

# CHAPTER 1

## INTRODUCTION AND OBJECTIVES

### 1.1 INTRODUCTION

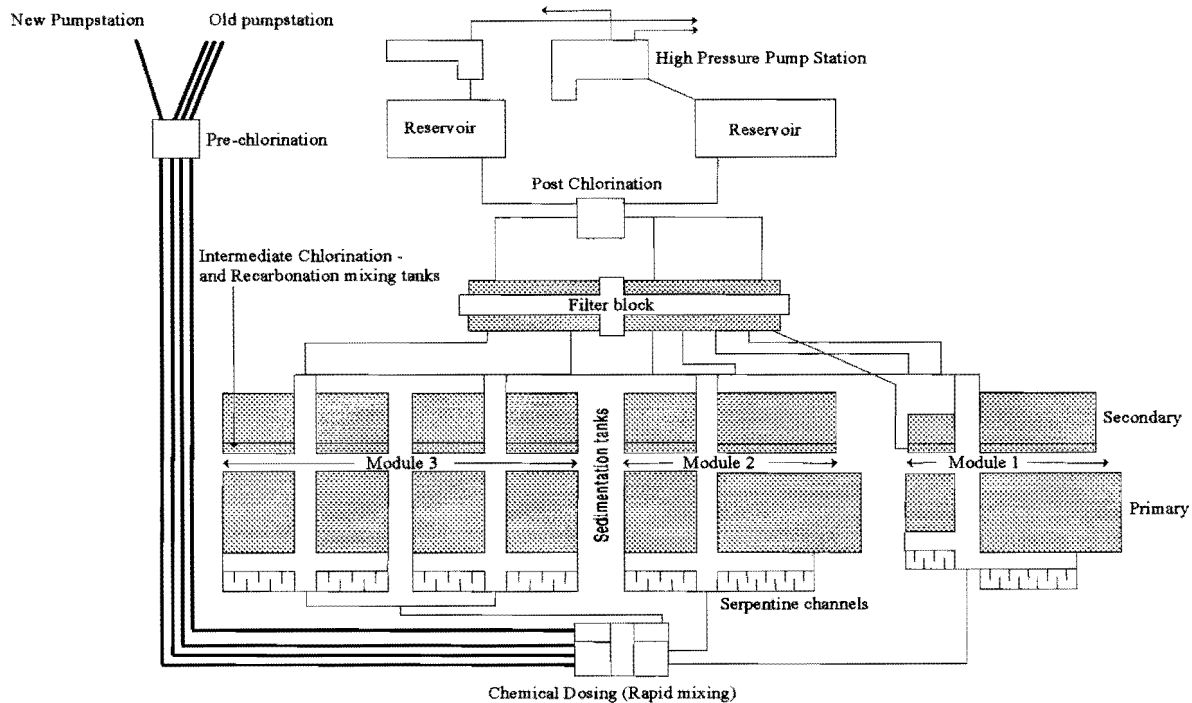
The Balkfontein plant of Goudveld Water, situated in a summer rainfall area, produces potable water from middle Vaal River water. The water in the river consists of a large fraction of used water from household, mining and industrial activities as well as a fraction arising from different types of agricultural practices. Analytical results of the water, obtained over many years, clearly indicate the constantly changing water quality mainly due to the eutrophic nature of the water in the middle Vaal River, seasonal variations in flow and upstream chemical pollution.

The eutrophic nature and changing raw water quality give rise to many operational difficulties and high treatment costs at the Balkfontein plant. Varying levels of turbidity and increasing concentrations of iron, manganese, natural organic matter (NOM) and algae (and related organic substances) have complicated water treatment and contributed to escalating costs over the years. At times, the deteriorating raw water quality has resulted in the aesthetic quality (turbidity, colour, taste and odour) of the treated water not being acceptable to the consumer. In addition, the trihalomethane (THM) values in the final water on occasion also exceed the recommended limit of 100 µg/l.

A possible solution to these problems would be to use advanced technologies such as activated carbon adsorption and ozonation. However, these treatment processes are expensive. It was therefore decided to evaluate and optimise existing processes and process configurations in order to possibly alleviate the problems without having to implement new technologies.

## 1.2 BACKGROUND INFORMATION

Figure 1 is an illustration of the plant. The plant consists of three modules, which have to be operated in parallel. The design capacity of the plant is 360 ML/d: 120 ML/d per module; a facility that enables the plant engineer to evaluate different treatment processes simultaneously.



**Figure 1:** A schematic illustration of the Water Treatment Plant at Balkfontein.

The two treatment processes traditionally used on the plant are pre-chlorination and coagulation with  $\text{FeCl}_3$  (pH 8,6), and the high lime process (pH 11,4) without pre-chlorination. The pH is reduced to approximately 8,0 after primary sedimentation, by adding  $\text{CO}_2$ -gas.

Samples of the final water, analysed at the Balkfontein laboratory, comply with the recommended limits as prescribed in SABS 241 (1984), for most of the time when using the high lime process. The chemical cost for this process is however 20 to 30% higher than the cost of the  $\text{FeCl}_3$  process. The high lime process is normally used during the rainy season when turbidities may exceed 1000 NTU.



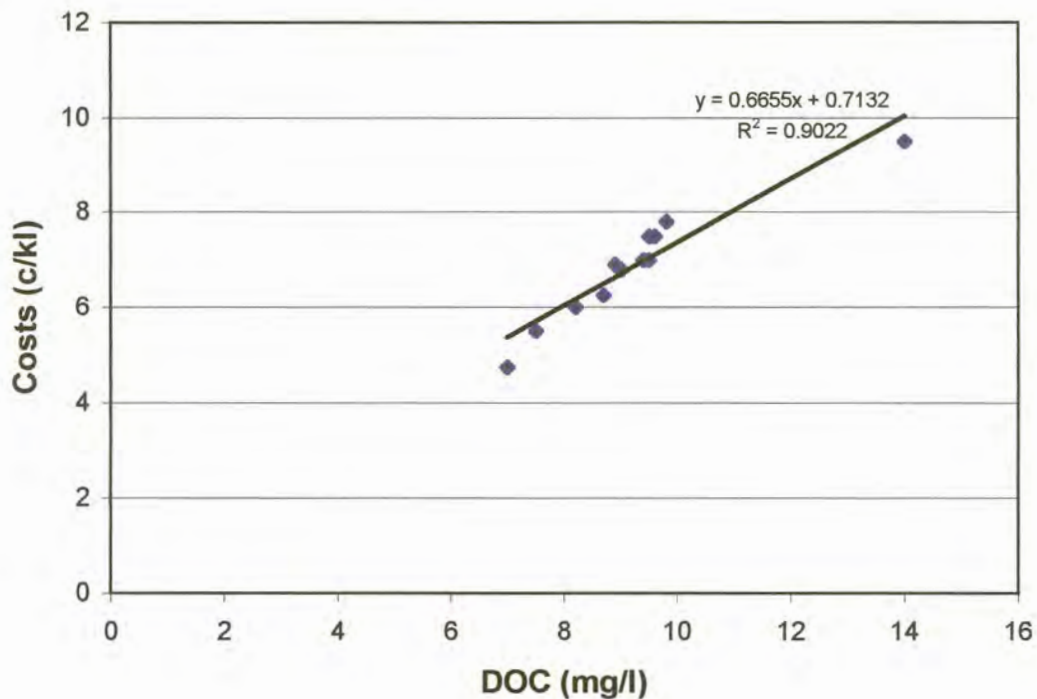
**Table 1:** Operating characteristics of the two modules of the Balkfontein water treatment plant used during full-scale investigations.

	Chemical Dosed	Module 2 (Design capacity – 120 ml/d)			Module 3 (Design capacity – 120 ml/d)		
		G-value (s <sup>-1</sup> )	Retention time	Volume (m <sup>3</sup> )	G-value (s <sup>-1</sup> )	Retention time	Volume (m <sup>3</sup> )
pH –adjustment	Lime	2 500	1,14 s		2 100	2,86 s	
Lime mixing channels		470	37,05 s		250	67,41 s	
Rapid Mixing units	FeCl <sub>3</sub> /M70	4 800	0,33 s		4 800	0,33 s	
Secondary dosing units	Poly-electrolyte	1 450	2,86 s		1 450	2,86 s	
Split channels:							
Channel		38	70,40 s		74	118,60 s	
Flume		1 260	4,10 s		980	3,65 s	
Channels (2 <sup>nd</sup> )					22	99,30 s	
Flume (2 <sup>nd</sup> )					1 600	2,97 s	
Serpentine channels:							
30 Ml/d units		45	966,80 s		45	966,80 s	
90 Ml/d units		32	821,50 s				
Primary sedimentation tanks			6,08 h	30 386	-	6,08 h	30 386
Secondary sedimentation tanks			3,8 h	18 991	-	6,08 h	30 386
Sand filters				1x 100.8 (x10 filters)			1 x 100.8 (x10 filters)

Pre-chlorination is applied ahead of coagulation at dosing concentrations of 4-6 mg/l. It was originally instated to enhance the flocculation of algae and to control taste and odour problems. Since 1994 increasing concentrations of manganese in the raw water, however resulted in chlorine also being used as a pre-oxidant for the removal of manganese. Pre-chlorination not only contributes significantly to the total chemical cost, but was also found to negatively impact on tastes and odours associated with cyanobacteria. It furthermore results in increased THM concentrations in the final water.

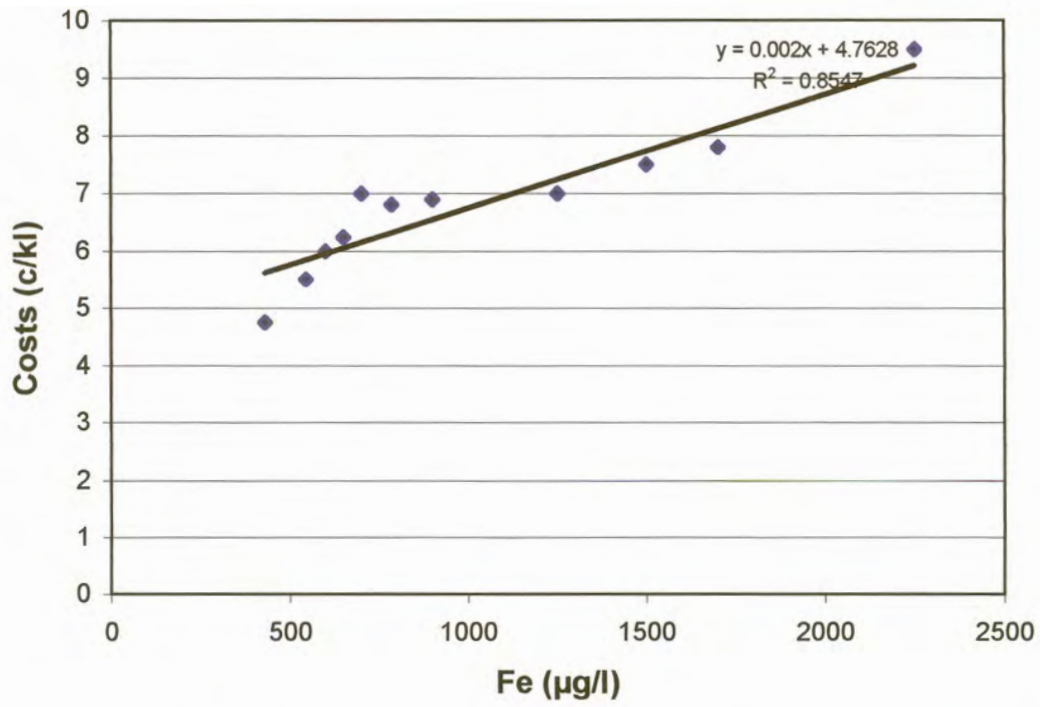
## Historical Quality

Historical records of water quality parameters provide a good insight in the variations that occurred over time, and on plant performance to deal with such variations. The daily raw water quality data from January 1994 to December 1996 were analysed and Figures 2-5 give the correlation between individual quality parameters and treatment costs. However, since the treatment cost cannot be apportioned to individual parameters, these correlations are for illustration purposes only.

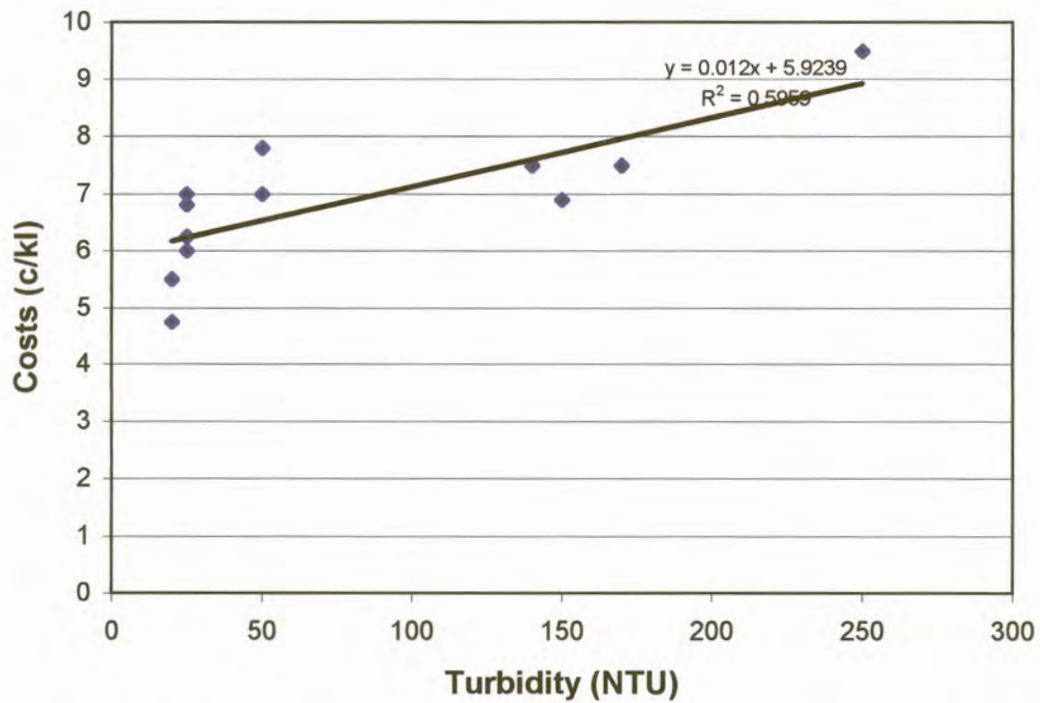


**Figure 2:** The correlation between DOC in the raw water and the chemical costs.

The results illustrated in Figure 2 indicate that the dissolved organic carbon (DOC) correlates positively with the chemical cost. Figures 3 and 4 show that heavy metals (of which Fe is an example) and turbidity levels in the raw water also correlate positively with the chemical cost, to a greater or a lesser extent.



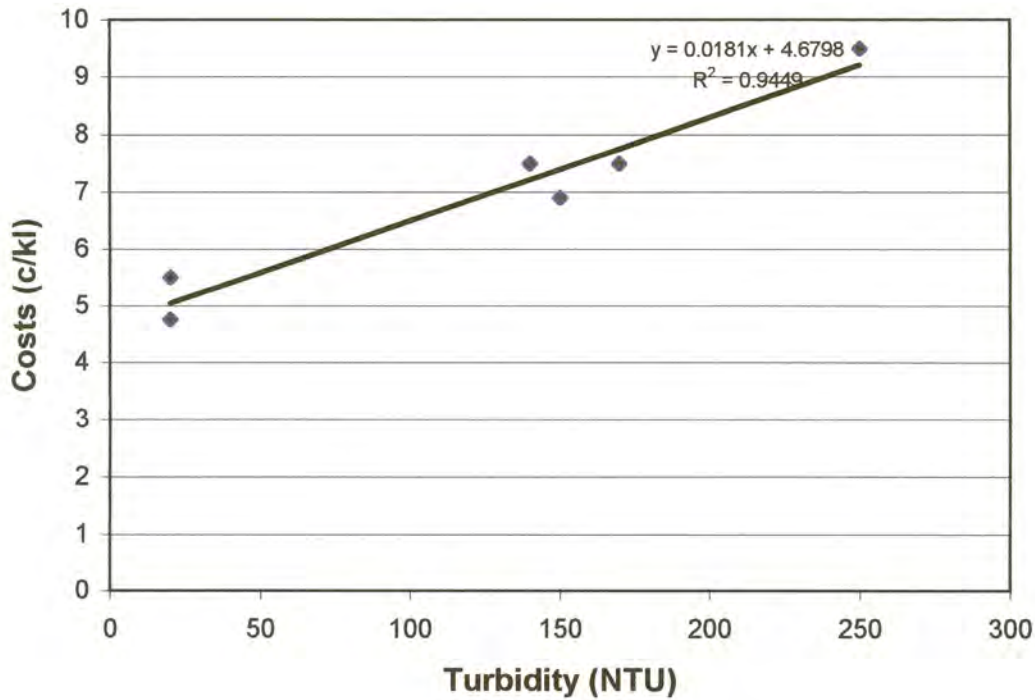
**Figure 3:** The correlation between iron in the raw water and the chemical cost.



**Figure 4:** The correlation between turbidity in the raw water and the chemical cost.

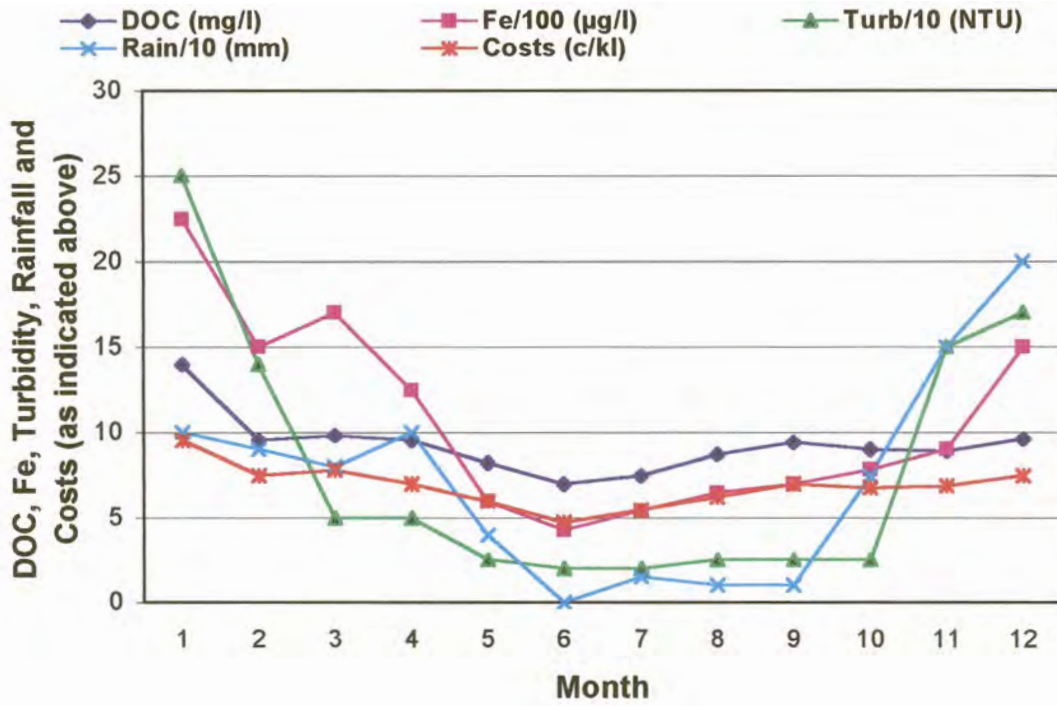


Figure 4 shows that the correlation between turbidity and costs was less significant than was the case with DOC and Fe. The exclusion of low turbidity figures which coincided with high levels of Fe, resulted in a better correlation being obtained between turbidity and cost, as illustrated in Figure 5.

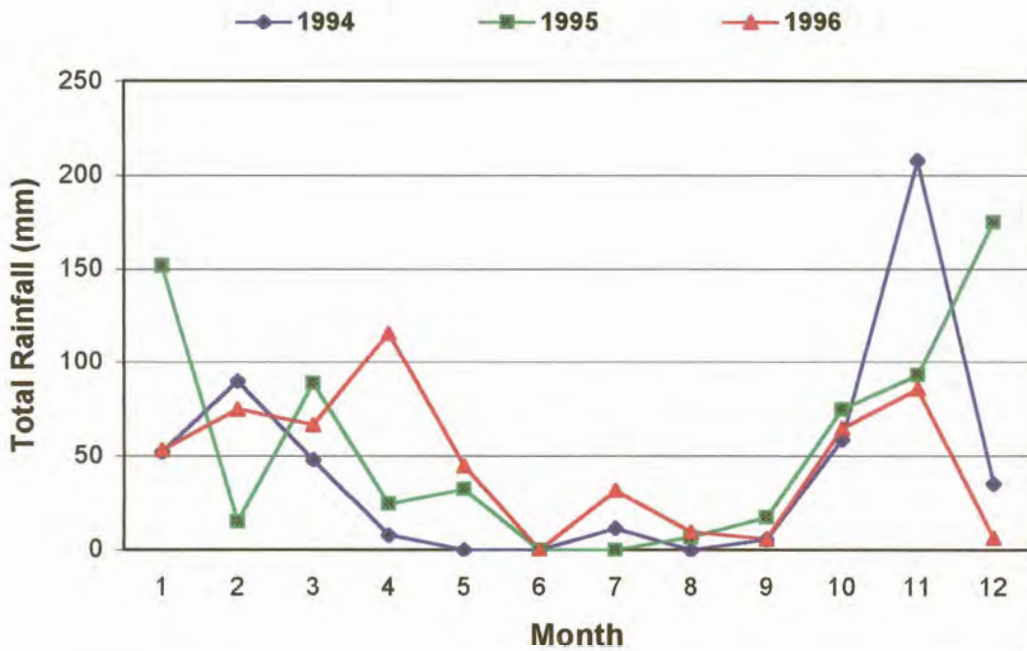


**Figure 5:** The correlation between turbidity in the raw water and the chemical cost (excluding low turbidity values coinciding with high iron values).

Since the concentration levels of these parameters have a seasonal cyclic nature, as shown in Figure 6, the treatment cost increases when concentration levels of the contaminants increase during the wet season.



**Figure 6:** Total rainfall and average chemical cost, DOC, Fe and turbidity levels in the raw water for the period 1994 to 1996.



**Figure 7:** Total monthly rainfall for the period January 1994 to December 1996.

Figure 7 shows the rainfall pattern for the period January 1994 to December 1996. This graph shows the decrease of rainfall during the winter months. This decrease coincided with the decrease in contaminant levels and costs as shown in Figure 6.

**The following have been identified in the laboratory as possible causes contributing to water quality problems and increasing costs:**

(i) Manganese and iron

The presence of relatively high concentrations of manganese and iron in the raw water, as a result of upstream pollution, gives rise to the poor aesthetic quality of the final product. The main problems for domestic use are objectionable taste and colour in the drinking water and staining of laundry. Oxidation of the dissolved metals, after post-chlorination, causes metal precipitates to form within the distribution network.

(ii) Algae

- Eutrophication, and the taste and odour causing substances produced by certain algal species contribute to the poor aesthetic quality of the drinking water at times.
- The presence of high algal cell counts of specific species in the raw water requires pre-chlorination for effective removal. Chlorination of the raw water containing a relatively high organic pollution load results in the formation of THMs. Chlorination furthermore contributes to the taste and odour problems and chemical costs.
- Algal cells and colloidal complexes of algogenic organic matter break through the sand filters and cause relatively high levels of turbidity at times.
- Algal related organic substances present in the raw water, as well as dissolved organic compounds, probably released by algae on chlorination, result in increased coagulant demand and increased treatment costs.

These factors are all, to a greater or lesser extent, interrelated and cannot be looked at in isolation. It is not possible to optimise for one aspect without considering the effects and interactions of the other factors. A very comprehensive study will be required should one want to quantify the effects of all these factors. The scope of such a study would be much larger than the limited study on which this thesis is based. It was therefore decided to identify some critical factors, from a cost point of



view, for this study and to develop a more comprehensive future project to investigate the interrelationship between all the factors mentioned above.

Although price increases are contributing to the increase in chemical costs, it is rather higher dosages and the use of secondary coagulants which are responsible for increasing costs. This increasing chemical cost (as much as 70% from 1994 to 1996) and consumer complaints, with regard to the aesthetic quality of their drinking water, were the main thrusts for this investigation. The role of pre-chlorination and the possibility of moving the point of chlorination and still obtain some benefits of pre-chlorination, (Strobel and Dieter, 1990; Carlson, 1991; Jiang and Graham, 1992 and White *et al.*, 1997) formed the framework for the experimental planning for the investigation.

The most critical factors contributing to increased treatment costs were identified as chlorine dosing (dosage and point of dosing), pH adjustment and coagulants used (type and dosage). The study was therefore planned to optimise these three parameters in order to improve final water quality and to reduce costs.

### **1.3 STUDY OBJECTIVES**

The main objectives of this study are:

- (i) To investigate on bench scale, the effects of chlorine dosage and point of chlorine dosing, pH and coagulant type and dosage on;
  - the removal of algae and algal products and
  - the formation of THMs.
- (ii) To identify from these investigations optimal process conditions of chlorine dosing, pH and coagulants for the plant, with respect to these parameters.
- (iii) To verify the performance of the plant, when operating under these conditions, by means of full-scale investigations.

## CHAPTER 2

### LITERATURE REVIEW

The treatment problems and possible causes, described in Chapter 1, cover a very wide field. A detailed literature review of all aspects that could be relevant falls outside the scope of this thesis. The literature review therefore focuses only on the main aspects of the study:

- Problems associated with algae and algal products in water treatment.
- Chlorination and the formation of THMs.

#### 2.1 PROBLEMS ASSOCIATED WITH ALGAE AND ALGAL PRODUCTS IN WATER TREATMENT

The removal of micro-organisms by flocculation and filtration is one of the major problems in the treatment of eutrophied water. The impairment of water treatment processes due to the presence of algae, especially cyanobacteria, in the raw water has been experienced in water treatment over the world.

In the Netherlands seasonal blooms of cyanobacteria were found to be responsible for serious problems experienced at treatment works. Algal blooms can cause taste and odour problems, interference with the coagulation and flocculation processes, increased disinfectant demand, THM production, frequent filter blocking, increased use of backwash water and the formation of scum (Vlaski *et al.*, 1996). These problems are typical of the problems experienced at water treatment works in South Africa. Under such circumstances coagulant doses have to be increased and algae are also found to pass through treatment processes. Sophisticated treatment processes often have to be used for the elimination of taste and odour problems. Higher production cost is ultimately the result (Vlaski *et al.*, 1996 and Visser, 1997).

The contamination of the Vaal River is a serious problem, which has been studied intensively over the past years. Research by Visser (1997) indicated that representatives of six different algal groups, namely Cyanophyceae (*Oscillatoria*; *Microcystis*; *Anabaena*), Bacillariophyceae (*Cyclotella*; *Nitzschia*), Chlorophyceae (*Chlorella*; *Monoraphidium*; *Scenedesmus*; *Chlamydomonas*), Euglenophyceae (euglenophyte), Dinophyceae (dinoflagellates) and Cryptophyceae (cryptophyte), are present in the Vaal River at the Balkfontein plant. High algal biomass in the raw water was accompanied by high species diversity in the final water and the purification process was not successful in the removal of algal cells in the absence of pre-chlorination. Except for the high lime process, which proved to be successful in the removal of algal cells, this research did however not include any full-scale experimental work without pre-chlorination.

Algae removal rates are very scattered, depending on the species (Visser, 1997). Removal rates for *Cyclotella*, the dominant diatom present in the middle Vaal River (Visser, 1997) are reported to vary between 10 and 70 % (Mouchet and Bonn elye, 1998). Removal rates for diatoms are estimated at 40–80 % and Chlorophyceae at 50–60 % (Mouchet and Bonn elye, 1998). With *Chlorella* being the dominant Chlorophyceae species found in the middle Vaal River (Visser, 1997), the poor removal rates of 10–50 % as reported by Mouchet and Bonn elye (1998) are mainly responsible for water quality problems during algal blooms (Experience, Balkfontein plant). *Chlorella* cells are small and pass through the entire purification process (Experience, Balkfontein plant; Visser, 1997).

Experience at the Balkfontein plant indicates that increasing the coagulation pH to obtain sufficient removal of manganese, could be detrimental to the removal of algal cells when applying pre-chlorination. White (1992) found that the efficiency of chlorine, as oxidant and to kill micro-organisms, is very much pH dependent. This is confirmed by Steynberg *et al.*, (1996) who found that at pH 9,5 chlorine was 40 times less effective in killing *Monoraphidium minutum* than at pH 7,0.

### 2.1.1 MORPHOLOGICAL AND PHYSIOLOGICAL CHARACTERISTICS

The morphological characteristics of algae play a very important role in their behaviour in water treatment. Motility, protective cells walls and physiological activities are described in literature by Tilton *et al.*, (1972) and Bernhardt and Clasen, (1991) as the main reasons for what happens in water treatment.

The way in which the morphological and physiological characteristics of algae affect their behaviour, and consequently their removal, in water treatment, can be described as follows:

- The shape of some species may prevent the accommodation of several of the algal cells into a single floc and in this way is responsible for their poor removal. Distinct spine and long bristles are some of the characteristics negatively influencing their elimination (Bernhardt and Clasen, 1991).
- Algal cells may be elongated in shape, arranged in filaments or colonies, or the cells may have long spines or other appendages that could affect the efficiency of flocculation. Others have flagella with which the cells could avoid flocculation or with which they could swim out of flocs (Wetzel, 1983 and Pieterse and Cloot, 1996).
- There are some types of algae which have pectin or polysaccharide components attached to their surface, which can induce the formation of gelatinous slime. Slime producing algae are, for example, *Oscillatoria simplicissima* and *Euglena* spp. In these instances the peripheral cell wall structures exert an influence on the flocculation process on account of their chemical structure, irrespective of their charge density (Bernhardt and Clasen, 1991). Most species have mechanically resistant cell coverings (cell walls, pellicle plates and bands, frustules or thecal plates) which may give them competitive advantage over fragile species in the river but contribute to difficulties during purification (Visser, 1997).

Apart from *Chlorella* and *Cyclotella*, some other species found to be dominant in the Vaal River at Balkfontein are: *Nitzschia*, *Chlamydomonas*, *Monoraphidium* and *Scenedesmus*



(Visser, 1997 and experimental work, Balkfontein laboratory). The morphological characteristics of some of these species, which are responsible for their behaviour in water treatment, are illustrated in Table 2 (Prescott, 1978; Wetzel, 1983 and Bold and Wynne, 1985) and Figures 8 to 10 (UOFS).

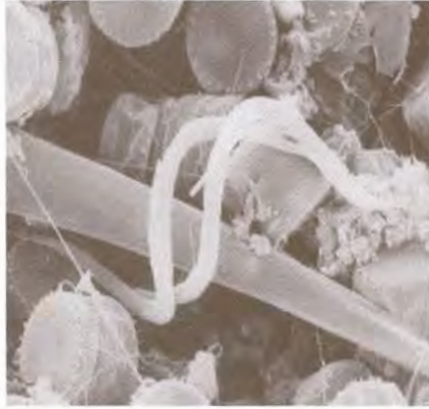
**Table 2:** The morphological characteristics of algae species present in the Vaal River.

	<b>Morphology</b>
<i>Cyclotella</i>	Circular cells, rectangular in girdle view. Form chains of short filaments with other cells. Outer membrane (frustule) consists of silica. (5-50 $\mu\text{m}$ ).
<i>Nitzschia</i>	Frustules narrowly linear; tapered at poles in valve and girdle view. Often occurs in gelatinous tubelike strands. (17-500 $\mu\text{m}$ ).
<i>Chlorella</i>	Cells are small; oval or spherical. (4-6 $\mu\text{m}$ ).
<i>Chlamydomonas</i>	Cells are round, elliptic to oval with flagella. (12-25 $\mu\text{m}$ ).
<i>Monoraphidium</i>	Cells strongly crescent-shaped, closely clustered, not entangled. (5-72 $\mu\text{m}$ ).
<i>Scenedesmus</i>	Cells are oval or crescent shaped; usually in a row of four, or multiples of four. Spines may be present, depending on species. (3,5-30 $\mu\text{m}$ ).



**Figure 8:** Electron micrograph of *Cyclotella meneghiniana* [Dept. of Botany and Genetics, University of the Orange Free State (UOFS), 1999].





**Figure 9:** Electron micrograph of *Monoraphidium* cells [Dept. of Botany and Genetics, UOFS, 1999].



**Figure 10:** Electron micrograph of *Scenedesmus* colonies [Dept. of Botany and Genetics, UOFS, 1999].

Although algal removal rates are depending on the species (Visser, 1997), the primary factor is the size of the organism with the smallest species being the most difficult to remove (Mouchet and Bonn elye, 1998). During coagulation, which is a phenomenon concerning surface area, these small organisms represent the highest rates of developed surface area to volume and account for most of the coagulant demand (Mouchet and Bonn elye, 1998). The type and number of algae may affect the sedimentation process, however the density of planktonic algal cells is normally slightly greater than that of water, so that the cells settle out (Visser, 1997).

Algal cells do have the physiological ability to respond to conditions in their immediate environment. These activities can affect the overall efficiency of the flocculation process in different ways. An algal entity affects its immediate environment when, for example,

assimilating CO<sub>2</sub> or other nutrients, when producing O<sub>2</sub> and when substances are excreted. Under these different circumstances algae (cells, filaments or colonies) can act as a sink (during uptake) or as a source (during excretion) of material (Pieterse and Cloot, 1996).

### 2.1.2 THE COAGULATION OF ALGAE

The available literature on the removal of algae and bacteria by coagulation and filtration has been reviewed (Bernhardt *et al.*, 1986, Bernhardt and Clasen, 1991, Edzwald, 1993 and Pieterse and Cloot, 1996). From this review the conclusion is drawn that although elimination of algae follows the same principle as removal of colloidal and dispersed particles, they however show specific properties that are not shared by colloidal particles. The following statements can thus be made:

- The stability of colloidal and dispersed micro-organic suspensions is largely dependent on the negative charge density of the particle surface and reduced by the destabilisation process and during coagulation.
- Adsorption coagulation with charge neutralisation forms the basis for destabilisation and aggregation of algal and bacterial suspensions. These processes can be promoted by adding positively charged poly-electrolytes or polymers.
- In addition to Van der Waals forces, the flocculation may also be affected by gravitation forces (because of larger sized entities) and forces created in the immediate vicinity of the cells by metabolic processes such as photosynthesis and respiration.

Charge neutralisation, the main coagulation mechanism for organic cationic polymers (Amirtharajah and O'Melia 1990), is more effective than sweep coagulation for the removal of algae (Jiang *et al.*, 1993). Experience at the Balkfontein plant indicates that poly-electrolytes are effective in the removal of diatoms. According to Basson and Pieterse (1996) and Visser (1997) this is due to the fact that diatoms excrete smaller amounts and less organic acids than green algae. Poly-electrolytes are also economically effective when compared with mineral coagulants used alone (Al-Layla and Middlebrooks, 1974). The capability of cationic poly-electrolytes to flocculate algae is however impaired by chlorination of microscopic small algae (Steynberg, 1994).

If a cationic poly-electrolyte is used, it is not always necessary to neutralise the particle charge so as to attain aggregation. In applying such poly-electrolyte it may suffice to reduce the negative charge of the algae causing a decrease in repulsive forces (Bernhardt and Clasen, 1991). The adsorption of the negative charged algae reverses the charge and this reduces the force of repulsion between the particles (Tilton *et al.*, 1972). The decrease in repulsive forces will bring about particle bindings. The absorbed polymers, because of their size, are able to form the strong bindings and bring about flocculation (Tilton *et al.*, 1972 and Bernhardt and Clasen, 1991).

*Enhanced coagulation* is described in the literature as the addition of coagulant in excess of the optimum for turbidity removal in order to obtain improved removal of the THM formation potential (THMFP) by conventional treatment (Amy and Krasner, 1995; Edwards, 1997 and Thompson *et al.*, 1997). Although Basson and Pieterse (1996) found minimal turbidity, as measured in a jar-test, to be no longer a sufficient criterium, examples of implementing enhanced coagulation for South African waters could not be found in literature. It has however long been applied in France for algae removal (Mouchet and Bonn elye, 1998). Tilton and Murphy (1972) and Bernhardt and Clasen (1991) found that the removal of filamentous, bulky algae or algal cells with bristle-like appendages is only possible when applying an excessive amount of flocculant.

### **2.1.3 ALGOGENIC ORGANIC MATTER**

The production of organic substances by algae and the role of chlorination in this respect, has been described by various authors. The mucilaginous outer cell wall layers, algal metabolic products or substances from the breakdown of cells might be the origin of such releases (Bernhardt *et al.*, 1985; Abika *et al.*, 1991; Jiang and Graham, 1992 and Wnorowski, 1992). These low molecular weight substances are considered to contribute substantially to the disturbance caused to flocculation (Bernhardt *et al.*, 1986).

The production of algogenic dissolved organic compound causes the impairment of the flocculation and filtration process (Bernhardt *et al.*, 1986 and Bernhardt, 1996). Dissolved and particulate organic substances are then found to be still present in the water after treatment, resulting in the consumption of the disinfectant added, by these

substances. This is particularly true in the case of long distance pipelines in which the water is contained for long periods of time (Jiang and Graham, 1992 and Bernhardt, 1996). In the presence of high concentrations of algal derived organic matter, surface- and mixed ligand complexes are formed. These complexes are of colloidal nature and they break through the filter and increase the turbidity and residual metal (from the metal salt) content of the filtrate (Bernhardt *et al.*, 1986).

Extracellular organic matter (EOM) may also have an adverse effect on the organoleptic properties of drinking water (Bernhardt *et al.*, 1986). Substances which impart tastes and odours to water and aquatic life were found to be mostly of microbial origin and resistant to chlorine dosage. Additional taste, odour and health problems are created by the chlorination procedure, and even more so when chlorination is applied in the early phase of the treatment process prior to the removal of intact algal cells and other organic matter. Chlorination of algal cells causes their lysis and release taste and odour producing substances and other organic compounds contained mainly within the cells (IOMs) (Bernhardt *et al.*, 1985; Abika *et al.*, 1991; Jiang and Graham, 1992 and Wnorowski, 1992).

The production of EOM varies for different species (Edzwald, 1993). Ten times more EOM is produced by *Scenedesmus* than by *Chlorella* and 36 times more by *Cyclotella*. The EOM produced mainly consists of high molecular weight organic matter which can be changed to substances of intermediate molecular weight by ozonation. The detrimental effect of chlorination on the removal of DOC (Abika *et al.*, 1991 and Steynberg, 1994) could, as in the case of ozonation, be due to the transformation of high molecular weight organic substances into compounds of lower molecular weight and the release of IOM and EOM.

#### **2.1.4 ALGAE AND THE FORMATION OF THMs**

As algal cells contain organic material it may be expected that algae can contribute to the formation of THMs on chlorination. The effect of chlorination and ozonation on EOM and the subsequent decrease in DOC removal (Abika *et al.*, 1991 and Edzwald, 1993 and Steynberg, 1994) could possibly be the reason why the presence of algae in eutrophied waters can be an important indicator for the formation of THM precursors.



Studies on the elimination of algae had in the past only been devoted to the effects that algae and algae-derived matter have on taste, odour and turbidity of water supplies, the clogging of filters and the inhibition of flocculation in water treatment plants. Many research results recently however have shown that both green algae and blue-green bacteria produce organic substances which are major sources of THM precursors (Van Steenderen *et al.*, 1991 and Jiang and Graham, 1992). It is therefore possible that, despite the effective algal removal by coagulation prior to chlorination, EOMs may still remain in the finished drinking water causing disinfection consumption (Bernhardt, 1996) and the formation of THMs on disinfection (Jiang and Graham, 1992). Although algae have been found to be sources of THM precursors, little of the work studied on algae has taken into account the relationships between high THMs and the kinds and quantities of algae.

## **2.2 CHLORINATION AND THE FORMATION OF THMs**

The main role of chlorination in conventional water purification is to disinfect the water in order to produce microbiologically safe water. In addition to disinfecting the finished water, it also provides a residual for the distribution system and destroys some harmful substances by oxidation (Wnorowski, 1992). The reaction between chlorine and organic matter, mainly of natural origin, however results in the formation of THMs (Casey and Chau, 1997). By removing some DOC before chlorination, the potential for the formation the THMs will therefore decrease (Jiang and Graham, 1992).

Improved removal of organic substances can be obtained by enhanced coagulation (Edwards, 1997 and Thompson *et al.*, 1997). The subsequent reduction in the potential for the formation of disinfecting by-products (DBP) may thus be within the reach of the plant manager at very little additional cost. An in depth investigation of the benefits of enhanced coagulation under South African conditions seems advisable. If this process is effective it may eliminate the need for sophisticated treatment processes. Pre-chlorination however, although it can facilitate the plant operation, probably has some adverse effect on DOC removal (Yeh and Huang, 1993). This is due to the larger molecular weight fractions being transformed to substances of lower molecular size, more difficult to remove (Amirtharajah *et al.*, 1993).



At the Balkfontein plant pre-chlorination of the raw water is applied prior to the removal of intact algal cells and other organic matter by sedimentation. The pre-chlorination step was originally incorporated at the front end of the treatment system to remove colour, to control taste and odour and algal growth and to improve coagulation and filtration, especially when algal cell numbers in the raw water were high. It is at this front end of the treatment process, where the water still contains dissolved and particulate contaminants, that Basson and Pieterse (1993) found the THM formation potential to be the greatest. The chlorination of algal cells results in the release of organic substances which, apart from producing taste and odour, also play an important role in the formation of THM precursors (Jiang and Graham, 1992 and van Steenderen *et al.*, 1991). The question therefore arises whether pre-chlorination should be practiced all the time or whether chlorine, being an effective disinfectant, should not only be used as such.

Many researchers discuss the advantage of extensive water treatment for the removal of chlorine consuming substances, ahead of chlorination. An alternative treatment approach could be to move the point of chlorine application to a position after coagulation and sedimentation (Strobel and Dieter, 1990; Carlson, 1991; Jiang and Graham, 1992 and White *et al.*, 1997). Studies by White *et al.*, (1997), at full-scale water treatment plants, demonstrated that this treatment can result in substantial reductions in DBP formation. The amount of THMs formed is however also directly dependent on the quantity of chlorine used (Strobel and Dieter, 1990). Chlorine consumption could therefore be a reasonably good indicator of the extent of DBP formation (Singer *et al.*, 1995). By removing organic carbon prior to chlorination, the requisite chlorine dosage will be less. This dosage strongly corresponds to the concentration of TOC at the point of chlorine addition and therefore to the potential for the formation of DBPs.

The elimination of pre-chlorination to lower the concentration of total THMs (TTHMs) in the finished water must however be considered very carefully before implementation, since all benefits of pre-chlorination as a treatment option, would be lost. It has long been recognised that chlorination of raw surface water not only provide some degree of taste and odour control, but also contributes to keeping intake lines and basins free of algae and slime; therefore controlling bacterial and algal growth. Increased growth, when excluding pre-chlorination, could then also be responsible for producing an increased THMFP (Reeds, 1983 and El-Dib and Ali, 1994).

Results presented by Singer *et al.*, (1995) and El-Dib and Ali (1994) show a progressive increase in TTHM values with the increase of pH values. Results furthermore indicated that the effect of pH on THM formation is much more significant above pH 8,0. A reduction of 50% in TTHM yield could be obtained by decreasing the pH from 9,0 to 7,0. El-Dib and Ali (1994) also stated that the THM reaction involves the formation of intermediate chlorinated organics which yield  $\text{CHCl}_3$  once the pH of the water is increased, even in the absence of chlorine.

## 2.3 SUMMARY

Algae and algal related organic substances present in the raw water give rise to not only water quality problems, but to increasing chemical costs due to higher coagulant and chlorine demand. From literature, aspects related to these problems can be summarised as follows:

### **The role of algae**

There exists little knowledge about the relationship between specific algae, algal cell numbers, and the release of organic compounds on cell lysis, IOMs and EOMs and the formation of THMs. The causes of disturbance in drinking water production from eutrophic raw water sources are, as follows:

- Bad odour and taste due to organic compounds of algal origin. This could be created by pre-chlorination.
- The impairment of flocculation due to the release of algal related organic compounds.
- Increased coagulant demand due to the demand by organic substance. This demand must first be satisfied before the metal salt, used as coagulant, is available for destabilisation.
- Increased chlorine demand for disinfection as result of the increased amount of organic compounds present in the drinking water. These organic compounds may also be responsible for regrowth in the distribution network.

Coagulants could however play a significant role in addressing algal related problems if applied correctly:

- Enhanced coagulation could be applied for the removal of algae and organic substances.
- Poly-electrolytes could be economically applied for the coagulation of algae.

### **Chlorination**

From literature it is clear that two schools of thought exist with regard to pre-chlorination. According to some researchers the exclusion of pre-chlorination, to minimise the formation of THMs, should be considered carefully due to the various benefits of this treatment option. Other authors emphasise the additional taste, odour and health problems created by chlorination prior to the removal of intact algae cells and other organic matter.

Chlorination also proves to contribute to the formation of lower molecular weight organic substances, more difficult to remove and therefore increasing the potential for the formation of THMs. Chlorination is less effective in the removal of algal cells and algal related products at increased pH-values.

### **Conclusions**

From this review it was possible to gather some knowledge about the nature and extent of problems experienced in water purification which are related to the presence of algae. It was thus possible to structure the experimental work in such a way that the objectives for this study could be met.

## **CHAPTER 3**

### **MATERIALS AND METHODS**

#### **3.1 INTRODUCTION**

The aim of the bench scale experimental work was to investigate and evaluate different options for the treatment of the eutrophic surface water from the middle Vaal River. During full-scale experimental work it is not really possible to exactly follow a plug of water through the treatment process. Laboratory investigations, however, ensure the researcher of a true comparison between what went into the system and what was achieved through a specific process.

Jar tests are conducted daily in order to determine conditions for optimum operation of the plant. As it was possible to do some comprehensive testing by means of jar tests, one could establish and compare the effects of the different processes and eliminate unnecessary full-scale experimental work. Experience has shown that jar test procedures have many uses other than coagulant dosage control. The plant manager can meaningfully compare processes without being subjected to rapid changing water quality. The question can however be raised as to whether the results in jar testing compare with those in the plant. It is therefore important to simulate as closely as possible the various conditions in the plant. Extrapolation of jar test results to plant behaviour, offers the opportunity to evaluate laboratory findings on full-scale (Hudson and Wagner, 1981).

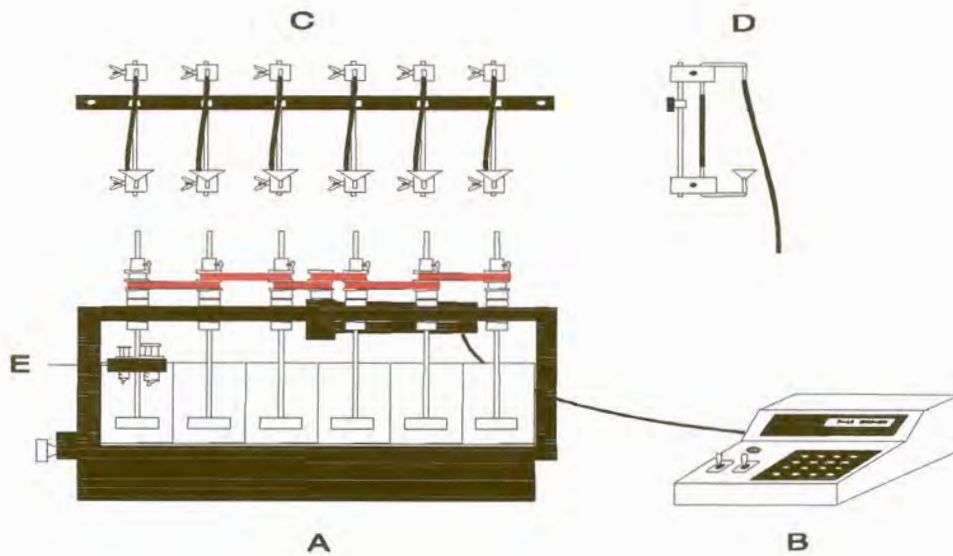
#### **3.2. EXPERIMENTAL PROCEDURE**

##### **3.2.1 JAR TESTS**

Jar tests were conducted for the period March 1997 to January 1998 by making use of a microprocessor jar test apparatus. The procedure was aimed at simulating the treatment process of coagulation and settling. The tests were conducted in sets of six samples (one litre each) in square beakers, two being control samples (C), two for pre-chlorination (PC)

and two for intermediate chlorination (IC).  $\text{FeCl}_3$ , supplied as a 43% solution, was used as primary coagulant. Dosing concentrations are expressed as mg  $\text{FeCl}_3$  (as product) / litre of raw water. A cationic organic polymeric coagulant was used as secondary coagulant. A chlorine stock solution was made by bubbling chlorine gas through deionised water (Steynberg *et al.*, 1996). The pH was adjusted by adding a 0,5% lime solution before coagulation.

Figure 11 is a schematic diagram of the jar test apparatus used for the laboratory investigations in this study.



**Figure 11:** The Jar test apparatus used in this investigation.

A: Jar Test apparatus with six standard jars.

B: Control unit

C: Multiple funnels (front view)

D: Multiple funnels (side view)

E: Syringes (in holder)

A schedule of all the tests performed is given in Table 3.



**Table 3: The procedure followed in conducting the jar tests**

(- indicates that this step was excluded from the procedure and + indicates that this step was included in the procedure)

	Control (C)		Pre-chlorination (PC)		Intermediate chlorination (IC)	
Lime addition: pH 9,8	-	x	-	x	-	x
Pre-chlorination 4mg/l	-	-	x	x	-	-
Primary Coagulant FeCl <sub>3</sub> : (various concentrations)	x	x	x	x	x	x
Secondary coagulant (cationic poly- electrolyte: 1 mg/l) when necessary	x	x	x	x	x	x
Flocculation	x	x	x	x	x	x
Sedimentation	20 min	10 min	20 min	10 min	10 min	10min
pH adjustment: 8,5	-	x	-	x	-	x
Chlorination of supernatant (IC) 2 mg/l	-	-	-	-	x	x
Sedimentation	-	10 min	-	10 min	10 min	10 min

All tests were conducted according to the following procedure:

Lime was added to adjust the pH to 9,8 where applicable. All the samples were then stirred for one minute at 250 revolutions per minute during which time pre-chlorination was also performed. The addition of the primary coagulant was followed by rapid stirring at 250 rpm for one minute. After adding the secondary coagulant, further stirring for one minute, at 200 rpm, followed. Flocculation was simulated by stirring at 40 rpm for eight minutes. The pH was adjusted by either adding a diluted HCl-solution after

sedimentation, while stirring at 40 rpm, or by bubbling air through the sample. Intermediate chlorination, when applicable, followed and the sample was stirred for another minute at 25 rpm.

The supernatant of each sample was drawn off, after the prescribed settling times, by means of a multiple funnel (Figure 11, C + D) to minimise movement of the settled floc. Most of the analyses were done on settled samples. To compare jar test results with sand filtered water, the supernatant in each case, was filtered through a Whatman No. 1 filter paper.

### **3.2.2 FULL-SCALE INVESTIGATIONS**

Different full-scale investigations were performed with the intention to evaluate and confirm the findings from the bench scale tests and to develop an optimum process for the full-scale plant. Due to high energy costs, operating procedures only allow for the plant to be operated at design flow capacity according to a prescribed time schedule. The programme for full-scale investigations had to be planned according to these procedures. Due to the operational constrictions, it was not possible to include all the objectives for this study into a single full-scale investigation. Laboratory findings could also not be investigated over extended periods of time and under different conditions, due to the operational limitations.

Modules 2 and 3, as illustrated in Figure 1 (see Chapter 1), were used for full-scale experimental work. Module 3 consists of four similar sections. Module 2 was used to investigate the role of pre-chlorination ahead of coagulation. Chlorine-dosing points were installed in two sections of Module 3, after primary sedimentation, to investigate the effect of intermediate chlorination. The other two sections of this module were used for control purposes. Samples were collected on the plant at the different points as illustrated in Figure 1 (see Chapter 1).

### 3.2.3 CHEMICAL AND PHYSICAL ANALYSES

Samples were analysed for pH, turbidity, chlorophyll-*a*, DOC, and THMs and algal identification and enumeration. Experimental methods as described in Standard Methods (1989) were used.

#### pH

pH Measurements were done by using a PYE UNICAM pH meter with temperature compensation.

#### Turbidity

Turbidity was determined by using a HACH RATIO turbidity meter.

#### Chlorophyll-*a*

Chlorophyll-*a* was measured by using a pigment extraction method described by Sartory (1982). Samples were filtered through a Whatman – GF/ C filter. Chlorophyll-*a* was then extracted from the algal cells in suspension (on the GF/C filter) in 10ml of 95% ethanol for a period of 5 minutes at 78° C.

After the ethanol extractions samples were allowed to cool, the absorption of the dissolved chlorophyll-*a* was determined at 750 and 665 nm with a spectrophotometer. 100 µl of 0,3 N HCl were added to the extract and the absorption was again determined at 750 and 665 nm. The chlorophyll-*a* concentration (µg/l) was then determined by using the following formula (Sartory, 1982):

$$\text{Chlorophyll-}a \text{ (}\mu\text{g / l)} = \frac{[(665\text{o}-750\text{o})-(665\text{a}-750\text{a})] \times 28,66 \times 10 \text{ ml}}{\text{Volume of sample filtered}}$$

Where            665o = adsorption before addition of acid  
                     665a = adsorption after addition of acid  
                     750o = background value before addition of acid  
                     750a = background value after addition of acid

## **THMs and DOC**

These analyses were done by the CSIR in Pretoria.

## **Algal identification and enumeration**

Samples were fixated by adding 1 ml of formalin to 100 ml of sample. Cell counts and the identification of the specific group and species were done by the Department of Botany and Genetics of the University of the Free State. The algae were counted by using the inverted microscope method. Algae are reported as number of organisms per ml of sample.