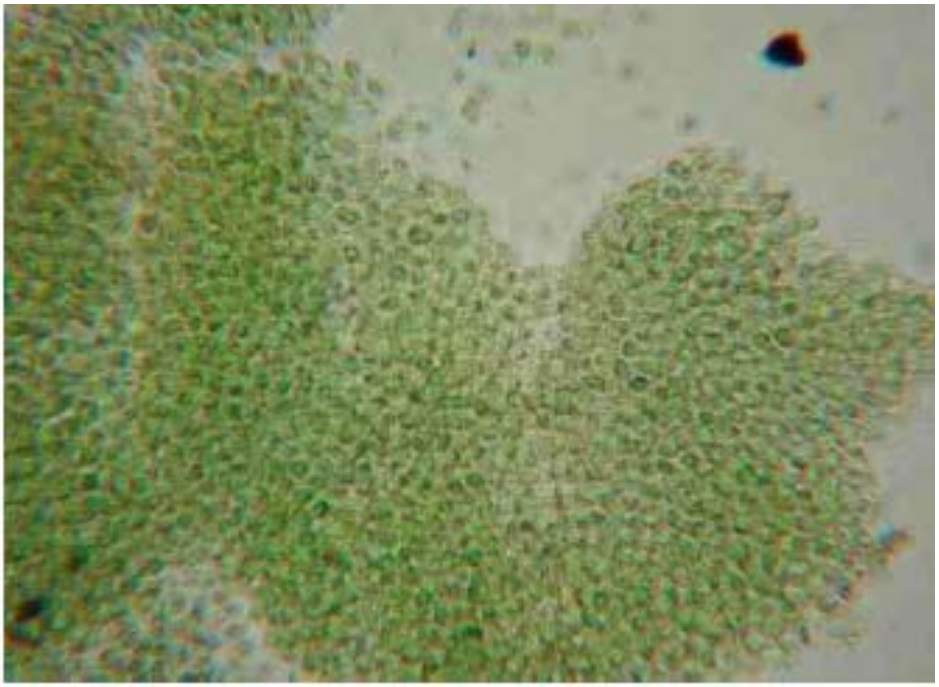

Figure 2 Microcystis bloom (Source Reynolds, 1987).

Toxins released by microcystins have been associated with human poisoning. Evidence for human poisoning include cases of gastro-enteritis reported in the population of a series of towns along the Ohio River as early as in 1931 (Tisdale, 1931). In Harare, Zimbabwe, children living in an area of the city supplied from a particular water reservoir, developed gastro-enteritis each year at the time when a natural bloom of *Microcystis* was decaying in the reservoir. Other children in the city with different water supplies were not affected and no infectious agent was identified (Zilberg, 1966). In February 1996, an outbreak of severe hepatitis occurred at a Brazilian haemodialysis centre in Caruaru (Jochimsen *et al.,* 1998). The pattern of liver plate disruption was identical to that found with previous laboratory animal experiments involving microcystin exposure. Cattle, sheep and bird kills, as well as increased incidences of liver

cancer, have been linked to algal toxin contact in Hartbeesport Dam in South Africa, Alexandria Dam in Austria, Haimen City, Jian-Su Province, Guangxi Province in China and Whitewater Lake in Canada (Lepistö et al., 1992.; Murphy *et al*. 2002; Moyo and Mtetwa 2002).

2.2.3 Anabaena

Anabaena is heterocyst-forming, photoautotrophic cyanobacteria that perform oxygenic photosynthesis (Wetzel, 1983). *Anabaena* grow in long filaments of vegetative cells and form long chains of cells, called a trichome, which sometimes grows in a spiral as shown in Figure 3. Anabaena has a specific gravity 1.10 and easily clog filters because of its shape

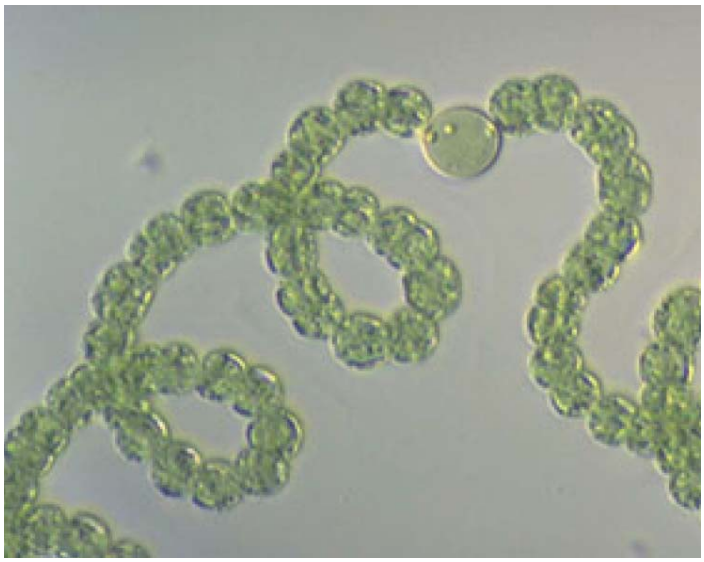

Figure 3 Anabaena in spiral form (Source: APHA 1998)

During times of low environmental nitrogen, about one cell out of every ten will differentiate into a heterocyst (Horne *et al.,* 1972; Huang *et al.,* 2005). Heterocysts then supply neighboring cells with fixed nitrogen in return for the products of photosynthesis, that they can no longer perform. Anabaena can hence survive even at low nitrogen concentration. (Reynolds, 1997).

2.3 Effects of algae in water treatment and on water quality parameters

Negative aspects of cyanobacteria have gained research attention (Knappe *et al.,* 2004). Cyanobacteria affect water treatment by impairment of coagulation and flocculation processes, filter clogging or premature filter breakthrough of particulate matter, increased chlorine demand and disinfection by-product concentrations (WHO, 1996; Chorus and Bartram, 1999). Algae also causes slime formation, corrosion of concrete or metal pipes, taste and odour problems and algal toxins maybe released, thereby affecting the final water quality. The detailed discussion on effects of algae on water treatment is presented in the sections that follow.

2.3.1 Filter clogging

Algae are frequently the cause for clogging of filters (Palmer, 1962; Hart et al., 1997). The algae form a slimy layer over the surface of the filter media, usually sand (Hart et al., 1997). In extreme cases, the clogging may recur so frequently that the water required to backwash the filter is great and the amount of filtered water which reaches the distribution system is greatly reduced. Thus the presence of filter clogging algae can slow down the processes of water treatment and add materially to its cost.

In Chicago, when water to be filtered contained about 700 cells per millilitre of water, the filter runs for sand filters were only 4 to 5 hours (Baylis, 1955). According to the study, on reduction of the algal count to about 100 cells/ml, the filter runs increased to 41hours. The occurrence of *Synedra* species in the source water of the CheongJu water treatment plant (South Korea) decreased filter run times of rapid sand filters to below 5 hours (Hang-Bae *et al.* 2001). In Washington D.C, filter runs were reduced from an average of 51 hours to less than 1 hour due to a sudden influx of algae in raw water with a concentration reaching 4800 cells/ml (Baylis, 1955). Anabaena (blue-green) is known to have caused filter trouble in Illinois and Minnesota. According to various studies, several filter clogging algae have been detected in the raw water from Lake Chivero to Morton Jaffray which include *Anabaena flos-aquae*, *Anacystis*, *Microcystis aureginosa* (blue green) and *Asteriolla Formosa*, diatoms (Munro, 1966; Thornton, 1982; Johansson and Olsson, 1998; Magadza and Ndebele, 2006).

2.3.2 Taste and Odour

One of the requirements in the production of potable water for communities is that the product should be free of obnoxious and abnormal tastes and odours (WHO, 1996). Of several causes tastes and odours, algae present in raw water are recognized as being either primary or at least one of the most important causes. On studies done in Central Missouri by the Public Health Department in 1955, it was found that practically all the taste and odours occurring were associated with the presence of algal blooms. According to a survey by Knappe *et al*., (2004), 90% of the surface water treatment plants in the US, under survey, reported odour problems due to the presence of algae in the raw water. Taste and odour algae have been detected in the raw water from Lake Chivero, for example, *Anabaena*, *Anacystis* and *Microcystis,* all blue-green algae (Munro, 1966; Thornton, 1982; Johansson and Olsson, 1998). Table 1 summarises common taste and odour compounds, algae genera that produce them and the odour characteristics.

2.3.3 Turbidity

Water turbidity can increase during an algae bloom due to the presence of algae cells (Harper,1992). However other factors such as storm events can influence turbidity fluctuations. Therefore, raw water turbidity trends should only be used for determining onset of algae blooms. In cases of filter breakthroughs, algae cells may increase the final treated water turbidity.

Table 1 Common compounds causing taste and odour problems in drinking water

Compound	Algae genera producing the compound	Odour descriptor
Geosmin	*Anabaena, Oscillatoria*	Earthy-corn-musty
Linolenic acid	*Microcystis, Chlamydomonas*	Sweet melon-water melon
B-cyclocitral	*Microcystis, Oscillatoria*	Sweet-fruity; chocolate-pipe tobacco
Isovaleric acid	*Chlamydomonas*	Rancid-cheesy-dirty socks-sour

(*Sources:* Lyonnaise des Eaux 1987, 1995; Rashash *et al.,* 1996).

2.3.4 Other problems caused by Algae

Algae may cause slime formation in water treatment plants (Paerl, 1988). Blue-green algae as a group are notorious slime producers. Corrosion of concrete and metal structures may also be a result of the presence of algae. This is because the algae can modify physical and chemical properties of water through increase in organic deposits, increase in dissolved oxygen (DO) in rawer water and changes in pH (Palmer, 1962; Harper, 1992; Maberly, 1996). On-line measurement of water parameters such as pH and DO can help utilities detect algae blooms in their source water, and hence avoid water treatment problems caused by algae.

2.4 Algal Control in Water Treatment

The management and control of cyanobacteria in water treatment works may be achieved through different approaches. The first preference for control is the prevention of eutrophication (Drikas, 1994; Chorus and Bartram, 1999). The next preference of management response is reservoir and water body management which can include some engineering techniques to alter hydro-physical conditions in the water body in order to reduce cyanobacterial growth. The control techniques which can be used in the management of raw water abstraction include the avoidance of contamination by positioning of offtakes, selection of intake depth, offtake by bank filtration, and the use of barriers to restrict scum movement (Cooke, 1993). Use of algaecides is another intervention technique. Copper sulphate, potassium permanganate, chlorine and ferric sulphate have been used as algaecides (Holden, 1970; McKnight *et al*., 1983; Raman, 1988; Hart *et al.,* 1997). Algaecides have been, and will continue to be, used as emergency measures for the control of cyanobacteria. The final option for management of cyanobacterial problems and cyanotoxins in water supplies is within the treatment system (Chorus and Bartram, 1999). The efficiencies of algae removal by the different water treatment processes are summarised in table 2.

Table 2 shows that a combination of coagulation, sedimentation and filtration can achieve a high percentage, (>90%), of algae removal. Requiring little or no capital investment, improving algae removal by coagulation and sedimentation can be an economical option for the mitigation of filter clogging problems in conventional water treatment plants. Furthermore, unlike oxidative treatment techniques that can lyse or stress algae cells (Sukenik *et al*., 1987; Lam *et al*., 1995; Peterson *et al*., 1995; Hart *et al*., 1998; Hall *et al*., 2000), coagulation and sedimentation processes are capable of

removing whole algae cells (Chow *et al*., 1999). Therefore, removal of intracellular taste and odour compounds and toxins can be achieved by coagulation and subsequent solid–liquid separation (Ando *et al*., 1992; Hart *et al*., 1998; Chorus and Bartram 1999; Hall *et al*., 2000).

Table 2 Water treatment performance on removal of algae algal toxins

Treatment Technique	Expected removal		Comments
	Cell Bound	Extra cellular toxins	
Coagulation/ flocculation/ dissolved air floatation	>80%	<10%	Removal only achievable for intact algal cells. If cells are damaged, the process does not effectively remove the toxins
Rapid filtration	>60%	<10%	Removal only achievable for intact algal cells. If cells are damaged, the process does not effectively remove the toxins
Combined coagulation, sedimentation and filtration	>90%	<10%	Removal only achievable for intact algal cells. If cells are damaged, the process does not effectively remove the toxins
Pre-chlorination	Very effective in enhancing coagulation	Causes lysis and release of dissolved metabolites	Useful to assist coagulation of cells, but applicable for toxic cynobacteria only if subsequent treatment processes will remove dissolved toxins
Adsorption- Granular activated carbon (GAC)	>60%	>80%	

(*Source*: Adapted from Yoo *et al*., 1995)

2.4.1 Coagulation, Flocculation, and sedimentation

Coagulation or flocculation involves the aggregation of smaller particles into larger particles using chemicals such as ferric chloride or aluminium sulphate (alum). Coagulation can be an efficient method for eliminating cyanobacterial cells from water, whereas soluble cyanotoxins are not very efficiently removed by this method (Drikas, 1994; Hall *et al.,* 2002). The efficiency of cyanobacterial removal is dependent on an optimization of chemical doses and coagulation pH (UKWIR, 1996). According to Chorus and Bartram, 1999, coagulation, flocculation and sedimentation can achieve a removal efficiency of greater than 80%.

According to Hang-Bae *et al.,* 2001, the coagulation of algae tends to be more complex than that of inorganic particles because of the wide variety of algal morphologies and sizes. The adsorption and charge neutralization mechanism that describes the destabilization and aggregation of colloidal matter is only effective for small algae that approximate spheres (Bernhardt and Clasen 1991, 1994). Consistent with this

mechanism, Tenney *et al*. (1969) observed a stoichiometry between the concentration of a mixed culture of green algae and the required cationic polymer dose to achieve optimal flocculation. Bernhardt and Clasen (1991) also observed that the longest filter runs in a direct filtration plant were obtained when an alum dose was added that neutralized the surface charges of the alga *Scenedesmus obliquus*. Again, Briley and Knappe, (1998) observed that the coagulation of small *Anabaena flos-aquae* filaments was optimal at pH 6 and metal coagulant doses that yielded the point of zero charge as determined by streaming current measurements.

Effective coagulation of algae occurs at coagulation pH values and with coagulant doses that either neutralize algae surface charge or yield sufficient floc for algae enmeshment (Knappe *et al.*, 2004). In water treatment processes that have sedimentation, the coagulation/flocculation process needs to yield relatively large floc, especially in the presence of algae, whose density is close to that of water (Edzwald, 1993). Coagulation of algae can hence be improved by use of coagulant aids. Cationic poly-electrolytes may be used in conjunction with metal coagulants (e.g. alum) to coagulate algae. Cationic polyelectrolytes can effectively remove the negative charge density of algae suspensions

The removal of motile algae presents another challenge. The algae can possibly liberate themselves from floc, and thereby affecting the subsequent processes such as Rapid sand filtration (Bernhardt and Clasen, 1991). Effective removal of motile algae may require that their motility be arrested by application of oxidants, sufficiently at low doses to avoid cell lysis. In the absence of oxidant addition, removal of motile algae is possible by coagulation and subsequent filtration, provided that sufficient doses of coagulant are added.

Proper coagulation conditions are therefore essential for the mitigation of problems caused by algae, especially the problem of filter clogging. Furthermore, the effective removal of algae by coagulation, flocculation and sedimentation translates into effective removal of intracellular toxins as well as odour band taste causing compounds.

2.4.2 Combined Coagulation, clarification and Rapid Filtration

The performance of rapid filtration, a method usually employed after coagulation to remove the residual floc, does not effectively remove cyanobacterial cells, if used on its own. Mouchet and Bonnélye, (1998) reported poor removal rates of 10-75 per cent. Lepisto *et al.,* (1996) evaluated full scale water treatment plants for their ability to remove cyanobacterial cells and found rapid sand filtration achieved only a 14 per cent reduction in cells.

Conventional water treatment commonly involves the combination of coagulation, clarification (sedimentation or dissolved air flotation) and filtration. Consequently, much of the limited research that has been published on water treatment performance for the removal of cynobacterial cells and toxins has looked at overall removal across the common combinations of coagulation-filtration and coagulation-clarification-filtration, rather than looking at each stage individually (Chorus and Bartram, 1999). Table 2 shows that combined coagulation, sedimentation and filtration can achieve algae removals of >90%. Leuschner (1984) studied phytoplankton retention by flocculation, sedimentation

and rapid filtration in a plant treating highly eutrophic river water. *Microcystis* spp, occurring as large colonies, were rarely observed in the finished water, but filamentous algae was poorly retained, showing an average breakthrough of 27 per cent of the filaments. Mouchet and Bonnélye (1998), reported that addition of a cationic polymer during flocculation substantially improved retention. The removal of whole, intact cells, by combination of coagulation, clarification and filtration presents the best opportunity to remove algal cells and toxins in water treatment.

In summary, currently available results indicate that conventional coagulation and rapid filtration processes can effectively remove intact algal cells, provided the coagulation conditions are optimal.

2.4.3 Use of algaecides

Algaecides are used in reservoirs to control cyanobacterial growth and to prevent or reduce to some extent the problems of toxins in the associated drinking water supply (Codd and Bell, 1996). They are used to provide effective short-term control of growth of cyanobacteria, at one point in time, especially where alternative drinking water sources are not available and preventive measures are not feasible or not yet effective (Codd and Bell,1996). Algaecide treatment has been proposed as being more cost-effective than toxin removal in drinking water treatment plants, as has been suggested for the control of off-flavour problems (McGuire and Gaston, 1988), because an extended period of persistent blooms greatly enhances the need for additional treatment for toxin removal. Some of the compounds that have been used and evaluated for potential as algaecides over the years are summarised in Table 3

Table 3 Compounds that have been used as algaecides

Compound	Formulation
Copper Sulphate	$CuSO_4.5H_2O$
Copper-triethalamine complex	$Cu\ N(CH_2CH_2OH)_3.H_2O$
Copper citrate	$Cu_3\ [(COOCH_2)_2C(OH)COO]_2$
Potassium Pemanganate	$KMnO_4$
Chlorine	Cl_2

(*Source:* Chorus and Bartram, 1999).

2.4.4 Copper Sulphate

Copper Sulphate ($CuSO_4$) is the mostly used algaecide (Bartsch, 1954; WHO, 1996; Burch *et al.,* 1998). Records of use of $CuSO_4$ date back from 1890 in Europe (Sawyer, 1962) and since the mid 1940s in Australia (Burch et al., 1995). $CuSO_4$ is widely used because it is economical, effective and relatively safe and easy to apply (Chorus and Bartram, 1999). Copper is affected by pH just like other heavy metals (Vijayarghavan *et al.,* 1999). Algal blooms comprises of binding sites which are occupied by light metal ions, such as sodium and calcium ions (Vijayarghavan *et al.,* 1999). Suitable pH is therefore required to exchange the light metal ions with Cu^{2+} ions. At low pH of below 6, excess of H^+ ions compete with Cu^{2+}occupying the sites. At high pH conditions(greater than pH 9), excess of hydroxyl ions combine with Cu^{2+} to form precipitates (McKnight et al., 1983; Vijayarghavan *et al.,* 1999). Both cases usually decrease Cu biosoption, therefore an optimum pH is required to achieve maximum biosoption. The copper

sulphate hence has to be applied at correct pH values to enhance its effectiveness as an algaecide.

2.4.5 Algaecidal Effect of copper on algae

The mechanism of toxicity of Cu^{2+} ions in algae has been studied. Cu ions prevent cell division and causes accumulation of the products of photosynthesis and thus the depression of photosynthesis (Nielsen *et al*., 1969; Mcknight *et al*.,1983).According to an assessment of the use of $CuSO_4$ for the control of cyanobacteria by Mcknight *et al.,* (1983), it was found that there is a wide difference in Cu sensitivity among species. The relative growth inhibiting concentrations for a range of algae are given in terms of cupric ion activity (i.e. $[Cu^{2+}]$). The relative toxicity is given in terms of ionic copper because algae react principally to the concentration of Cu^{2+} or loosely complexed copper rather than the total dissolved metal in the water. Most filter clogging and taste and odour algae are susceptible to $CuSO_4$.

Several authors have cited different dose rates of copper which are lethal to algae. Prescott (1948) gave a list of recommended dose rates by several authors and also pointed out that it is difficult to formulate general rules. For example, one author stated that a dose of 0.12 – 0.8 mg/l was required to kill *Aphazomenon flos-aquae* , and another author gave the doses as 0.05 – 0.1 mg/l. The difference was accounted for by the fact that the second author used a spray method of application that was more effective.

In 1963, Fitzgerald and Faust found that the toxicity of copper varied with the medium in which algae were growing. The figures they quoted for the toxic concentration of copper for blue green (0.05 mg/l) were lower than those of earlier workers. Other factors which have been found to influence the sensitivity of algae to copper are light intensity and the degree of aeration of the medium, (Gibson, 1972). Another complication is that some algae seem to be able to resist high concentrations of copper.

The presence of activated carbon in the water can also reduce the toxicity of copper. GAC, which is used to remove taste and odour causing compounds may reduce the toxicity of copper. It has been widely recognized that metal removal by activated carbon adsorption is due to the surface complex formation between the metal ions and the acidic surface functional groups. Presence of acids also modify carbon surfaces by increasing their acidic surface functional groups. Mostafa, (1997) studied adsorption of mercury, lead and cadmium on activated carbon modified with sulphuric acid and observed a significant increase in metal ion adsorption. He proposed that sulphuric acid might introduce acidic surface oxides on the carbon surface. Toles *et al.,* (1999) reported that air oxidation of phosphoric acid activated carbons yielded carbons with greater copper uptake. Copper adsorption showed good correlation with surface functional groups

If algaecides are used, they must be applied at the early stages of bloom development and water treatment processes when cell densities are low, in order to reduce the potential for liberation of the high concentrations of intracellular toxins that may be associated with dense blooms. Early application will further enhance the effectiveness of treatment because cyanobacterial cells can form a major part of the "copper demand" along with other organic matter in natural water. Contact time between the algaecide and algae is

also increased. Efficient removal of algae is dependent on optimization of chemical doses, pH and contact time between water and chemicals. Mouchet and Bonnélye, (1998) have shown that the coagulant dose necessary for algal removal, even after algaecide treatment is proportional to the sum of alkalinity and the logarithm of cell number.

A major limitation of algaecides is the release of toxins and of taste and odour compounds from the cells (Jones and Orr, 1994; Lahti *et al.,* 1996). Studies have indicated that cyanotoxins are predominantly intracellular in healthy cells, and are only released into the water at an advanced stage of bloom senescence, or following treatment with chemicals such as algaecides (Bourke *et al.,* 1983; Lahti *et al.,* 1996). These dissolved toxins will then disperse and be diluted throughout the water body, but will not be removed by conventional flocculation and filtration procedures. The dangers of treating dense blooms with algaecides was demonstrated in an incident which occurred on tropical Palm Island, Australia, where members of the community became ill with hepato-enteritis following treatment of the water supply reservoir with copper sulphate for a cyanobacterial bloom problem (Bourke *et al.,* 1983). In some cases algaecide treatment may be unsuccessful or only partially successful. This can be due to inadequate dispersal and contact with the target organisms, variable sensitivity of cyanobacteria, and reduced toxicity of the algaecide, for example complexation of copper (Burch *et al.,* 1998).

From the literature, it is clear that preventive measures such as watershed management are more desirable since they do not lead to lysis of algal cells. Other water treatment processes such as a combination of coagulation, flocculation, sedimentation and filtration are also desirable and can achieve intact algal cell removal. Though algaecides can provide a short term solution for effective algal control, they have to be used with care, and the correct doses applied to avoid further problems such as production of toxins due to algal cell lysis.

CHAPTER 3

3 STUDY AREA

The Harare Metropolis, which lies upstream of Lake Chivero, in the upper Manyame catchment, consists of the city of Harare, and its satellite towns of Chitungwiza, Ruwa, Norton and Epworth. The city and its satellite towns lie within the catchment area of the main sources of water supply and as a result the drainage from the city and towns flows into the water supply lakes. According to Gumbo, (2005), the existing urban water and drainage system is a single-use-mixing system where water is used and discharged to waste. Wastewater is flushed into sewers and after some treatment, the effluent is discharged to the main drinking water source, Lake Chivero.

Lake Chivero has been the subject of a number of studies in the past years. The studies on Lake Chivero have a common concern of deteriorating water quality (Marshall and Falconer 1973, Nduku, 1976, Thornton, 1982, Magadza 1997, Moyo 1997). Lake Chivero is the main supply reservoir for Harare and its satellite towns. The Lake was constructed in 1952 for the supply of water to City of Harare as well as irrigation commitments to nearby farms. Lake Chivero catchment has an area of 2230 km^2 with the surface area of the Lake being 25.3 km^2 . The Lake has a capacity of 25000 m^3 and a mean depth of 9.5m.

In the mid to late 60s the lake became hypereutrophic, with odours of rotting blue green algae, especially *Anabaenopsis*, being evident in the lake's vicinities (Thornton, 1982). *Eichhornia crassipes*, the water hyacinth also appeared on the lake and spread at an alarming rate. Studies carried out during that period concluded that sewage effluent was the main source of nutrient enrichment in the lake. Other studies have also shown that Lake Chivero receives sewage effluent in excess of 120 000 m^3/day from an industrialized and densely populated area via Firle and Crowborough sewage treatment works, (Nhapi *et al.,* 2002). Though sewage is the most identifiable source of pollution, contributing to 40% of nutrient input into the lake, non point sources also contribute a significant amount of nutrients,(Nhapi *et al.,* 2002; Gumbo, 2005). The high nutrient levels in Lake Chivero has also resulted in the proliferation of algae (blue-green algae). The algae has caused problems in portable water treatment at Morton Jaffray (MJ) water works in Harare (Nhapi *et al.,* 2002; Gumbo, 2005) .

3.1 Morton Jaffray Water Works

Potable water for Harare city and its satellite towns is supplied, via Morton Jaffray (MJ) water works, from two principal reservoirs, Lakes Chivero and Manyame. MJ water works is about 35km to the Southwest of Harare. Figure 4 shows the location of MJ water works.

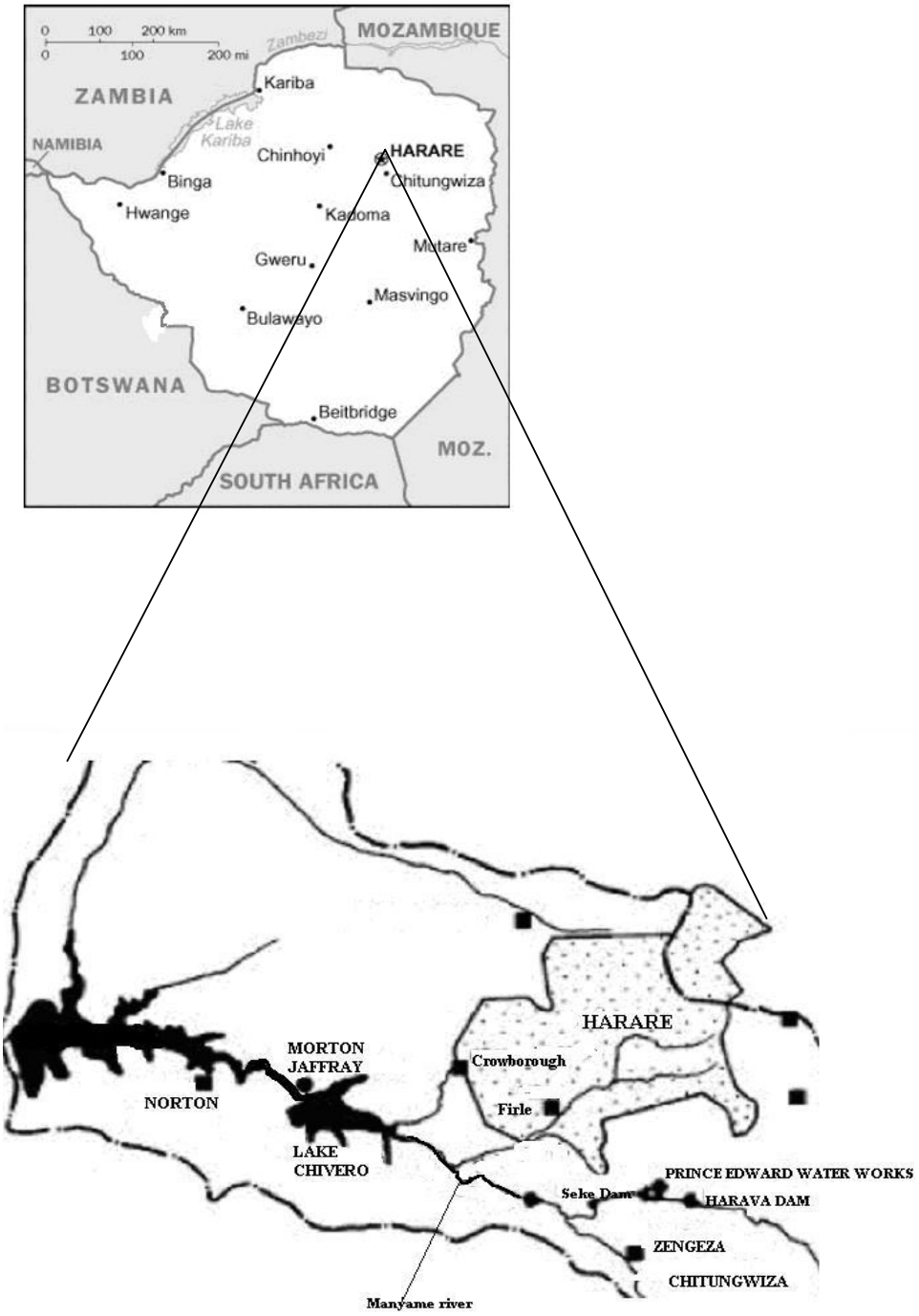

Figure 4 Location of Morton Jaffray water works.

The water from Manyame flows by gravity for about 15.4 kilometres, in a slopping unpaved underground tunnel. It is then pumped to the mixing chamber, where it is blended with Lake Chivero raw water. Raw water, from Lake Chivero flows by gravity to the mixing chamber.

MJ water treatment plant has three treatment units, the oldest unit having been built in 1954. Unit two and three were constructed 1976 and 1994 respectively. The design output capacities in cubic meters (m^3) per day for Phases 1, 2 and 3 are 160 000, 227 000 and 227 000 respectively, making a total of 614 000 m^3. The treatment works were constructed when pollution was still low, the water treatment requiring only aluminium sulphate, lime and chlorine. Today eight chemicals, (activated carbon, sulphuric acid, algaekill 2500, aluminium sulphate, sodium silicate, chlorine, hydrated lime and ammonia) are used. This reflects that the raw water quality has deteriorated.

Water impurities occur in three fine states, that is, suspended, colloidal and dissolved matter. Different treatment processes are employed at MJ to remove these impurities and render the water potable. The water treatment flow scheme is shown in figure 5.

The total inflow of water to the mixing chamber is estimated to be about 24000 m^3/hr. The raw water from Lakes Chivero and Manyame is mixed in the ratio 2: 1 respectively. At this point, granulated activated carbon (GAC) is added, the doses ranging from 10 to 50 mg/l. The dose depends on the season as well as the intensity of colour. GAC aids in the removal of taste and odour causing substances. Sulphuric acid (H_2SO_4) is also added in the mixing chamber to lower the pH to about 7.5-7.7, so as to decrease the chemical demand. There is also some considerable amount of aeration to strip off gases such as hydrogen sulphide.

From the mixing chamber, the water flows into the distribution chamber at an approximate flow rate of 350-400 m^3. The water then flows into 6 baffled channels, each leading to a clarifier. Hydrated aluminium sulphate (coagulant), activated silica (coagulant aid) and algaekill 2500 (algaecide) are added into each channel. Aluminium sulphate doses range from 65 to 80 mg/l, whilst algaekill 2500 doses is about 0.8 mg/l to 1.2 mg/l. Flow rates of water into the channels are not measured. The channels are made in such a way that thorough mixing of chemicals and water occurs and also to aid flocculation before the water gets into the clarifiers.

Phase 1 works makes use of Alexandra and radial clarifiers. Phases 2 and 3 have got 3 pulsator clarifiers each. The pulsator is a sludge blanket-type clarifier which utilizes a hydraulic pulsating system to maintain a homogenous sludge later within the clarifier.

Each clarifier has a design capacity of 3600m^3/hr, but is currently being 20% overloaded to cater for the high demand. The pulsator clarifiers have the following dimensions:

- Unit surface area 1250m^2
- Vacuum chamber surface area 20.5 m^2
- Settling surface area 1065 m^2
- Overall height of water 4.5m

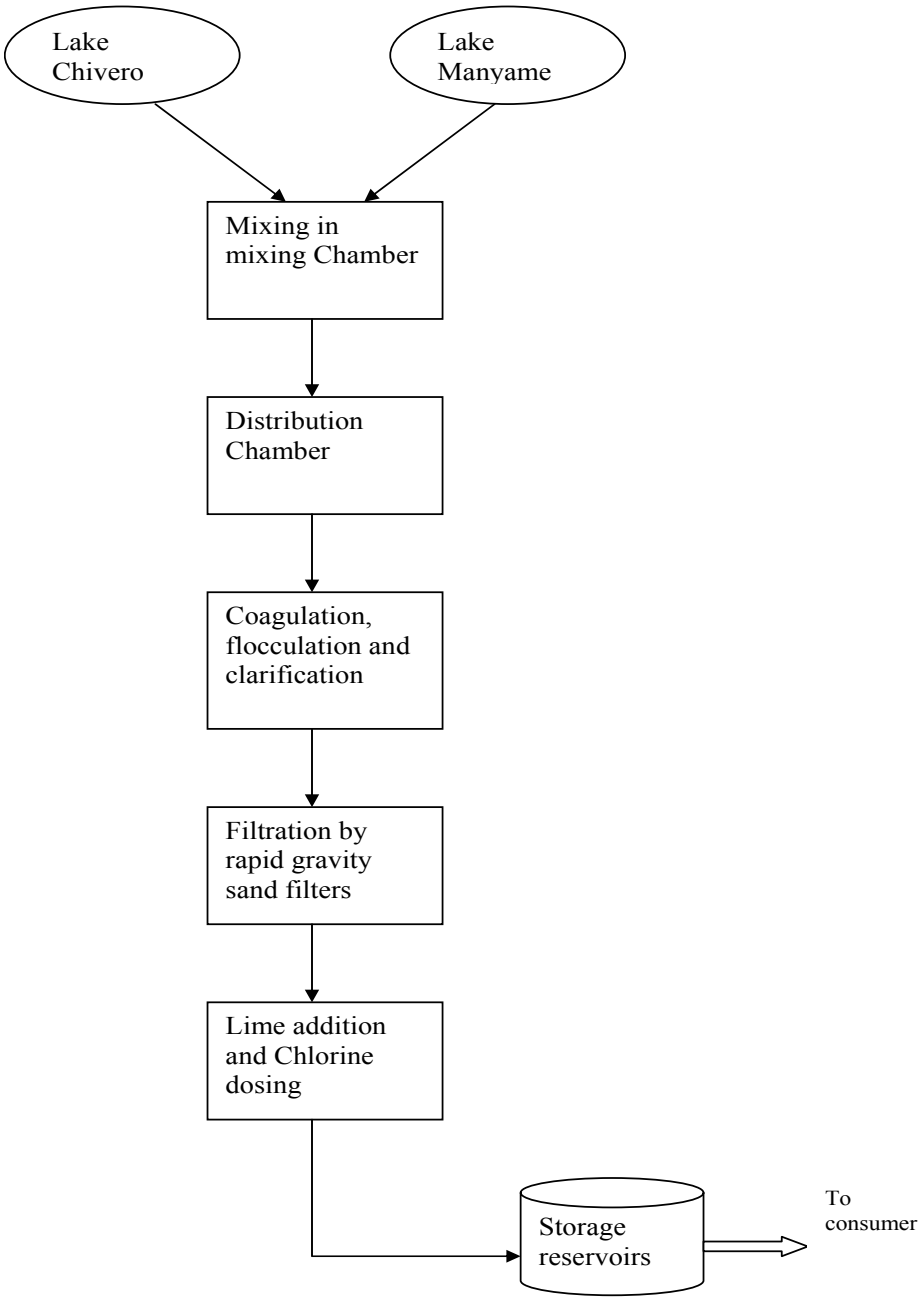

Figure 5 MJ water treatment flow scheme

Each clarifier has got a rectangular flat bottom tank, with perforated pipes at its base. The coagulated water enters the clarifier through these pipes. Invented V shaped baffles are directly above the perforated pipes and these aid in distributing flow evenly over the bottom of the sludge blanket. There is continuous growth and removal of sludge. The excess sludge flows into hoppers at one section of the clarifier. Desludging is done periodically, approximately after every 6minutes.

The clarified water goes out of the clarifier through launders and flows into the rapid sand filters (RSF). In the filters, purification of water is done through passing water though a filtration media and removal of suspended solids that passed the clarifiers is achieved. Phase 1 has 26 filters, with a design capacity of $140m^3$/min, whilst phases 2 and 3 have 18 filters each, of the AQUAZUR V type, with a design capacity of $180m^3$/min/unit. The filter media is made up of $8m^3$ of 4-8mm gravel support and $110m^3$ of fine sand.

The filters are backwashed after every 8 hours due to frequent loading. At times the filter run time is reduced to 4 hours. For the backwashing, compressed air and water are used. Air is introduced first, from the bottom of the filter, then a small amount of water to carry out the dirt from the air scour. After air supply is stopped the wash water valve is fully opened for the final rinsing to occur.

After filtration the treated water passes through a lime and chlorine dosing chamber for pH control. The lime and chlorine demands are determined in the laboratory. Chlorine doses range from 1.05 to about 1.25mg/litre, while lime doses are in the range 12-35mg/l. After disinfection, the water is then pumped to storage reservoirs for distribution to consumers.

CHAPTER 4

4 MATERIALS AND METHODS

The methods of study involved literature review, field and laboratory experiments as well as analysis of records.

4.1 Research Design

This research was exploratory and formal. The research was carried out over a short period of time, January to May 2007, hence represented a snapshot of one point in time. This hence, might present limitations as far as the identification of trends is concerned.

The research environment was both field and laboratory based. Methods of data collection included monitoring (water treatment process at Morton Jaffray was monitored) and laboratory based simulations. To assess the effects of algae on water treatment processes literature review was done. In addition, the possible effects of algae were studied at the Morton Jaffray (MJ) water treatment plant (WTP), for phase 2 and 3 treatment units. The two water treatment units have a total design capacity of 454 Mega litres per day. The WTP treats water by coagulation, flocculation, clarification and rapid filtration. Algae removal was monitored at each stage of treatment. The algae types present at each treatment stage were also monitored. Turbidity, temperature and pH were also measured. Turbidity and pH can be affected by the presence of algae, whereas temperature is one factor that determines the succession of algae in a water body. Water inflow rates for the two treatment units were also measured to help determine the possibilities of under-dosing and over-dosing of chemicals, which could affect the algae removal and cause algae related problems.

To determine the effective coagulation conditions for algae removal, as well as the impacts of algaecide dose and contact time, simulations of different water treatment processes were carried out using the jar tests. For these simulations, raw water from Lake Chivero was used, mainly because it represented a "pure" sample before any chemicals were added. There was no access to collect the Lake Chivero-Lake Manyame blend before addition of GAC and sulphuric acid. For determining the coagulation conditions, coagulation, flocculation and clarification processes were simulated as explained in the sections that follow. In addition to these process, flow from the intake tower at Lake Chivero to Morton Jaffray WTP was also simulated by use of the jar test. This simulation represented a scenario whereby the contact time between the algaecide and the algae could be improved, without interference of other chemicals such as granular activated carbon and alum. The jar tests were carried out for different contact times, including the current scenario where the algaecide and coagulant are dosed at the same time.

The water treatment process at Morton Jaffray could not be manipulated, hence researcher had no power over the variables being monitored. However, manipulation of the variables was done experimentally in the laboratory, through simulations of the different water treatment processes of concern.

Data collection began in January 2007, with emphasis on the records of certain water parameters in the water treatment processes at Morton Jaffray water works. Sample collection and analysis began in February 2007 and ended in May 2007.

4.2 Sampling Programme

Water samples for process monitoring and Jar tests were collected from the water treatment works from February 2007 to May 2007. Table 4 shows the sampling dates. Sampling was done from 9am.

Table 4 Sampling dates

Campaign Number	Dates
1	26/02/07
2	12/03/07
3	14/03/07
4	19/03/07
5	22/03/07
6	27/03/07
7	12/04/07
8	16/04/07
9	26/04/07
10	22/05/07

4.2.1 Sampling locations

Figure 6 shows the sampling points considered during this study. The sampling points were chosen so as to be able to monitor removal efficiency of algae at each treatment stage. Raw water was sampled from both Lakes Chivero and Manyame (Pk1 and Pk2). Raw water, mixed with Granular Activated Carbon (GAC) and Sulphuric acid was taken from the distribution chamber, (Pk3), before the coagulant and algaecide were dosed. Pk6 was chosen so as to monitor any possible algal re-growth in the distribution system. The number of samples and frequency of sampling were determined by the financial resources that were available as well as when necessary equipment was available to the author.

4.2.2 Sample collection method, transportation and storage

Water samples for process monitoring were collected in 200 ml amber bottles. Amber bottles were used since these reduced photosensitive reactions to a considerable extent. The amber bottles were prepared by washing with liquid soap and water, rinsing with distilled water and sterilizing them in an autoclave. Samples were collected as grab samples. Water samples for jar tests were collected in 5 litre plastic containers which had been washed in soapy water followed by rinsing with distilled water.

After the samples had been collected and containerized, the outside of the containers was cleaned paper towels to remove any spilled sample from the exterior of the container and labelled with appropriate field identification number. Samples were transported to the laboratory within 2 hours after collection. Samples for algae analysis were immediately

preserved with 4% formalin (after measuring parameters such as pH, temperature and conductivity) and then refrigerated, at <4^{0}C whilst awaiting analysis.

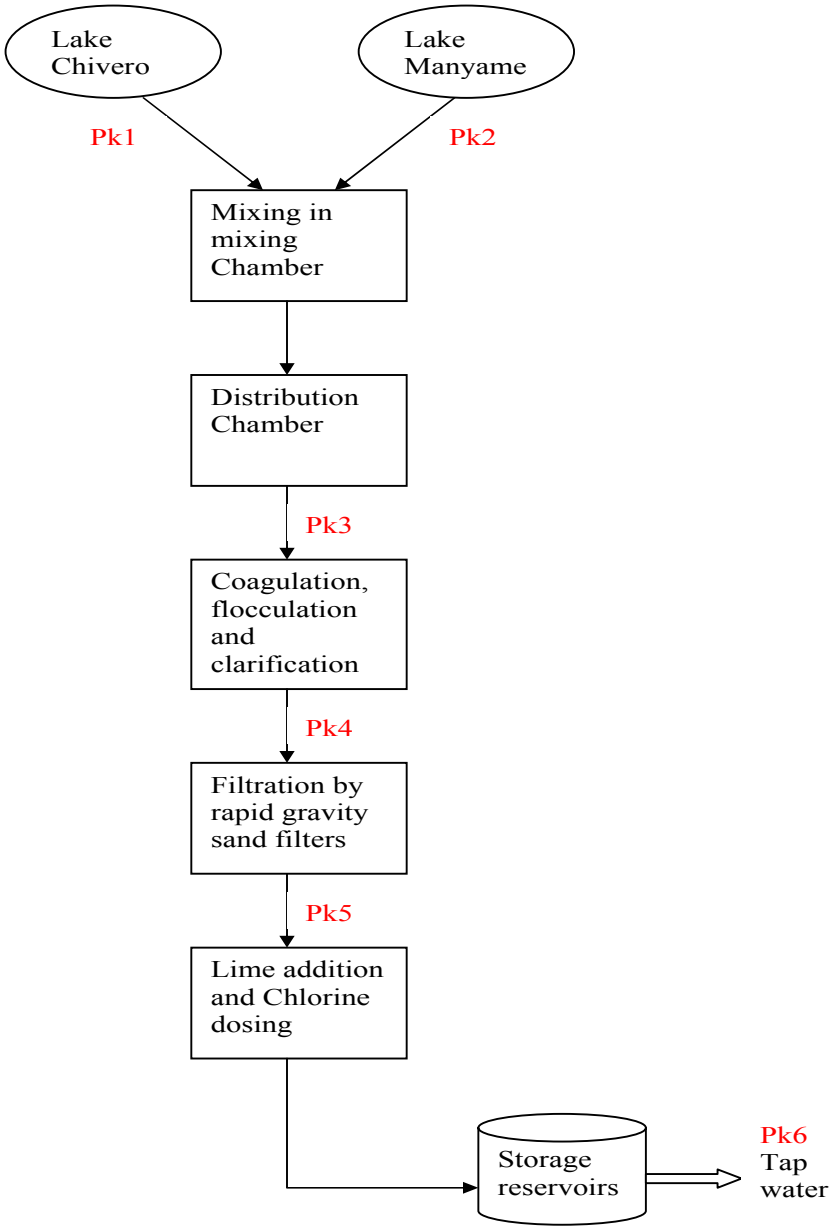

Figure 6 Sampling locations

4.2.3 Parameters measured

The parameters that were measured are shown in Table 5

Table 5 Parameters measured

Parameter	Level of measurement
pH	
Electrical Conductivity	µS/cm
Turbidity	NTU
Total algae	Cells/ml
temperature	^{o}C
Total flow	m^3/day

4.3 Measurement and Analytical Methods

4.3.1 pH measurements

pH measurement is one of the most important frequently used test in water chemistry (APHA, 1998). Practically, every phase of water supply and wastewater, e.g. coagulation and disinfection, are pH dependent. pH measurements were done in the field and laboratory by use of an Ecosan pH meter and Paqualab photometer according to recommendations by APHA (1998).

4.3.2 Electrical Conductivity and temperature

Electrical conductivity is the numerical expression of the ability of an aqueous solution to carry an electric current APHA (1998). An Ecosan EC meter was used for measuring electrical conductivity and temperature according to standard methods by APHA (1998).

4.3.3 Flow measurement

The float method was used for measuring flow rates. The principle of all velocity-area methods is that flow (Q) equals the mean velocity (V_{mean}) multiplied by the cross-sectional area (A): Q (m^3/s) = A (m^2) × V_{mean} (m/s).

A series of floats were timed over a measured length of flocculation channel. The results were averaged and a flow velocity was obtained. This velocity was then be reduced by a correction factor of 0.85, which then estimated the mean velocity as opposed to the surface velocity. By multiplying the cross sectional area of flow and corrected flow velocity, the volume flow rate was estimated.

4.3.4 Turbidity

Nephelometric method for measuring turbidity is highly sensitive and has high precision (APHA, 1998). The method was used for measuring turbidity, in the laboratory using a Hatch 2100N turbidimeter.

4.3.5 Enumeration and identification of algae

- *Sample preparation*

Samples were prepared according to the APHA (1998) standards 10200C and D. A measured volume of water was filtered through a filter membrane having a pore diameter of 0.45µm, using a hand vacuum pump as shown in Figure 7

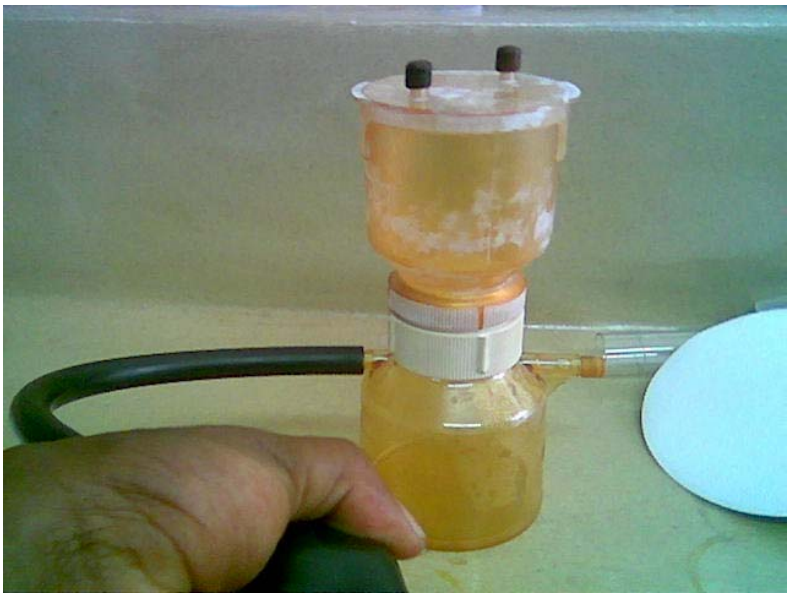

Figure 7 Filtration unit

The filter paper was then removed from the filtration unit using a forceps, (Figure 8), and washed with 10ml distilled water. The algae was then concentrated by centrifugation at 1000 revolutions per minute (rpm) for 10min. The supernatant was decanted, leaving a volume of about 1ml.

Figure 8 Removing filter paper from the filtration unit

- *Slide mounts and counting of algae*

The settled 1ml sample concentrate was agitated and a sub-sample withdrawn using a graduated pipette. A small volume was then transferred to the counting chamber of a Neubauer haemocytometer. The slide was mounted onto a microscope stage, being careful to have secure mounting. Algae was allowed to settle for about 0.5 -1.0 minute

before counting. The centre square of the Neubauer haemocytometer was used for counting. (Appendix A)

4.3.6 Jar Tests

For jar tests, Lake Chivero water samples were used. Raw water from Lake Chivero was used, mainly because it represented a "pure" sample before any chemicals were added. There was no access to collect the Lake Chivero-Lake Manyame blend before addition of GAC and sulphuric acid. The Jar tests were conducted using a Stuart Scientific programmable flocculator. The different scenarios are explained in the sections that follow.

- *Zero Scenario*

The zero represented a case whereby removal of algae could be accomplished by coagulation, flocculation and sedimentation using a coagulant (alum) and coagulant aid (magnafloc). No algaecide was added in this scenario. Table 6 shows the experimental conditions for the zero scenario.

Table 6 Zero scenario simulation

Stage	Mixing Intensity	Mixing time (t)	Chemical additions
Rapid mix	200rpm	2 minutes	Coagulant (Alum) at t = 1
Flocculation	20rpm	15 minutes	Coagulant aid (LT 25)
Sedimentation	0rpm	30 minutes	None

Coagulation and flocculation was performed in 1000ml glass beakers. The raw water was mixed well and 500ml sample was placed in each beaker and the test carried under conditions presented in Table 6. After 30 min settling, the supernatant was sampled and analysed for turbidity, pH and algae counts according to APHA Standard Methods (1998). All jar tests were performed at a temperature of 22 ± 2°C.

The Aluminium sulphate (alum) stock solutions were prepared in the laboratory at a concentration of 10mg/ml. Samples of the flocculant aid were obtained from Morton Jaffray water works. The flocculant aid, LT25, was obtained in liquid form.

4.3.7 Other Scenarios

After determining the best alum dose for the lake Chivero water, a series of other jar tests were carried out, this time, varying the concentration of an algaecide as well as the time the algaecide was dosed. This was also done for alum doses of 65 and 80mg/l, since these were the most used doses at Morton Jaffray water treatment works, during the time of this research. The different scenarios are shown in tables below. Table 7 shows scenario 1, which the current practice at MJ water works.

Table 8 shows the experimental conditions for the simulation of varying the contact time between the algaecide and the algae (Scenario 2). That is simulation of addition of algaecide at the intake tower (30minutes contact). A 45 minutes contact time for the

algaecide and the algae was also considered. The algaecide was obtained in liquid form from Morton Jaffray water works. The algaecide is Copper Sulphate based, with a concentration of 15 to 30% $CuSO_4$.

Table 7 Scenario 1: Current MJ practice

Stage	Mixing Intensity	Mixing time (t)	Chemical additions
Rapid mix	200rpm	3 minutes	Coagulant (Alum) at t = 1, algaecide at t = 3
Flocculation	20rpm	15 minutes	Flocculant aid (LT 25) 5 minutes of flocculation
Sedimentation	0rpm	30 minutes	None

Table 8 Applying the algaecide at Lake Chivero intake tower

Stage	Mixing Intensity	Mixing time (t)	Chemical additions (t in minutes)	Comment
Flow from source to the WTP	20 rpm	30 minutes	Algaecide at t =0, GAC at t = 30	30 minutes contact time before other chemicals
	20 rpm	30 minutes	Algaecide at t = 10, GAC at t = 30	20 minutes contact time before other chemicals
Rapid mix	200 rpm	1 minute	Coagulant (Alum)	
Flocculation	20 rpm	15 minutes	Flocculant aid (LT 25) 5 minutes of flocculation	
Sedimentation	0 rpm	30 minutes	None	

4.3.8 Translation of laboratory results to the actual water treatment

The results obtained from the laboratory jar tests were used without alteration to give recommendations to the to the actual water treatment plant. No translation factor was taken into account. This was due to the complexity of the similarity factors between the laboratory reactor and the full scale reactor (the water treatment plant). The geometric and dynamic similarities of the reactors were not considered in this study.

CHAPTER 5

5 RESULTS AND DISCUSSION

5.1 Types and effects of algae on the water treatment and water quality.

To assess the possible effects of algae on water treatment and water quality, algae identification was done, with reference to APHA 1998, identification key. Table 9 shows the types of algae that were found at different water treatment stages at Morton Jaffray water works.

Table 9 Types of algae at different stages of water treatment

Location	Algae Types				
	Filter Clogging	**Taste and Odour**	**Polluted Water**	**Clean Water**	**Other Surface Water**
Raw water (PK1 and PK2)	*Anabaena, Cloesterium, cyclotella*	*microcystis, Anabaena, Pandorina, Volvox*	*Anabaena, Chlamydomonas,*	*Cyclotella, Ankistrodesmus*	*Scenedesmus , Eudorina*
Distribution Chamber (PK3)	*Anabaena, Cloesterium,*	*microcystis, Anabaena, Volvox*	*Anabaena, Chlamydomonas,*	*Ankistrodesmus*	*Eudorina*
Clarified water (PK4)	*Anabaena,*	*Microcystis*	*Anabaena, Chlamydomonas,*	*Ankistrodesmus*	*Eudorina*
Filtered water (PK5)	*Anabaena*	*Microcystis*	*Chlamydomonas*	*Ankistrodesmus*	*Eudorina, Gonium*
Final treated tap water (PK6)		*Microcystis*	*Chlamydomonas*		*Gonium*

Based on observations and interpreted according to APHA, (1998).

The raw water had different types of filter clogging algae . However, *Anabaena* species were the predominant filter clogging algae detected in the clarified water even when other species existed in the raw water. Thus, coagulation, flocculation and sedimentation (clarification) effectively removed other algae species, and hence filter clogging could be related to the presence of *Anabaena* spp. in the clarified water. *Anabaena* has been known to cause filter clogging in many water treatment plants (Hang-Bae *et al.,* 2001; Knappe *et al.,* 2004). The occurrence of these types of algae could be the reason for the frequent filter clogging at MJ, hence the reduction of filter runs to 4-8 hours. This greatly reduced water production since clean treated water was used for the backwashing process. According to a survey carried out by Knappe *et al.,* (2004), 60 out of 114 water treatment plants under survey experienced filter clogging, 80% of which related filter clogging to the presence of *Anabaena, Microcystis* and *Ankistrodesmus.*

The presence of different taste and odour algae may cause odour problems at MJ water works. *Microcystis* and *Anabaena* are known to produce unpleasant odours due to their ability to produce odour and taste causing compounds such as geosmin and 2-methylisoborneol (MIB). A survey in the US showed that 90% of water treatment plants

under survey reported taste and odour problems, and related them to the presence of taste and odour algae (Knappe *et al.,* 2004). *Anabaena* has been associated with geosmin and MIB episodes in Japan (Ashitani *et al.,* 1988). Presence of taste and odour algae has a cost implication because of the increased addition of GAC to remove the odours. During the period of study, records at one of the Water supplier's laboratories showed that there were informal complaints, to the water supplier by water consumers, that the water had a bad taste and odour.

Table 9 shows that *Microcystis* was present in filtered and tap water. This has a negative impact on the quality of drinking water. This type of algae is known to release toxins such as hepatotoxins, hence posing a health risk to the consumers. Although the amount of toxins in the water was not measured in this study, previous studies on Lake Chivero, the major source for drinking water, (e.g. Johansson and Olsson, 1998; Magadza and Ndebele, 2004) have shown that there is a high level of toxins, (13.9 µg/l and 19.86 µg/l respectively), especially in the raw water, associated with *Microcystis spp*. The high concentration of algae in the water is a health concern and potential threat to the water consumers, in that it exposes the consumers to a greater risk of contracting gastroenteritis and liver cancer, as well as other toxin-related diseases. Acute poisonings of humans by cytotoxins have been reported in Brazil, Australia, Zimbabwe, and the United States (Chorus and Bartram, 1999). In 1998, human consumption of water in Bahia, Brazil, led to gastro-enteritis epidemic, and this was related to the presence of Anabaena and Microcystis in the water (Chorus and Bartram, 1999).

Table 10 presents the turbidity, pH and temperature measurements of the different sampling points.

Table 10 Turbidity, pH and temperature measurements for the water treatment process.

Source	Turbidity (NTU)		pH		Average Temperature ^{0}C
	Range	Average	Range	Average	
Raw water (PK1 and PK2)	2.54 – 6.33	4.46 (n=40)	7.26 -8.1	7.8 (n=40)	25.5 (n=40)
Distribution chamber (PK3)	1.89 – 5.59	3.48 (n=20)	6.72 – 8.1	7.2 (n=20)	23.2 (n=20)
Clarified water (PK4)	0.63 – 1.96	1.14 (n=20)	6.75 – 7.4	7.03 (n=20)	23.2 (n=20)
Filtered water (PK5)	0.41 – 1.95	1.07 (n=20)	6.8 – 7.4	6.97 (n=20)	24 (n=20)
Tap (PK6)	0.44 – 2.34	1.03 (n=20)	6.5 – 7.7	7.1 (n=20)	25.3 (n=20)

The water turbidities measured during the period of study could also be related to the presence of high concentrations of algae, particularly in the raw water. In filtered water,

high turbidities could have been due to filter-breakthroughs of algae, though the turbidity could have been affected by presence of other substances. Studies by Hang-Bae et al., 2001, showed that during a study period (10 February–15 April 1998) Raw water turbidity for TaeCheong reservoir water ranged from 1.1–3.2 NTU compared to the raw water algae concentrations of 400 to 2,700 cells/ml. The temperatures of the water could have also promoted growth of algae in the water treatment plant.

5.2 Water treatment algae removal efficiencies

The algae concentrations at the different water treatment stages during the period of study are summarized in table 11. The raw water total algae counts ranged from 875 to 6000 cells per millilitre of water. Algae was found to be present in all stages of water treatment, and even in the distribution system (PK6). Figure 9 shows the total algae count for all the treatment stages for the 26th of February, 19th and 22nd of March. The general trend shows that there is a reduction in algae numbers from the raw water, through different stages up to the final treated water.

Table 11 Average algae concentration at MJ

Stage	Concentration of algae (total count in cells/ml)
Raw water (PK1 and PK2)	875 – 6000
Distribution chamber water (PK3)	225 – 3150
Clarified water (PK4)	65 – 180
Filtered water (PK5)	75 – 225
Final treated (PK6)	1 – 125

Figure 10 shows the cumulative algae removal achieved by activated carbon, clarification (coagulation, flocculation and sedimentation), filtration and disinfection, for 5 different days during the period of study at Morton Jaffray WTP. Generally, there is an increase in the cumulative percentage removal of algae as the water moves through different stages. This shows that each treatment stage contributed to removal of algae, though the individual treatment stage percentage removals differed.

Figure 11 shows the removal efficiencies for individual treatment processes on different days during the research period.

As shown in Figure 11 algae removal by coagulation, flocculation and sedimentation (clarification) was the most efficient process in removal of algae, with algae removal percentages ranging from 68 to 94%. Addition of GAC (at the distribution chamber) also removed algae to a great extend, though there was a minimum removal of about 19%.The maximum algae removal percentage after addition of GAC was 83%.

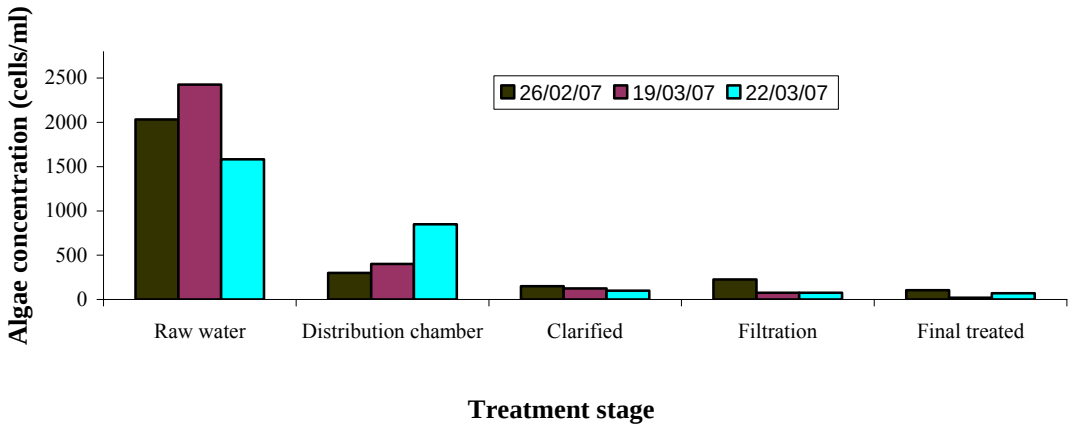

Figure 9 Algae count for 26th February, 19th and 22nd of March.

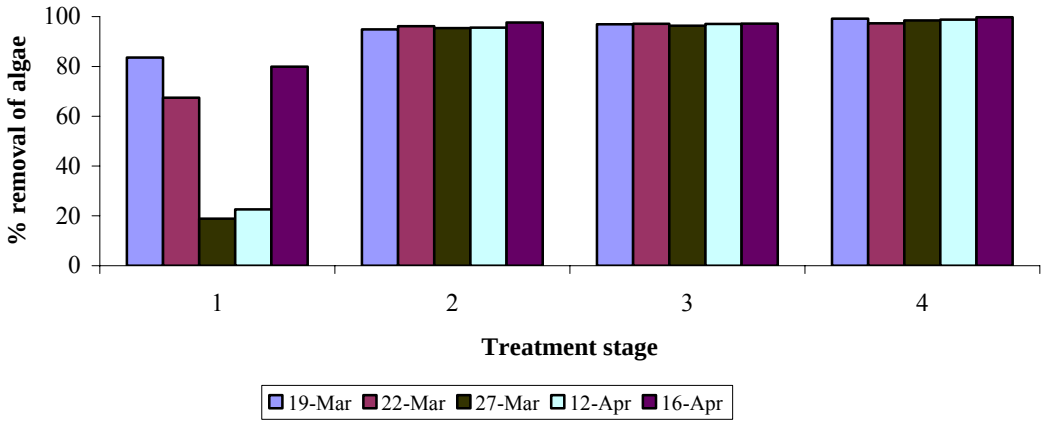

Figure 10 Cumulative removal of algae at different water treatment stages 1 : (PK3- mixing chamber), 2 (PK4- Clarified water), 3 (PK5- filtered water) and 4 (PK6- tap water).

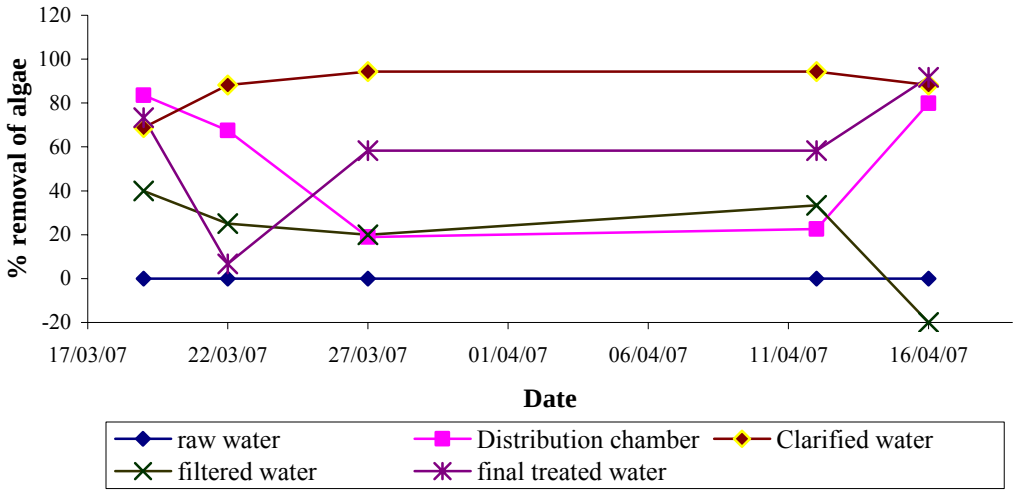

Figure 11 Algae removal efficiencies for individual water treatment stages

The filtration unit however had low and inconsistent percentage algae removal efficiencies. Figure 11 shows algae removal efficiencies -20 to 40% for the filtration process. The possible reasons for such low efficiencies could be filter breakthroughs of algae as well as possible re-growth of algae in the filtration units. The reasons for re-growth of algae could be due to the reduced toxicity of the algaecide. According to Gibson, (1972), algae treated with algaecides may appear to die, but when placed in a non-toxic medium, they resume growth. Again, the temperature, 23 ± 2°C. of water in the filtration units as well as presence of sunlight offered a possibility of algal re-growth. Filtered water samples were collected at a point when filter efficiency ranged between 66-71%. (Appendix B)

5.2.1 Flow measurements

Water flow rates were also measured to help determine the possibilities of under-dosing and over-dosing of chemicals, such as alum and algaecide, which could affect the algae removal and cause algae related problems. Figure 12 shows the inflow measured for treatment units, phases 2 and 3 during the time of study.

The highest inflow recorded during this period was 612 000m^3/day (612Megalitres), and the least was 208 080 m^3/day. The results show that the treatment units are being overloaded, as the design output of 452 000 m^3 (452 Mega litres). Inflow to the clarifiers of phase 2 and 3, was low from the 19th to the 22nd of March due to the fact that some pumps were not working. There is a possibility of under-dosing of chemicals due to plant overloading, hence reducing the effectiveness of the chemicals.

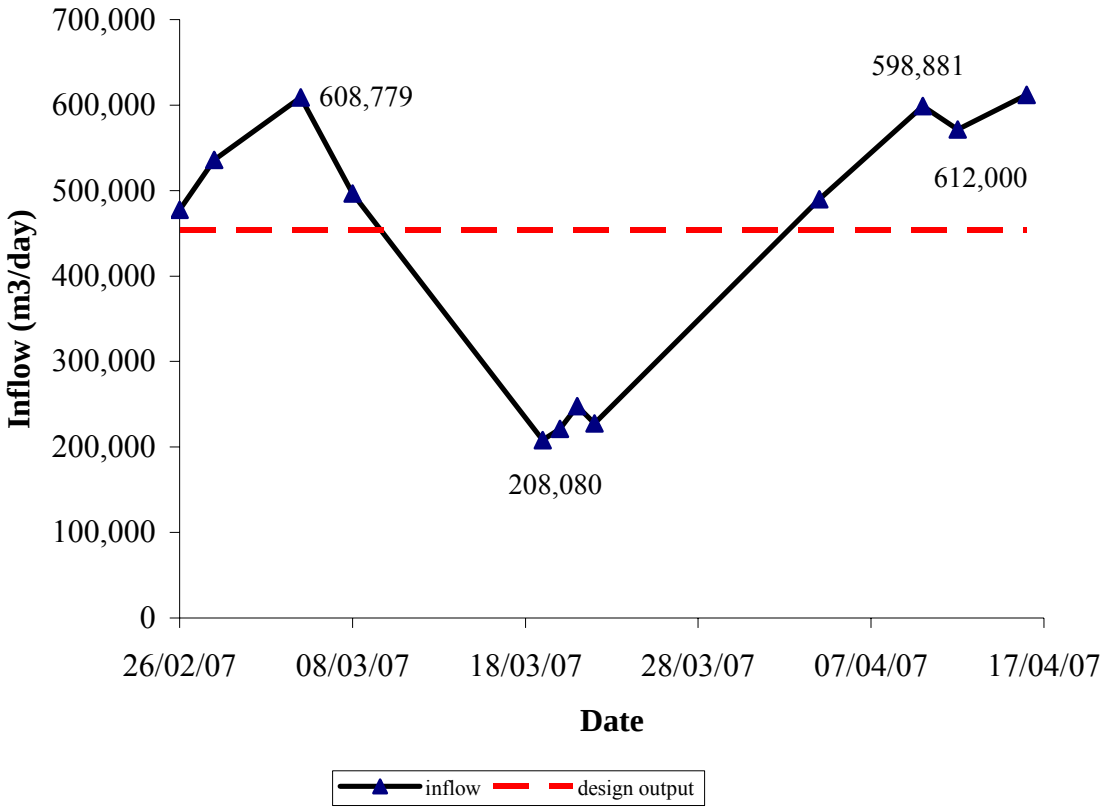

Figure 12 Water inflows for phases 2 and 3

The algicidal effect of algaecide used at MJ could also be affected by the fact of plant overloading, that is the contact time between the algaecide and the targeted algae is reduced. Also overloading of treatment units such as filtration units could reduce the efficiency in removing the algae, and increase risk breakthroughs of toxic algae.

5.2 Jar tests

5.2.1 Coagulation of algae

The results of this subsection are based on the laboratory simulations of the coagulation, flocculation and sedimentation using the jar test in the laboratory. Jar tests were used to determine the conditions that lead to improved algae removal. To demonstrate the dependence of algae removal on coagulant dose figure 13 summarises settled water algae counts and turbidity as a function of alum dose, at a pH of 7.5.

The lowest settled water turbidity were observed for alum dose of 90 mg/l. Figure 13 shows that algae removal was most effective with alum doses that also yielded low settled water turbidities.

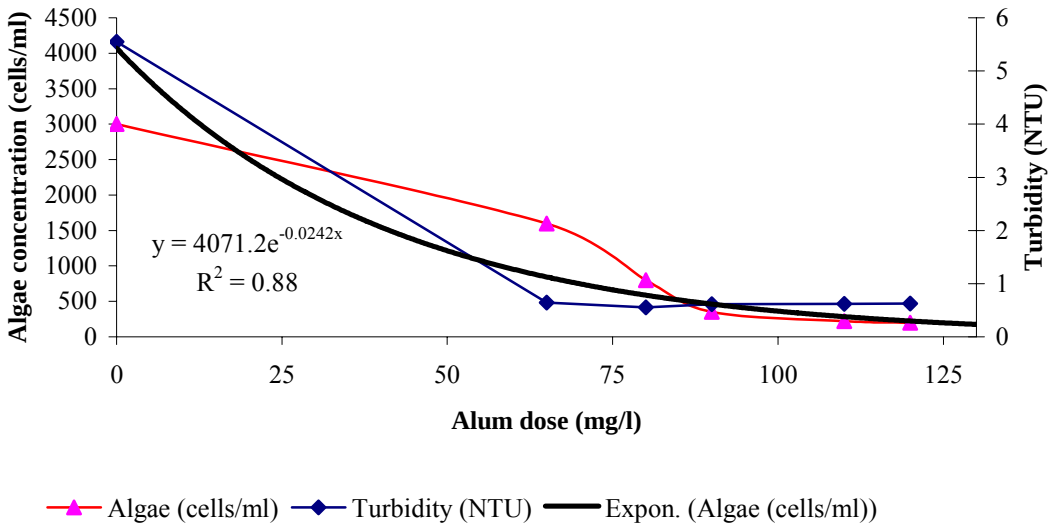

Figure 13 Effect of alum dosage on settled water turbidity and removal of algae

Though low alum dosages could remove turbidity, to achieve the maximum allowable turbidity by WHO guidelines and Zimbabwe standards (5NTU and 1NTU respectively), a significant amount of algal cells still remained in the water at the end of the tests. Figure 5.5 also shows that algal cell removal increased with increase in alum dose. The clarification process can hence be effective in removing algal cells when the alum dose is increased.

The effect of coagulation pH on algae removal and settled water turbidity was examined for Lake Chivero water. Jar tests were conducted at pH 7.0 and 7.5. Figure 14 shows the percentage removal of algae at pH 7 and 7.5 and different coagulant doses.

Algae removal was more effective at pH 7, with the highest removal achieved at 120mg/l (97.53%). However best conditions were obtained at 110mg/l. At this dose lowest turbidity of 0.67 NTU and 97.26% algae removal were achieved. At 120mg/l of alum, higher turbidity of 0.73 was obtained and small flocs were formed. These results indicate that excellent algae removal can be achieved prior to filtration in water treatment when proper coagulation conditions are employed.

Coagulation at pH 7, combined with an alum dose of 110mg/ l achieved 97% algae removal. This suggest that proper coagulation conditions can greatly reduce the algae load to rapid sand filters. Again, because intact algal cells are removed by coagulation, followed by sedimentation, removal of intracellular toxins and odour causing compounds can be achieved.

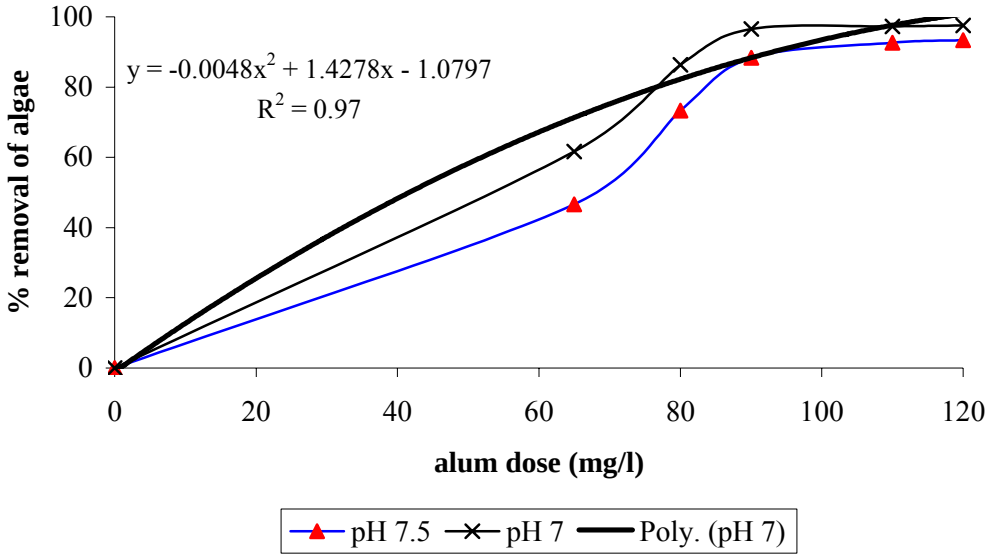

Figure 14 Effect of coagulant dose and coagulation pH on removal of algae

Studies conducted by Knappe *et al.,* 2004, showed that algae counts decreased with increase in alum dose, and the best conditions were obtained at pH 6.0, at an alum dose of 118mg/l. At pH 7, a higher alum dose of 225mg/l was required. However, according to the same study, turbidity removal improved at pH 7 and 7.5. Algae removal was high with alum at a pH of 7.5. (Jiang et al., 1993). Hang-Bae *et al.,* reported high removal of algae at pH 6.8-7. Though coagulation at low pH, e.g. pH 6, are effective in for removal of algae, there maybe a drawback in that coagulation at pH 6 may require addition of high doses of acid to lower the pH, hence increase the lime demand, and in turn increase water treatment costs.

Figure 15 shows the sensitivity of percentage removal of algae due to slight changes of alum doses at pH 7 (based on the trend-line, taking 110mg/l as the optimum dose). The sensitivity test was done to check the effect of changing the alum dose, on the percentage removal, in a case of an unanticipated change in doses. The algae removal percentage was calculated using the percentage removal obtained at 110mg/l as the reference point.

A ±5% change in alum dose leads to a slight change in percentage removal of algae as shown in figure 5.7. A 5% change in dose (115.5mg/l) will lead to a percentage algae removal of 99.79% as compared to 97.89% at 110mg/l. Alum doses may hence be maintained at 110mg/l ± 5%, though higher doses can increase treatment costs.

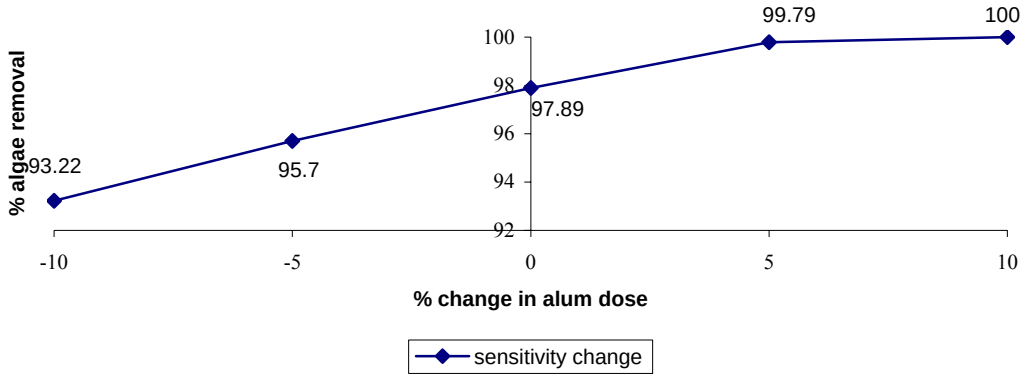

Figure 15 Sensitivity of changing alum dose

5.2.2 Effect of algaecide dose and contact time on algae removal

Jar tests were also carried out to determine the effect of contact time and algaecide dose on the removal of algal cells. The actual mechanisms of effect of copper on algae was not studied in this research.

The results presented in table 12 are based on the jar tests simulations of coagulation, flocculation and sedimentation in the laboratory. Table 12 shows the effect of algaecide dose and its contact time on the removal of algae, at different alum doses.

At 30 minutes contact time before coagulation (simulation of applying algaecide at Lake Chivero), the best floc was obtained at an alum and algaecide dose of 80mg/l and 0.8mg/l respectively. At higher alum and algaecide doses, high turbidities (Appendix D) and small flocs were obtained. For example turbidities of 1.1 and 1.64 NTU were obtained at 0.8 and 1mg/l algaecide, respectively, for an alum dose of 110mg/l. Thus, larger flocs aided in removal of algae cells as well as turbidity. A contact time of 45 minutes before coagulation yielded high percentage removals of algae (93- 99%).

The best removal conditions were obtained at 80mg/l and 0.8mg/l alum and algaecide doses respectively. At these chemical doses, the floc formed was big and settled faster, and a turbidity of 0.87NTU was achieved. High turbidities were also observed at higher doses of algaecide, for example, though algae removal reached 97.78% at 80mg/l alum and 1mg/l algaecide, the turbidity was 1.09NTU. At high algaecide doses (>0.1mg/l), heavy flocs were formed about 15 minutes after addition of the algaecide, but were disturbed at rapid mixing after alum dosing. This caused higher turbidities at the end of the jar tests as shown in figure 16 (110mg/l and 30mins contact time). Possibilities that could explain poorer turbidity removal include re-stabilization because of charge reversal or changes in floc size and density that adversely affected floc settleability.

A different case was observed when the algaecide and alum were added at the same time (scenario 1: simulation of current MJ practice). The algae removal efficiencies were slightly lower, ranging between 60% to 93%. The highest removal was obtained at alum and algaecide dose of 110mg/l and 1mg/l respectively. The decrease in efficiency could

be attributed to the decreased contact time, as well as removal of copper from the water by carbon adsorption.

Table 12 Effect of algaecide dose and contact time on removal of algae

		Alum dose			
		0	**65**	**80**	**110**
Simulation	**Algaecide dose (mg/l)**	**settled algae count :cells/ml (in brackets) and % removal of algae**			
30 minutes contact time before coagulation	**0.05**	(4760) 0	(410) 91.39%	(170) 96.43%	(58) 98.78%
	0.1	(4760) 0	(360) 92.44%	(150) 96.85%	(90) 98.11%
	0.8	(5000) 0	(355) 92.9%	**(215) 95.7%**	(60) 98.5%
	1	(5000) 0	(320) 93.6%	(142) 97.16%	98.8
Alum and algaecide dosed at the same time (zero contact before coagulation	**0.05**	(4960) 0	(2000) 59.68%	(1200) 75.81%	(1154) 76.73%
	0.1	(4960) 0	(1760) 64.52%	(1100) 77.82%	(720) 85.4%
	0.8	(4560) 0	(1540) 66.23%	(1000) 78.07%	**(400) 91.23%**
	1	(4560) 0	(1500) 67.11%	(400) 78.29%	(45) 93%
45 minutes contact before coagulation	**0.8**	(4500) 0	(300) 93.33%	**(200) 95.56%**	(50) 98.89%
	1	(4500) 0	(280) 93.78%	(100) 97.78%	

At reduced contact time (scenario 1) and low alum, e.g. 65mg/l alum, filter clogging algae persisted at the end of the jar test regardless of the algaecide dose. This shows the importance of adequate contact time between algaecide and the algae.

Experiments by Gibson, 1972 showed that the growth of algal cells falls exponentially as the concentration of copper medium is increased. The plateau for the experiments by Gibson reached a plateau at 3mg/l of copper. At concentrations less than 0.8mg/l, re-growth occurred when the algae was re-inoculated.

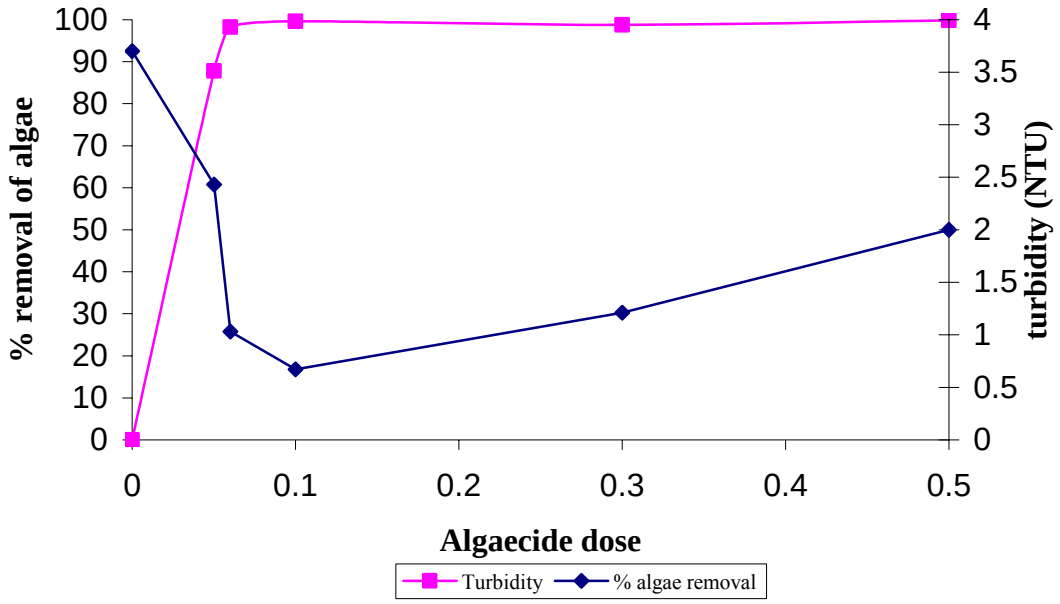

Figure 16 Effect of algaecide dose on percentage removal of algae and settled water turbidity. (Contact time of 30minutes before coagulation with 110mg/l alum.)

Gibson, 1972, then concluded that the lethal dose of copper as copper sulphate is between 0.8 – 1mg/l, but for a rapid algicidal effect, a larger dose would be required. Earlier studies by Fitzgerald and Faust (1963) quoted 0.05mg/l as toxic concentration of copper for blue-green algae. Other lethal doses such as 0.12-0.5mg/l (Prescott, 1948) have been quoted. This difference in lethal doses could be attributed to the medium in which algae are growing, for example, in the presence of activated carbon the toxicity of copper may be reduced due to carbon adsorption. At low pH, <6, toxicity of copper is also reduced.

The results of this study also show that contact time between algaecide and algae is important for effective removal of algae. Chorus and Bartram, 1999, recommend a minimum contact time of 30 minutes before sedimentation. Studies with other chemicals and oxidants used to remove algae and algae related problems have also show that the contact time with the target organism is important. Cornish *et a*l., 2000, observed that Hydrogen Peroxide effectively removed microcystin-LR after 30 minutes.

To determine the sensitivity of algae removal with respect to changes in algaecide dose, a sensitivity test was done based on 80mg/l alum dose, at 30 minutes algaecide contact time before alum dosing. Figure 17 shows the effect of algaecide doses on percentage removal of algae. Figure 18 shows the sensitivity test for algae removal.

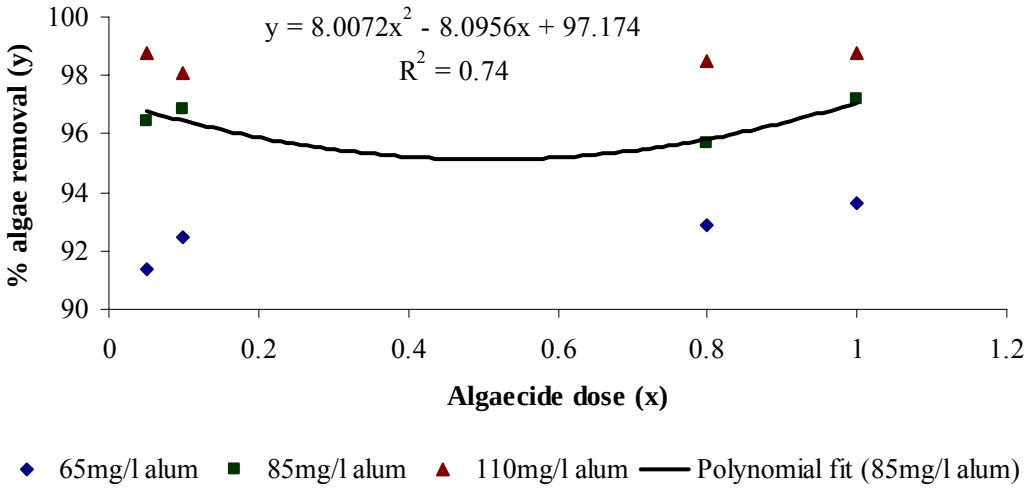

Figure 17 Effect of algaecide dose on percentage removal of algae.

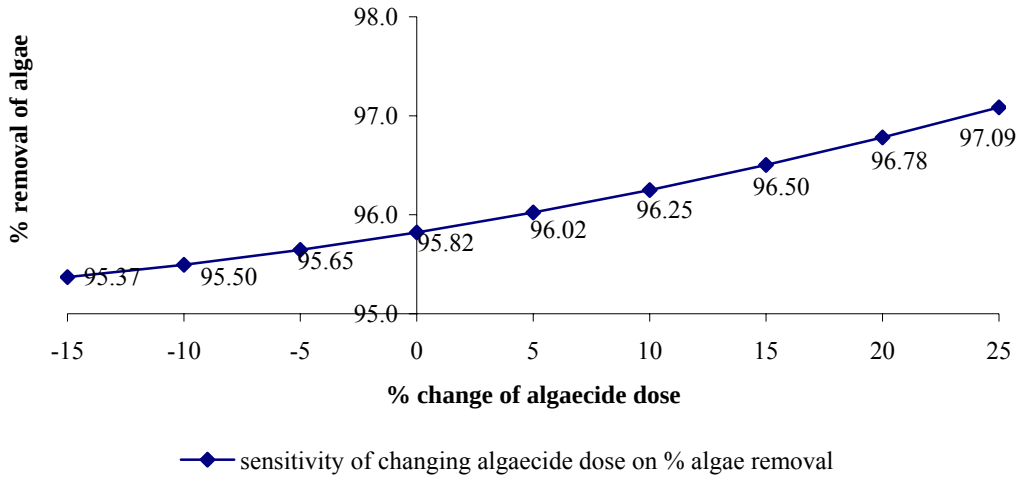

Figure 18 Sensitivity of removal of algae with respect to change in algaecide dose

The percentage removal of algae is not very sensitive at slight changes of algaecide doses as shown in Figure 18. At ± 15% change in algaecide dose (0.68 – 0.92mg/l), the change in algae removal is -0.45 to 0.68 percentage units. It is therefore possible to maintain a ±15% change in algaecide dose, at increased contact time, and still achieve satisfactory algae removal. However, unmonitored changes in algaecide doses can increase treatment costs.

Another important issue in the removal of algae in drinking water treatment is the settling time after coagulation. Figure 19 shows the settled water algae counts obtained with initial algae concentration of 4500cells/ml.

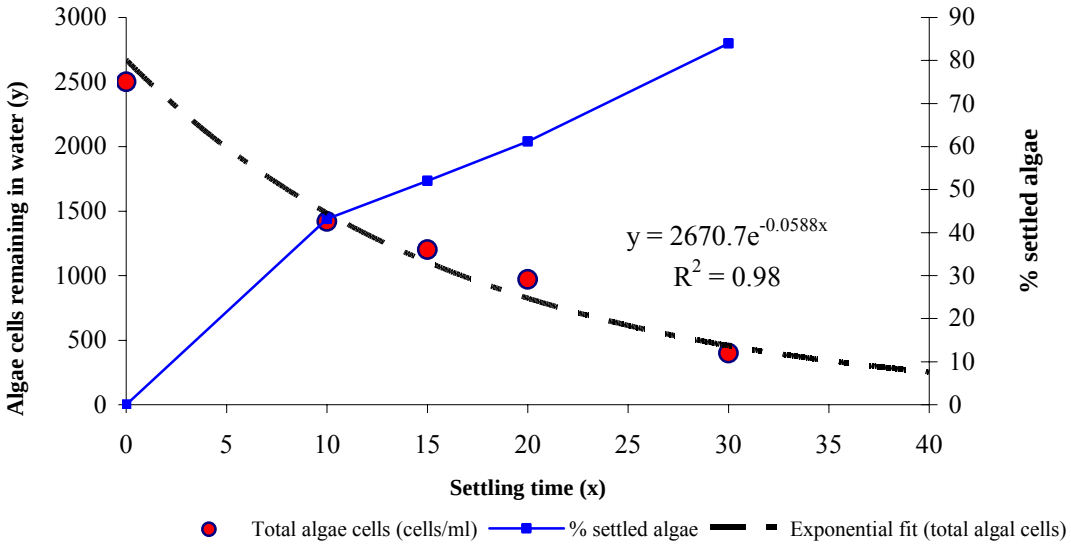

Figure 19 Effect of settling time on settled water algae counts

After coagulation and Flocculation, at 0 minutes settling time, an algae count of 2500cells/ml was obtained. Algae removal was poor for settling times of 10 minutes or less. However, after 15 minutes of settling, 52% algae removal was achieved. Improved algae removal was observed with increased settling time, with a removal of 84% being achieved after 30 minutes of settling. Projections showed that the higher the settling time, the higher the percentage settled algae. Settling time is therefore important in effective removal of coagulated algae. In cases overloading of a treatment unit, settling time is reduced, and in turn this may have a negative impact on removal of algal cells.

Knappe *et al.*, 2004, investigated the settleability of algae-laden floc for Falls lake water and they reported that algae removal was poor for settling times of 10 minutes. At 20 minutes the observed algae removal in excess of 50%, but settled water algae counts remained 10 times higher than those measured after 2 hours of settling.

5.3 Cost implications of varying chemical doses

This subsection presents the estimated costs of employing different chemical doses, in relation to the algal removal Table 13 presents the total estimated cost of treating an average of 550 000 m^3 per day, at different doses of alum and algaecide.

Table 13 Estimated costs for treating 550 000 m^3 of water/day

Alum Dosage (mg/l)	Total Alum Used (kg)	Cost Of Alum Used (US$/kg)	Algaecide Dose (mg/l)	Cost of Algaecide Used	Total cost
65	35750	35750	0.05	27.5	35777.50
65	35750	35750	0.1	55	35805
65	35750	35750	0.8	440	36190
65	35750	35750	1	550	36300
80	44000	44000	0.05	27.5	44027.50
80	44000	44000	0.1	55	44055
80	**44000**	**44000**	**0.8**	**440**	**44440**
80	44000	44000	1	550	44550
110	60500	60500	0.05	27.5	60527.50
110	60500	60500	0.1	55	60555
110	60500	60500	0.8	440	60940
110	60500	60500	1	550	61050
110	60500	60500	0	0	60500

Note: Unit costs of alum and algaecide = US$1 and US$18 respectively

Unit costs of Z$250/kg and Z$4500/kg of alum and algaecide respectively were considered. The official exchange rate used for converting Z$ to USD (United States dollar) was 1USD: Z$250.

During the time of study, alum doses of 65-80mg/l were being used at Morton Jaffray, with an algaecide dose of >1mg/l. The estimated costs for treating 550 000m^3 at these doses range from about US$36 190 – US$44 550 per day. At such high costs, problems of algae still occurred. From the previous results, a combination of 80mg/l and 0.8mg/l alum and algaecide, at a contact time of 30 minutes before sedimentation achieved high algae removal of 95.7%. The cost of treating 550 000m^3 at these doses was estimated to be US$44 440. This costs US$110 less than the costs incurred at current practice at MJ. At 110mg/l (Zero scenario simulation), satisfactory removal was achieved at an algaecide dose of 0.8mg/l. The cost of treating 550 000m^3 of water at these doses is US$60 940, which is US$16 500 more expensive as compared to a dose of 80mg/l ; 0.8mg/l alum and algaecide. The costs show the importance of optimizing treatment. Though dosing the algaecide will require initial capital for installing the dosing unit, there is a potential saving when the day-to-day operational costs are considered.

CHAPTER 6

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The conclusions of the study were as follows:

1. The main effects of algae on water treatment processes and water quality were:
   - Filter clogging and bad taste and odours, which can be associated with the presence of filter clogging *Anabaena* and *Cloestrium*, as well as *Microcystis* and *Volvox* which release odour and taste causing compounds in the raw water as well as treated water.
   - The final treated water contained *Microcystis,* a toxin producing algae which can pose a health risk to water consumers.

2. The water treatment units were being overloaded by an average of 20% to 35% of their design capacity and this was related to the poor removal of algae due to reduced contact time between algae and chemicals, as well as reduced settling time, and under-dosing of chemicals.

3. Initial jar tests yielded best coagulation conditions for algae removal at pH 7. There was an increase in percentage removal of algae as the alum dose was increased and the best removal was achieved at 110mg/l alum.

4. Contact time, algaecide dose as well as alum dose contributed to the effective removal of algae.
   - Simulations of dosing the algaecide at the Lake Chivero intake tower showed that at 80mg/l and 0.8mg/l alum and algaecide respectively, a 95.7% algae removal was achieved. This showed the importance of contact time between algaecide and algae, before sedimentation.
   - Addition of 0.8mg/l of the algaecide, 30 minutes before the coagulant was added achieved algae removal efficiencies of >90%, even at low alum doses of 65mg/l
   - In the absence of an algaecide, high alum dose of 110mg/l was the most effective in removing algae, with removals up to 97%. The high dose of alum led to formation of larger flocs.
   - Simulations of scenario (adding algae and algaecide at the same time) showed that even high doses of algaecide and alum achieved lower removals as compared to the dosing at intake tower simulation.

Based on the results of this study, effective removal of algae can be accomplished by coagulation with alum at higher doses (110mg/l) than the doses (65-80mg/l) currently being used at MJ, if the alum and algaecide are dosed at the same time. However, at increased contact time, removal of algae can be increased.

There is little doubt that there is a considerable variation in the effect of the algaecide at different contact times. It has been shown that the filter clogging Anabaena is more susceptible to the algaecide when the contact time between the Anabaena and the algaecide is increased. Chemical doses and their application should be optimized; under-

dosing will result in poor removal of algae in clarification and problematic filtration, with the risk of breakthrough of algal cells containing toxins. Overdosing of chemicals can also have a negative impact on water quality as well as on the cost of treating water.

6.2 Recommendations

The following recommendations are being made in the view of working towards improving water quality and reducing water treatment problems caused by algae at MJ water:

1. It is recommended that the copper sulphate algaecide currently being used, be dosed at the raw water intake tower at Lake Chivero. This will greatly increase the contact time between the algaecide and algae, as well as reduce the interference between copper and other chemicals such as GAC.
2. The recommended doses for algaecide and alum are 0.8 – 1mg/l and 80-110mg/l respectively. The costs of water treatment with respect to these doses are shown in table 5.5.
3. Water flow rates should be measured frequently so as to adjust chemical dosing flow rates accordingly. This will reduce the risk of under-dosing and over-dosing of chemicals, and may help in reducing operation costs in terms of chemical consumption.
4. It is also recommended that frequent monitoring of algae at the different stages of water treatment be done as this will reveal, at any time, the performance of each treatment stage. Focus can then be directed on the less efficient stage.
5. There is need for further studies which take into account the similarity factors between the laboratory reactors and the water treatment plant itself.
6. There is need to carry out a similar study during the worst scenario(September-October) of the state of the raw water source (Lake Chivero)

CHAPTER 7

7 REFERENCES

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APPENDICES

APPENDICES

Appendix A: Neubauer Haemocytometer counting chamber

The haemocytometer is so named because it was originally used to count red blood cells. The Neubauer haemocytometer is made up of thick glass and has s counting grid engraved in the center of the counting chamber. The whole chamber has 9 squares (See figure below). The 4 corner squares have 4X4 subdivisions. The center square Have 5x5 subdivisions which are further divided into 4x4. Each smallest square is $0.0025mm^2$ and the chamber depth is 0.1mm; therefore the volume overlying each small square is $0.00025mm^3$

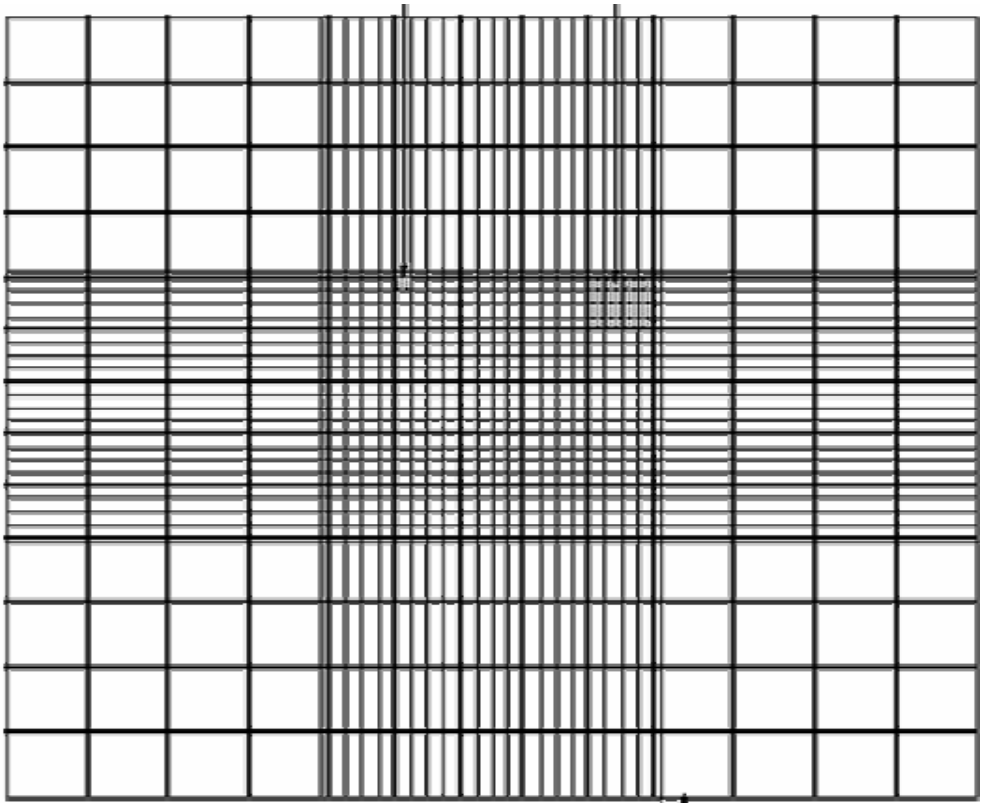

Figure 20 Neubauer counting chamber

450 x magnifications was used during the counting procedure. The square subdivisions (centre square) were scanned from left to right, up, down and algae were counted. Algae were counted for each square as shown in the figure below. To make sure algae touching lines were not counted twice, cells were counted as in the example shown below: Cells with an X were not counted for subdivision 1. That is for every subdivision, cells touching the top and the left were counted, as well as cells which fell into the subdivision.

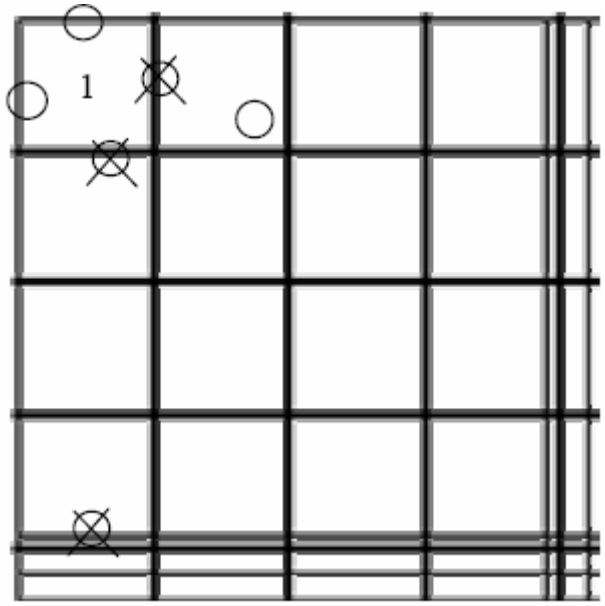

Figure 21 Counting technique.

Appendix B: Filter efficiencies for a full filter run

The filter efficiencies over one filter run were measured. Efficiencies were measured in terms of % removal of turbidity. Figure 7.1 shows the filter efficiency and output turbidity for a full filter run.

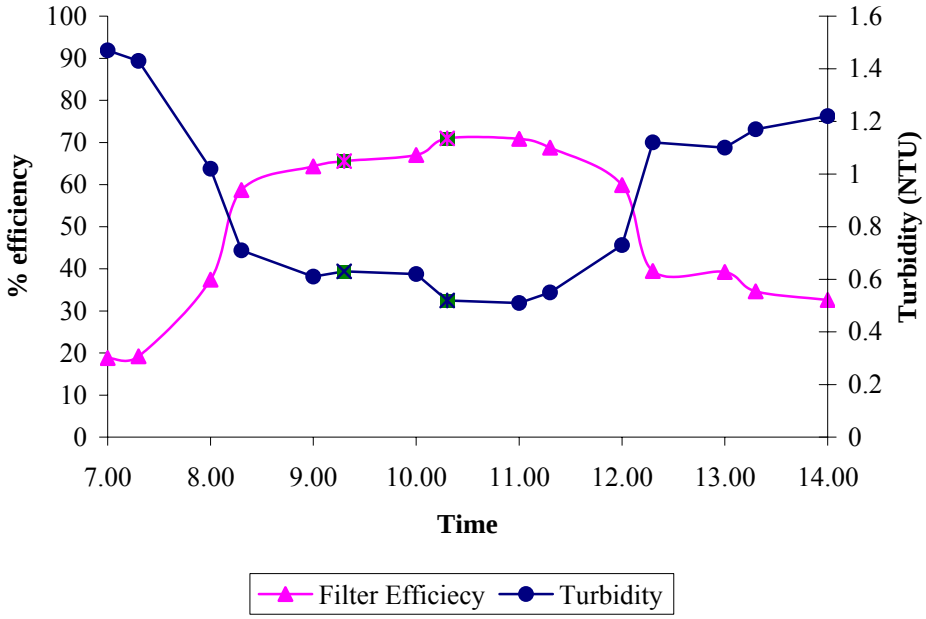

Figure 22: Filter Efficiency and output turbidity for a full filter run

During the sampling campaign, samples for monitoring the efficiency of filters in the removal of algae were sampled between 0930 hours and 1030 hours. During this time, filter efficiencies were in the range of 66-71% and output turbidity was 0.63 – 0.52NTU respectively.

Appendix C: Results of water treatment Process Monitoring at Morton Jaffray

Table 14 Cumulative Algae Removal Efficiencies after different treatment stages

	26-Feb	12-Mar	14-Mar	19-Mar	22-Mar	27-Mar	12-Apr	16-Apr
Raw water	0	0	0	0	0	0	0	0
Distribution	85.31	-157.14	69.43	83.59	67.43	18.89	22.55	79.92
Clarified	92.65	82.86	87.44	94.87	96.17	95.41	95.57	97.64
Filtered	88.98	91.43	95.09	96.92	97.13	96.33	97.05	97.17
Final water	94.86	85.71	100	99.18	97.32	98.47	98.77	99.76

Table 15 Total algae count

Date	Raw water (cell/ml)	Distribution chamber (cell/ml)	Clarification (cell/ml)	Filtration (cell/ml)	Final treated (cell/ml)
26/02/07	2033	300	150	225	105
12/03/07	875	225	150	75	125
14/03/07	2533	775	65	125	1
19/03/07	2427	400	125	75	20
22/03/07	1583	850	100	75	70
27/03/07	3267	2650	150	120	50
12/04/07	4067	3150	180	120	50
16/04/07	6000	850	100	120	10
Average	2848	1150	128	117	54

Appendix D: Results of the Jar Simulations

Date	Jar	Alum added (mg/l)	Algaecide added (mg/l)	Initial pH	Final pH	Turbidity	Total algae count (cells/ml)	% Removal
8-Mar-07	control	0		7.5	7.5	4.32	4200	0.00
	1	60		7.5	6.95	2.36	2400	42.86
	2	65		7.5	7	2.41	1700	59.52
	3	80		7.5	7.05	2.23	900	78.57
	4	90		7.5	6.8	1.8	750	82.14
	5	100		7.5	6.9	1.53	400	90.48
14-Mar-07	control	0		7.5	7.58	5.55	3000	0.00
	1	65		7.5	7.43	0.642	1600	46.67
	2	80		7.5	7.2	0.556	800	73.33
	3	90		7.5	6.94	0.615	350	88.33
	4	110		7.5	6.7	0.619	220	92.67
	5	120		7.5	6.42	0.623	200	93.33
22-Mar-07	control	0		7	7.33	3.24	3650	0.00
	1	65		7	6.83	1.18	1400	61.64
	2	80		7	6.61	0.73	500	86.30
	3	90		7	6.47	0.757	125	96.58
	4	110		7	6.39	0.67	100	97.26
	5	120		7	6.35	0.73	90	97.53
Note: 0.5mg/l of coagulant aid was added to each beaker								
13-Apr-07								
	control	0	0	7	7.15	3.7	5750	0.00
	1	110	0.05	7	6.9	2.43	700	87.83
	2	110	0.06	7	6.77	1.03	100	98.26
	3	110	0.1	7	6.59	0.671	20	99.65
	4	110	0.3	7	6.54	1.21	70	98.78
	5	110	0.5	7	6.49	2	10	99.83
Note: 0.5mg/l of coagulant aid was added to each beaker		Note: Algaecide was added first, then stirred at 20revs/min for 30mins before alum was added	Note: Heavy flocs were formed in Beakers 4 and 5, 5 minutes after addition of algaecide					

Date	Jar	Alum added (mg/l)	Algaecide added (mg/l)	Initial pH	Final pH	Turbidity	Total algae count (cells/ml)	% Removal
26-Apr-07								
	control	0	0	7	7.1	3.39	4760	0.00
	1	65	0.05	7	6.88	2.04	410	91.39
	2	65	0.1	7	6.72	1.95	360	92.44
	3	80	0.05	7	6.7	1.68	170	96.43
	4	80	0.1	7	6.63	1.64	150	96.85
	5	110	0.1	7	6.52	1.63	90	98.11
Note: 0.5mg/l of coagulant aid was added to each beaker		Note: Algaecide was added first, then stirred at 20revs/min for 30mins before alum was added	Note: small flocs were formed in Beakers2, 4 and 5, 15 minutes after addition of algaecide	Best floc was formed in jar 3.				
27-Apr-07								
	control	0	0	7	7.23	3.52	4960	0.00
	1	65	0.05	7	6.91	3.11	2000	59.68
	2	65	0.1	7	6.87	3	1760	64.52
	3	80	0.05	7	6.77	2.86	1200	75.81
	4	80	0.1	7	6.71	2.3	1100	77.82
	5	110	0.1	7	6.59	1.9	720	85.48
Note: 0.5mg/l of coagulant aid was added to each beaker		Note: Algaecide and alum were added at the same time,		Best floc was formed in jar 5.				
27-Apr-07								
	control	0	0	7	7.1	4.2	5000	0.00
	1	65	0.8	7	6.83	2.1	355	92.90
	2	65	1	7	6.79	1.88	320	93.60
	3	80	0.8	7	6.72	0.96	215	95.70
	4	80	1	7	6.6	0.99	142	97.16
	5	110	0.8	7	6.5	1.1	60	98.80
Note: 0.5mg/l of coagulant aid was added to each beaker		Note: Algaecide was added first, then stirred at 20revs/min for 30mins before alum was added		Best floc was formed in jar 3.				

Date	Jar	Alum added (mg/l)	Algaecide added (mg/l)	Initial pH	Final pH	Turbidity	Total algae count (cells/ml)	% Removal
27-Apr-07	control	0	0	7	7.1	4.35	4560	0.00
	1	65	0.8	7	6.92	1.9	1540	66.23
	2	65	1	7	6.89	1.32	1500	67.11
	3	80	0.8	7	6.7	0.98	1000	78.07
	4	80	1	7	6.63	0.97	990	78.29
	5	110	0.8	7	6.51	0.92	400	91.23
Note: 0.5mg/l of coagulant aid was added to each beaker		alum and algaecide were added at the same time.	Best floc formed in jar 5					
22-May-07								
	control	0	0	7	7.12	5.42	4500	0.00
	1	65	0.8	7	6.9	1.12	300	93.33
	2	65	1	7	6.87	1.09	280	93.78
	3	80	0.8	7	6.63	0.87	200	95.56
	4	80	1	7	6.6	0.90	100	97.78
	5	110	0.8	7	6.56	0.92	50	98.89
Note: 0.5mg/l of coagulant aid was added to each beaker	Contact time of 45 minutes before addition of coagulant		best floc was formed in jar 3					