AN INVESTIGATION INTO A TREATMENT STRATEGY FOR THE BERG RIVER WATER AT THE VOËLVLEI WATER TREATMENT PLANT

By

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DECLARATION

I declare that this dissertation is my own unaided work and that it has not been previously submitted in whole, or in part, for the award of any degree at any other tertiary institution. Each significant contribution to, and quotation in, this dissertation from the work(s) of other people has been acknowledged by complete references.

Raymond Joseph Swarts

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Signature

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"This dissertation is dedicated to my late father, Rev. A. H. Swarts who was my source of inspiration and who always encouraged me to further my studies"

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SUMMARY

Since the demand for fresh potable water increases every year, it is important to have future water demand strategies in place. People expect a secure, high quality, water supply and the water supply industry is governed by increasingly stringent water quality guidelines and legislation. The Cape Metropolitan Area (CMA) faces the challenge of an increasing demand for fresh water in excess of the existing supply. The City is responsible for the planning and development of the local water supply resources as well as managing the water demand in the CMA and to supplement the water supply to the City of Cape Town from local sources. The 'Voëlvlei Augmentation Scheme' was identified as one of the options to augment the water supply to the CMA. This option would involve pumping winter water from the Berg River via a pipeline to the Voëlvlei water treatment plant (WTP).

The Voëlvlei WTP was designed to treat water from the adjacent Voëlvlei Dam. This Voëlvlei WTP raw water has a higher turbidity and a lower colour in comparison to the Berg River water. The plant's treatment conditions were optimized to remove this high turbidity. The Voëlvlei WTP raw water also contains a relatively high manganese concentration and coagulation therefore occurs at a high pH with ferric sulphate to remove the manganese during the initial stages of the water treatment process. As the quality of the Berg River water is different to that of the Voëlvlei WTP raw water, it might not be possible to treat the Berg River water at the Voëlvlei WTP using the plants current treatment parameters. The Berg River water could possibly be blended

with the Voëlvlei WTP raw water before treatment at the WTP. If the Berg River water, or its blends, could not be treated at the Voëlvlei WTP using the plants current treatment parameters, then this water would have to be pre-treated before entering the plant. Various forms of pre-treatment could be used, e.g., conventional water treatment using either aluminium or ferric sulphate as primary coagulants or ion-exchange water treatment using the MIEX® resin or even a combination of both.

The main objective of this study was to determine a treatment strategy for the Berg River water at the Voëlvlei WTP. It is therefore important to determine if the Berg River water could be treated at the Voëlvlei WTP using the current treatment regime. Also, if the Berg River water should be blended with the Voëlvlei WTP raw water, this study would determine which blend would be the most suited for treatment at the Voëlvlei WTP. If the Berg River water could not be treated directly at the Voëlvlei WTP, a pre-treatment strategy for this water should be determined. The cost of pre-treatment of the Berg River water as compared to the cost of direct treatment at the Voëlvlei WTP should also be evaluated.

In order to determine the best treatment strategy for the Berg River water at the Voëlvlei WTP, it was important to sample the Berg River water and the Voelvlei WTP raw water at regular intervals over a period of at least a year to determine its quality and the impact of seasonal changes. Various laboratory physical (e.g., turbidity) and chemical (e.g., total alkalinity) analyses were conducted on the Berg River water and Voëlvlei WTP raw water to determine its quality. The experimental procedure focused mainly on the Jar test which simulates the coagulation, flocculation and sedimentation processes at the Voëlvlei WTP. Jar tests were conducted on the Berg River water and the Voëlvlei WTP raw water using ferric sulphate and aluminium sulphate as coagulants to determine the optimum pH and optimum coagulant dosage concentration for each coagulant. The Berg River water was also blended with the Voëlvlei WTP raw water in three different proportions and Jar tests were conducted on these blends using ferric sulphate as the coagulant at a coagulation pH of 5.0 and a Fe^{3+} dosage of 5.0 mg/L. Jar tests were also conducted on these blends with the Voëlvlei WTP treatment parameters using ferric sulphate as the coagulant at a coagulation pH of 9.2 and a Fe^{3+} dosage of 3.5 mg/L.

The analytical results showed a similar pattern for the characterization of the Berg River water and the Voëlvlei WTP raw water. The iron and aluminium concentrations were consistently low during the summer months with significant increases during the winter months. There were no significant seasonal impact on the UV absorbance and colour. The Jar test results of the Voëlvlei WTP raw water and the Berg River water with ferric sulphate as the coagulant showed an optimum Fe^{3+} dosage of 3.0 to 4.0 mg/L and 4.0 to 6.0 mg/L, respectively, with an optimum coagulation pH range of 6.6 to 9.5 and 5.0 to 10.0, respectively. The Jar test results of the Voëlvlei WTP raw water and the Berg River water with aluminium sulphate as the coagulant showed an optimum Al^{3+} dosage of 2.5 to 3.0 mg/L and 4.0 to 5.0 mg/L, respectively, with an optimum coagulation pH of 6.0 to 7.0 and 6.0, respectively. The Jar test results obtained for all 3 blends were similar to each other. The UV absorbance of the treated water was consistently below the operational specification, while the turbidities were inconsistent and did not always comply with the SANS 241:2006 Specification (Class I) for drinking water. The iron of the treated water was also consistently above the specified value of <0.200 mg/L. The Jar tests conducted on all 3 blends, with the Voëlvlei WTP treatment parameters, also yielded similar results. The UV absorbance of the treated water was consistently above the maximum operational specification of 0.100, while the turbidities were also consistently above the SANS 241:2006 Specification of <1 NTU.

Both ferric sulphate and aluminium sulphate can be used as coagulants to treat the Berg River water, although ferric sulphate would be the preferred choice due to its wide coagulation pH range and also because of differences in their health effects. The Voëlvlei WTP coagulates at a pH of 9.2 to remove turbidity and any manganese that might be present in the raw water. The manganese would not be removed at the low coagulation pH of aluminium sulphate. The specified treatment parameters, including the Voëlvlei WTP treatment parameters, used in treating the raw water blends were not effective and further investigation and research is necessary to determine its optimum treatment parameters.

This study concluded that the Berg River water cannot be effectively treated at the Voëlvlei WTP using the plants treatment parameters, even if it is blended with the Voëlvlei WTP raw water. Therefore, the best treatment strategy for the Berg River

water at the Voëlvlei WTP would be pre-treatment of the water before entering the Voëlvlei WTP.

Although there are various ways of pre-treating the Berg River water, this study has identified the following possible pre-treatment strategies:

   (i)   pre-treatment with ferric sulphate and lime
  (ii)   pre-treatment with ferric sulphate and lime in conjunction with MIEX® resin
 (iii)   pre-treatment with MIEX® resin only

Further research and investigation would be necessary to determine the best pre-treatment strategy in terms of cost and efficiency. The pre-treated Berg River water would have to pass through the Voëlvlei WTP treatment process (i.e. high coagulation pH) to remove any manganese that might be present in the water.

It is recommended that more samples should be taken at various points along the Berg River upstream of the Voëlvlei WTP over a longer period of time to compare the quality of water at these points in the river and also to monitor the effect of various run-off sites. Further research and investigation is necessary to determine the optimum treatment parameters for the Berg River water when blended with the Voëlvlei WTP raw water. Other blending ratios, different to those used in this study, should also be investigated. A more in-depth investigation is also necessary to determine the actual capital and operational costs for the pre-treatment of the Berg River water.

Keywords: Voëlvlei raw water, Berg River water, Voëlvlei water treatment plant, Jar tests, Coagulation dosages, Ferric sulphate, Aluminium sulphate, Raw water blends, Treatment parameters, Pre-treatment, Treatment strategies.

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LIST OF ABBREVIATIONS

CMA	-	Cape Metropolitan Area
WTP	-	Water Treatment Plant
DWAF	-	Department of Water Affairs and Forestry
ML/day	-	Megalitres per day
mg/L	-	Milligrams per litre
SANS	-	South African National Standards
NOM	-	Natural Organic Matter
UV/VIS	-	Ultra-Violet Visible
DOC	-	Dissolved Organic Carbon
ICP-OES	-	Inductively Coupled Plasma Optical Emission Spectroscopy
SSB	-	Scientific Services Branch
NTU	-	Nephelometric Turbidity Units
ZAR	-	Zuid Afrikaanse Rand (South African Rand)
ha	-	Hectare
km	-	Kilometre
m	-	Metre
m^2	-	Square metre
mm	-	Millimetre
nm	-	Nanometre
g	-	Gram
rpm	-	Revolutions per minute

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CHAPTER 1

INTRODUCTION

1.1 Background

The demand on water supply has increased over the last century due to population growth and the increase in the uses of water. People expect a secure, high quality, water supply and the water supply industry is governed by increasingly stringent water quality guidelines and legislation, ensuring that customers receive the highest quality drinking water at all times (DWI, 1998). The Cape Metropolitan Area (CMA) faces the challenge of an increasing demand for fresh water in excess of the existing supply. Other than short-term water restrictions, there are potentially two long-term strategies, which can relieve the pressure of the CMA's currently available water supply sources, namely:

- ➢ Managing the water demand, and
- ➢ Augmenting the water supply.

Ways of implementing these strategies are the subject of ongoing, participatory, investigations by the City of Cape Town. The City is responsible for the planning and development of the local water supply resources as well as managing the water demand in the CMA. In October 1999, the then Cape Metropolitan Council (CMC) initiated the *Integrated Water Resource Planning Study (IWRP Study)* to undertake a pre-feasibility level investigation of alternative options to manage the demand for water in the CMA, and to supplement the water supply to the City of Cape Town from local sources (City of Cape Town: Water Services, 2002).

The most recent prediction of future water demand in the CMA was undertaken during two workshops held in 2000 by the Department of Water Affairs and Forestry (DWAF), and presented in a report entitled "*The effects of water conservation and demand management on the growth of urban and agricultural water demands on the Western*

Cape System and the timing of the implementation of the Berg River Project" (City of Cape Town: Water Services, 2002). The studies identified 17 water demand management and supply augmentation options. The Voëlvlei Augmentation Scheme was identified as one of the options to augment the water supply to the CMA. This option would involve pumping winter water from the Berg River via a pipeline to the Voëlvlei water treatment plant. It also entails changes to the existing water treatment works (City of Cape Town: Water Services, 2002).

Although some research work had been conducted in the mid 1970's, late 1990's and in 2001 on the possible treatment of the Berg River water at the Voëlvlei WTP, and also the pre-treatment thereof, not much more information is available on this topic. There have been some publications on the Berg River but these have focused mainly on the deteriorating nutrient status (De Villiers, 2007), metal contamination (Jackson *et al.*, 2007) and bacterial pollution (Paulse *et al.*, 2007) of the river water. Even though no publications could be found with a direct relation to the treatment of the Berg River water for potable use, especially at the Voëlvlei WTP, the above-mentioned publications provide critical information as to the quality (chemical and biological) of the river water upstream of the Voëlvlei WTP and this could have a major impact on the treatment strategy being investigated further downstream.

1.2 Problem statement

This Voëlvlei WTP treats on average about 140-180 ML per day and gets its raw water from the Voëlvlei dam which is situated next to the plant. This plant, which supplies water to the City of Cape Town and surrounding areas, was designed to use ferric sulphate and poly Hi-T flocculants for the purification process of its raw water. The Berg River flows northwards past Hermon and Gouda and is situated approximately 1 km from the Voëlvlei WTP. Being one of the City of Cape Town's future water augmentation schemes, the Berg River water would have to be pumped to the Voëlvlei WTP for treatment should the need arise. The Berg River water has a lower turbidity and higher colour in comparison to the water of the Voëlvlei dam which has a much higher turbidity

and lower colour. It is therefore questionable if the Berg River water could be treated at the Voëlvlei WTP using the plants current treatment parameters as these parameters were specifically designed to treat the high turbidity water of the Voëlvlei dam.

A map of Cape Town and its surrounding areas is shown in Figure 1(a), including the location of the Berg River in close proximity to the Voëlvlei Dam and WTP.
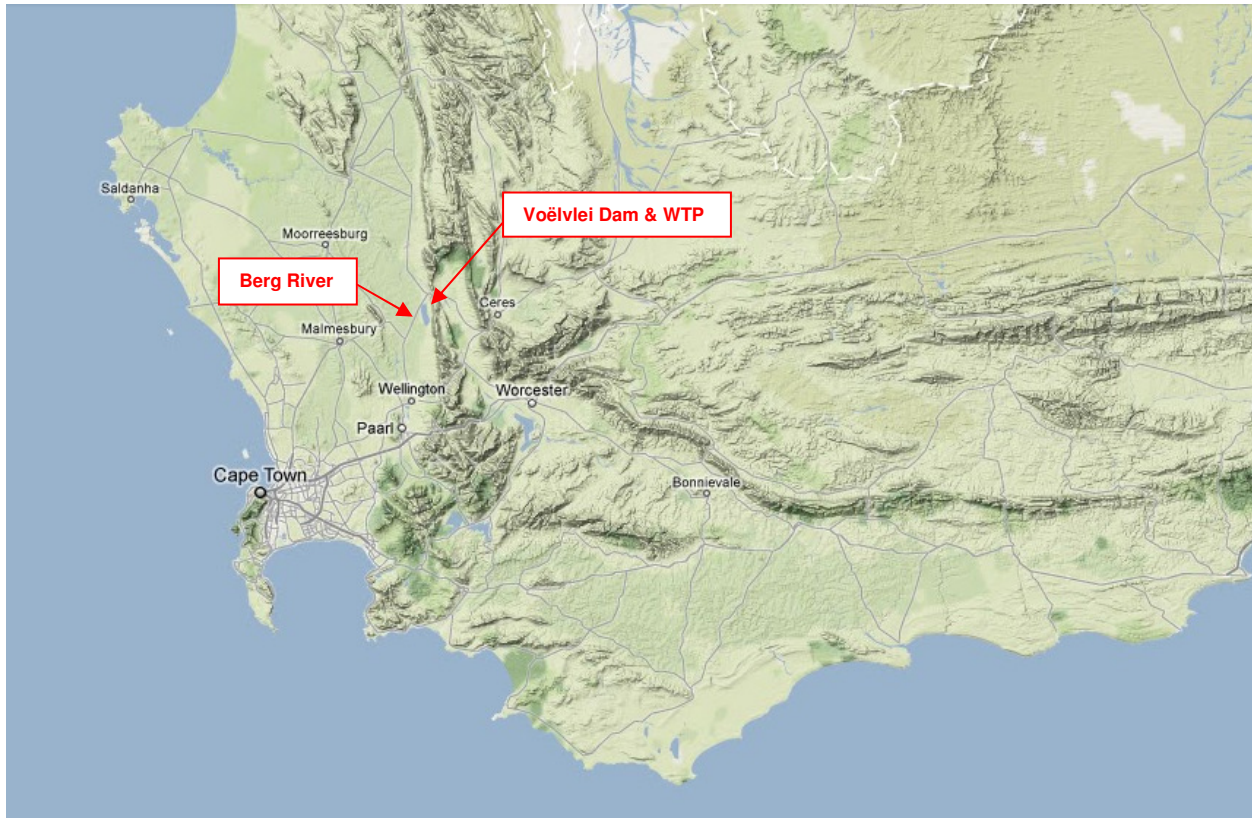
Figure 1(a)   Map of Cape Town and surrounding areas

1.3 Research objectives

The main objective of this study was to determine a treatment strategy for the Berg River water at the Voëlvlei WTP.

The specific objectives were:

a) Characterisation of the Voëlvlei WTP raw water
b) Characterisation of the Berg River water

c) Treatment of the Voëlvlei WTP raw water

d) Treatment of the Berg River water

e) Treatment of raw water blends

f) Treatment of raw water blends with the Voëlvlei WTP parameters

g) Evaluation of treatment strategies to determine the best treatment option

h) Preliminary cost evaluations

1.4 Chapter overviews

This dissertation has been divided into the following chapters with a brief description of each:

a) *Chapter 1 – Introduction*

This chapter introduces the topic and explains why this research study is being undertaken. It gives a brief overview of and background to this study and indicates clearly its objectives. It also provides the scope of this study and also outlines the various chapters in this dissertation.

b) *Chapter 2 – Literature Review*

This chapter looks at all the research being conducted in direct or indirect relation to this topic and its various parameters. It looks at the results, findings and conclusions of other researchers and their impact on this study.

c) *Chapter 3 – The Voëlvlei WTP and Berg River*

This chapter provides some background information on the Voëlvlei WTP and the Berg River. It also describes the water treatment process used at the Voëlvlei WTP.

d) *Chapter 4 – Materials and Methods*

This chapter focuses mainly on the experimental procedure and the various laboratory equipment used. It explains the experimental procedures used, the

various analysis undertaken, different chemical preparations and also highlights the various laboratory instrumentation used.

e) *Chapter 5 – Results and Discussions*

This chapter looks at all the results obtained from the various experimental procedures and discusses them in detail. The chemical results obtained from the annual monitoring of the Berg River and Voëlvlei Dam raw waters are also displayed and discussed in this chapter.

f) *Chapter 6 – Cost Evaluation*

This chapter evaluates the cost of the various treatments being investigated. It focuses mainly on the comparative costs between pre-treatment of the Berg River water and direct treatment at the Voëlvlei WTP.

g) *Chapter 7 – Conclusions and Recommendations*

This chapter looks at the various conclusions reached based on all the results obtained during the study. It also provides certain recommendations for the future which are also based on the results and conclusions of this study. In this way it summarises the full research project and brings closure to this dissertation.

h) *Chapter 8 – References*

This chapter gives an overview of the literature referenced during the course of this study.

i) *Chapter 9 – Appendices*

This chapter contains various appendices applicable to this study. Most of the experimental results and monitoring data are presented in various formats in the appendices.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Water shortage is becoming a major problem in South Africa, as dams serving communities with drinking water and water for daily household use, have been less than 30% full in recent years. River water, in combination with groundwater, is considered a suitable alternative as a utilizable and potable water source (Paulse *et al.*, 2007).

Since the demand for fresh potable water - within the Cape Town City Metropole - increases every year, it is important to have water demand strategies in place for future demand. Even though the Voëlvlei Augmentation scheme has been an option for quite a while now, there has been no related work published with reference to the characterization of the Berg River water and the treatment thereof at the Voëlvlei WTP. Some initial research work was performed by the Scientific Services Branch of the City of Cape Town on the Berg River water with possible treatment at the Voëlvlei WTP, but none of this work had been published or documented in any water related literature.

Despite the lack of literature references on the characterization and treatment of the Berg River water for potable use, a substantial amount of literature references were obtained having a direct influence on the various aspects of this study. In this literature review, all these literature references are looked at with special attention being focused on their impact on this study. As a result, this literature review is divided into different headings and sub-headings which deal with the different aspects of this study.

2.2 Water quality of the Berg River

The last twenty years have witnessed a growing awareness of the fragile state of most of the planet's drinking water resources. In order to cope with the growing pollution of our hydrosphere, educational and legislative programmes are being implemented and two main strategies of water treatment are applied:

- Chemical treatment of polluted drinking water, surface water and groundwater and;

- Chemical treatment of wastewaters containing biocidal or non-biodegradable components (Legrini *et al.*, 1993).

Pollutant removal in drinking water may only involve techniques adopted in government regulations, such as coagulation, flocculation, filtration, sterilization and conservation procedures to which have been added chemical treatment techniques involving a limited number of chemicals. Chemical treatment of contaminated surface and ground water containing biocidal or non-biodegradable components is part of a long term strategy to improve the quality of our drinking water resources by eliminating toxic materials of anthropogenic origin before releasing the used waters into the natural cycles. Recent developments in the domain of chemical water treatment have led to an improvement in oxidative degradation procedures for organic compounds dissolved or dispersed in aquatic media, in applying catalytic and photochemical methods (Legrini *et al.*, 1993).

It is critical that the quality of the Berg River water should be monitored as this would have a major impact on its treatment process. Before a treatment strategy for the Berg River water at the Voëlvlei WTP could be devised, it is important to characterize the river water over a period of time as this information should play a critical role in deciding which treatment process should be applied and how it should be applied. Rivers in South Africa are steadily becoming more and more contaminated due, in large part, to urbanization (Paulse *et al.*, 2007).

2.2.1 Metal contamination of the Berg River

When metal concentrations exceed a stipulated limit (South African Bureau of Standards, 2001), they become toxic to the surrounding environment not to mention the impact it would have on treatment processes. Sources of metal contamination include industrial and medical waste, pesticides, petroleum by-products, household products, as well as urban and pharmaceutical waste. Domestic and household sources of metal contamination generally occur as a result of corrosion of metal plumbing fittings, galvanized roofs and wire fences and healthcare products e.g., shampoos, baby

creams, etc. Aluminium coated roofs, saucepans and utensils are also possible sources of contamination (Jackson *et al.*, 2007).

In their study, Jackson *et al.* (2007) concluded that the aluminium and iron were recorded at consistently higher concentrations than all the other metals analysed for in water, sediment and biofilm samples. On average, the results generated for water for aluminium and iron were higher than the quality guidelines recommended by the Department of Water Affairs and Forestry (DWAF), 1996. Jackson *et al.* (2007) also noted that the highest metal concentrations were obtained in the sediment and biofilm samples, yet no freshwater guidelines for metals in sediment and biofilms are available from DWAF.

The research work by Jackson *et al.* (2007) was mainly being performed upstream of the Voëlvlei WTP and it is important to take note of these results as this should probably shed some light on the metal results obtained during the characterization of the Berg River water further downstream as being performed in this study. Once a treatment process has been decided upon for the Berg River water, these metal results should play an important part in the optimization of this process and therefore it is critical that these metal concentrations be constantly monitored further upstream and also at the point of withdrawal. It is important that these metals (e.g., aluminium, iron, zinc, manganese, copper, lead, nickel, etc.) be removed during the treatment process, as the final treated water would have to comply with the metal specifications as laid out by the South African National Standards (SANS) 241 Specification for drinking water. Therefore, not only do these metal concentrations in the Berg River water play an important part in the optimization of the treatment process, but they play an even more important part in the choice of the treatment process itself.

2.2.2 Nutrient status of the Berg River

Eutrophication, excessive plant growth in response to nutrient enrichment, is considered to be one of the most serious problems facing freshwater ecosystems. Under eutrophic conditions, oxygen content in water is one of the factors fluctuating during the day/night cycle (Graca *et al.*, 2002). The major nutrients that contribute to eutrophication are

phosphorus as phosphate ions (PO_4^{3-}), nitrogen as nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) ions. Nutrient levels of many freshwater ecosystems have increased dramatically over the last couple of decades in response to widespread agricultural activity and increased discharge of domestic wastes (De Villiers, 2007). A particular problem facing developing countries like South Africa is the significant increase in urban runoff and increasingly so from overloaded or dysfunctional municipal wastewater treatment plants and un-sewered human settlements (Barnes, 2003; De Villiers, 2007).

De Villiers (2007) concluded that the two most likely anthropogenic sources of nutrients along the Berg River are agricultural runoff and effluent from overloaded municipal sewage works and un-sewered communities. Both sources are expected to peak in magnitude along the middle section of the Berg River, between Paarl and Hermon, the most heavily cultivated and most populated area along the river. This includes informal human settlements that have developed along the banks of the river. Diffuse nutrient sources, such as agricultural runoff, produce seasonal concentration profiles co-incident with river runoff, i.e., concentrations that peak during high runoff conditions. Evidence for increased NO_x levels during low runoff conditions supports an increased point-source scenario. It is also suggested that overloading of wastewater treatment plants during high runoff conditions or flooding of informal human settlements during winter storm events may result in nutrient enrichment during high runoff, related to these point sources.

De Villiers (2007) also concluded that a worst-case future scenario for the nutrient status of the Berg River would be a combination of increasing agricultural loading and point source pollution, and decreased streamflow in response to damming in the upper catchment or increased extraction of the river water. If the downstream flushing effect of runoff originating in the upper catchment is reduced, with respect to the Berg River dam, it can be confidently predicted that nutrient levels in the Berg River will significantly increase above their already unacceptable high levels (De Villiers, 2007).

As a result of this study, it is important to constantly monitor the nutrient levels in the Berg River (upstream and at the extraction point) and also during the treatment process as these nutrient levels in the final treated water would have to comply with the national specifications (SANS 241, 2006).

2.2.3 Bacterial pollution in the Berg River

An increase in urbanization has led to an upsurge in informal settlements in the Western Cape in South Africa where the inhabitants of these settlements experience a distinct lack of resources. Inadequate sanitation behaviour and a lack of adequate sewage disposal facilities may lead to the leaching of potentially harmful substances, from waste, household products, etc., into the environment. The Berg River can be regarded as one of the rivers in the Western Cape that is increasingly being polluted with respect to bacterial contamination. This increased pollution is of great concern, as the Berg River serves as a water source to towns, cities, rural communities, farms and recreational users in the area (River Health Programme, 2004; Jackson *et al.*, 2007).

Raw sewage spills from sewer pump stations in Wellington, overstressed sewer mains in the Paarl area and stormwater effluent from informal settlements in the Paarl and Wellington areas were identified as possible sources of pollution. The microbial counts significantly exceed the stipulated water quality guidelines indicating that these rivers need to be monitored regularly.

In their study, Paulse *et al.* (2007) concluded that, on average, the microbial counts exceeded the maximum limit for river water (South African Bureau of Standards, 1984). The highest overall counts were observed at a site where stormwater drainage pipes from the informal settlement discharge into the river.

In relation to this dissertation, the Berg River water should be constantly monitored (at the extraction point) for microbiological contamination as this would have a major impact on the treatment process and also on the quality of the final treated water.

2.3 Adequate sampling

Accurate and precise quantification of chemical indicators of water quality are essential for supporting effective management and legislation. Owing primarily to logistic and financial constraints, however, national and regional agencies responsible for monitoring surface waters tend to quantify chemical indicators of water quality using a single sample from each waterbody, thus largely ignoring spatial variability. The concentrations

of nutrients and other substances in waterbodies, however, vary considerably in both space and time (Donohue & Irvine, 2008).

In their study, Donohue and Irvine (2008) concluded that both total sample variability and intra-sample variability were shown to vary significantly over time and among determinands. Their results showed that the variability within a single 5 litre water sample can, on occasion, and in spite of considerable effort to homogenize samples and reduce analytical variability, be extremely high. Based on their studies, they recommend that, in situations where it is practicable to take only a single sample with which to assess the status of a waterbody, a minimum of three sub-samples should be analysed from that water sample for robust quantification of both the concentrations of determinands and total sample variability.

Although the information in the study by Donohue and Irvine (2008) is important and should be taken note of, the amount of samples taken in this study, and its frequency, should be adequate for the purposes intended. Weekly samples of the Berg River water and the Voëlvlei WTP raw water were taken over a period of at least 12 months to determine any seasonal fluctuations in the quality of these two raw waters. The amount of data generated would be sufficient to characterize the Berg River water and the Voëlvlei WTP raw water at their respective sampling points (see Chapter 5, sections 5.2 and 5.3).

2.4 Physical and chemical analytical parameters

Process selection for the treatment of water is normally based on an overall assessment of the quality of the raw water. In practice this means that water quality and treatment are evaluated in terms of general quality parameters such as turbidity on the one hand and specific quality parameters on the other hand such as the presence of high levels of iron in the raw water. The turbidity of the raw water determines which clarification processes (coagulation-flocculation, sedimentation, and filtration) should be used, while the presence of specific substances of concern (e.g., iron, manganese, etc.) determines the inclusion of specific processes in the treatment train (Schutte, 2006).

In order to select an appropriate treatment process, it is important to first determine the quality of the river water. Weekly samples should be taken of the river water for a period of at least 12 months and analysed for various chemical and physical parameters, e.g., pH, conductivity, turbidity, alkalinity, colour, chloride, sulphate, various metals, etc. All these results and its seasonal trends should help to determine which chemical water treatment process should be selected. These analyses should also be performed on the treated water (see Chapter 4: Materials and Methods) to see which water treatment process would be the most effective in treating the river water to acceptable drinking standards.

The Berg River water could be considered as having a relatively low alkalinity and hardness and is also slightly acidic with reference to its pH measurement. This type of water is corrosive to metals and aggressive to cement materials. Consequently, stabilization is required prior to distribution. Usually stabilization is effected via lime (to increase alkalinity and calcium concentrations) and CO_2 addition to obtain a slight supersaturation with respect to $CaCO_3$ (Loewenthal & Marais, 1976; Lahav et al., 2001). Dosages to be applied depend on the initial characteristics of the water, i.e., pH, total alkalinity (referred to as 'alkalinity') and calcium concentration. In this regard, alkalinity and pH measurements for these waters pose problems (Lahav et al., 2001). As most laboratories measure alkalinity by titration to a fixed end-point (i.e. colorimetric or pH end-point), Lahav et al. (2001) indicated that this is unsatisfactory because of the difference between the true titration end-point and that used or reflected by the indicator used. An automatic titrator should be used to determine the alkalinity potentiometrically which is considered to be far more accurate than the manual method where colorimetric indicators are used. The problem of pH instability in low alkalinity waters can be partially resolved using glass and reference pH electrodes specifically designed for these waters (Lahav et al., 2001). These electrodes should be used in this study which should result in stable and accurate pH measurements.

2.5 Chemical water treatment

The principal objective of a water treatment plant is to produce water that is fit for domestic use at a reasonable cost. Several treatment processes (sometimes called unit processes and unit operations) are linked together to form a treatment plant in order to produce water of the desired quality. The objective is to remove undesirable constituents from the raw water to produce treated water of the required quality and to process the residuals from the treatment processes in a form that can be safely and easily disposed of or reused (Schutte, 2006).

As far as water treatment is concerned, there are two different types of water, viz., the one containing predominantly suspended particles (visible and/or colloidal) leading to a turbid water, and the other containing dissolved materials which gives the brown colour to water. The brown water of the Western Cape region ranges from the almost colourless Wemmershoek water to the very dark water of Simonstown. In each case, the main object of water treatment is to:

➢ Destabilise this foreign colloidal matter so as to incorporate it in the form of a flocculant. This is known as coagulation or rapid mixing stage.

➢ Allow the flocculant, so formed, to grow in size by stirring slowly so that it may settle out. This is the flocculation stage (Morrison, 2006).

2.5.1 Coagulation

Coagulation still remains the most widely practiced method of removing particulate and organic matter in chemical water treatment (Sinha *et al.*, 2004). Colloidal particles found in water typically have a net negative surface charge. The size of colloids is such that the van der Waals forces of attraction between particles are considerably less than the repelling forces of the electrical charge. Under these stable conditions, Brownian motion keeps the particles in suspension. Brownian movement (i.e., random movement) is brought about by the constant thermal bombardment of the colloidal particles by the relatively small water molecules that surround them. Coagulation is the process of destabilizing colloidal particles so that particle growth can occur as a result of particle collisions (Metcalf & Eddy, 2003; Jiang & Graham, 1998). Various types of metal

coagulants are used in water treatment, with two of the most commonly used conventional coagulants being aluminium sulphate, ferric chloride and ferric sulphate. With the application of conventional and normal coagulation-flocculation technology, aluminium and ferric salts have been popular coagulants selected for the removal of the inorganic and organic contaminants from water and wastewater (Yu *et al.*, 2002; Rebhun & Lurie, 1993).

When aluminium and ferric salts are added to water, Al and Fe (III) ions will hydrolyze rapidly to form a range of metal hydrolysis species, which play an essential role in coagulation and the following flocculation performance (Gao & Yue, 2005). When dosed into alkaline or slightly acid water (as in the case of the Berg River water), these metal salts, viz., aluminium and ferric sulphate, combine with hydroxide ions from the water giving rise to a series of charged ions containing several metal ions before being precipitated as insoluble metal hydroxide, i.e., $Al(OH)_3$ or $Fe(OH)_3$. These multi-charged ions play a large part in destabilising the clay and silica but only occur for a second or two during the mixing process. Consequently, the rate of mixing is an important process parameter. If too slow, floc formation in the dosed water will also be slow as there will be non-destabilised particles present that will not easily be incorporated into the floc. The necessary hydroxide ions should also be present in the water, either added before or after or already present. In this connection the important factor is the final pH. A pH should be chosen that gives a low final Al or Fe content. The effective dosage with its optimum pH should be determined experimentally (see Chapters 4 and 5).

2.5.1.1   Coagulation with aluminium sulphate

Aluminium sulphate, also known as Alum $Al_2(SO_4)_3.16H_2O$, is dissolved in water and the aluminium ions, Al^{3+} that form, have a high capacity to neutralise the negative charges which are carried by the colloidal particles and which contribute to their stability. During flocculation when the water is slowly stirred the aluminium hydroxide flocculant (flocs) enmesh the small colloidal particles. These flocs settle readily and most of them can be removed in a sedimentation tank.

It is important to note that since aluminium may be harmful at high concentrations it must be allowed to precipitate completely as the hydroxide. Complete precipitation is a function of the pH of the water and the pH must therefore be very carefully controlled (Schutte, 2006).

Reaction: $Al_2(SO_4)_3 + 3Ca(HCO_3)_2 \longrightarrow 2Al(OH)_3 + 3CaSO_4 + 6CO_2$
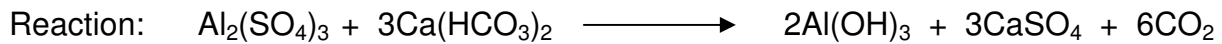
2.5.1.2   Coagulation with ferric sulphate

Ferric Sulphate [$Fe_2(SO_4)_3$] is also commonly used as a coagulant. When added to water, the iron precipitates as ferric hydroxide [$Fe(OH)_3$] and the hydroxide flocs enmesh the colloidal particles in the same way as the aluminium hydroxide flocs do. The optimum pH for precipitation of iron is not as critical as with aluminium and pH values of between 5 and 9 give good precipitation.

Reaction: $Fe_2(SO_4)_3 + 3Ca(HCO_3)_2 \longrightarrow 2Fe(OH)_3 + 3CaSO_4 + 6CO_2$
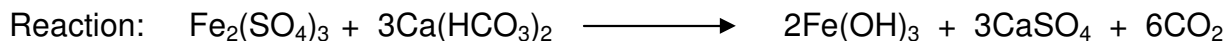
2.5.1.3   Factors affecting coagulation

Coagulation is influenced by the raw water chemical composition, temperature, pH, coagulant type and dose and rapid mix intensity and duration (Rossini *et al.*, 1999).

The impact of temperature on coagulation has previously been attributed to either a viscosity change and/or a change in the rate of Fe hydrolysis (Hurst *et al.*, 2004). Hurst *et al.* (2004) observed that for the same coagulant dose, cold temperature conditions (viz., 5 ^{o}C) produced smaller flocs than at warmer temperature conditions (viz., 20 ^{o}C). Hurst *et al.* (2004) also concluded that for effective and robust performance during rainstorm events it is important to control coagulant dose and pH on both raw water turbidity and the nature and concentration of the natural organic matter (NOM).

The coagulant dose and the pH control are probably two of the most important parameters affecting the coagulation process. The determination of the optimum dose of coagulant is based on the Ultraviolet (UV) absorbance of the raw and treated waters at 254 nm and/or 300 nm (see Chapters 4 and 5). The Voëlvlei WTP raw water (obtained

from the adjacent Voëlvlei Dam) is composed mainly of turbidity and the water treatment process at the Voëlvlei WTP was therefore optimised to remove turbidity by coagulation in order to obtain potable water which complies with the South African National Standard (SANS) 241:2006 Specification for turbidity (SANS 241, 2006). The Voëlvlei WTP operates at an optimum coagulation pH of 9 to remove turbidity and some colour from its raw water using ferric sulphate as the coagulant. This optimum dose and pH were determined using the Jar test apparatus (see Chapter 4: Materials and Methods).

2.5.2 Flocculation

Flocculation follows coagulation and is often regarded as part of one process, viz., coagulation–flocculation. The objective of flocculation is to cause the individual destabilised colloidal particles to collide with one another and with the precipitate formed by the coagulant in order to form aggregates that could easily be removed by means of sedimentation or flotation. Flocculation involves the stirring of water at a slow rate to which a coagulant has been added, causing the individual particles to collide. Flocculation is considered to be part of coagulation, although some handbooks treat it as a separate process. Flocculation can take place in different types of equipment. A simple mechanical stirrer can be used for flocculation or a specially designed channel with baffles to create the desired flow conditions can also be used to flocculate the particles in water. The basis of the design of a flocculation channel is that the flow velocity of the water has to be reduced from a high initial value to a much lower value to enable large, strong aggregates to form. If the flow velocity is too high the aggregates may break up again, causing settling of the broken flocs to be incomplete. Flocculation is controlled through the introduction of energy into the water (through paddles or by means of baffles in the flocculation channel) to produce the right conditions (required velocity gradient) for flocs to grow to the optimum size and strength. The velocity gradient (or G-value) is an extremely important factor that determines the probability of particles to collide and form flocs. If G values are too low, the probability of collisions is low and poor floc formation results. If too high, shear forces become large and this may result in break-up of aggregates. Aggregates and flocs are removed from water by

means of separation processes, i.e., sedimentation and sand filtration; or flotation and sand filtration (Schutte, 2006).

2.5.2.1 Floc structural characteristics

The aggregation of fine particles and colloids into larger particles is a well-established means of removing turbidity, colour and other organic and inorganic pollutants at water treatment plants (Jarvis *et al.*, 2006). These larger aggregates, known as flocs, may be defined as highly porous, irregularly shaped and loosely connected aggregates composed of smaller primary particles. The size and structure of flocs are considered fundamental to the operation of water treatment processes. Measuring floc physical characteristics can be achieved by using a number of different techniques such as microscopy, laser diffraction techniques, Coulter counters and settling rates. Floc strength, breakage and re-growth have been examined using a range of macroscopic and microscopic techniques (Jarvis *et al.*, 2006).

The addition of flocculants (e.g. polymer compounds) results in a change in the structural characteristics of the floc (e.g. floc shape, size, porosity, density, water content and composition), leading to a desired increase in settling rate and floc stability (Droppo *et al.*, 2008). Such structural changes will also influence the chemical and biological behaviour of the flocs. In general, coagulants produce flocs through the destabilization of particulates with a negative charge, whereas flocculants encourage floc growth by creating polymer bridges between particles/colloids, although the distinction between the two can be complicated as multiple mechanisms of floc formation may occur (Droppo *et al.*, 2008). Floc strength is a particularly important operational parameter in solid/liquid separation techniques for the efficient removal of aggregated particles. Unit processes at water treatment plants are generally designed to minimize floc breakage, however, in reality, often this is not the case, with regions of high shear being prevalent. Flocs must resist many stresses that they encounter if they are to prevent being broken into smaller particles. Floc strength is dependent upon the inter-particle bonds between the components of the aggregate. This includes the strength and number of individual bonds within the floc. Therefore, a floc will break if the

stress applied at its surface is larger than the bonding strength within the floc. Increased floc compaction is considered to increase floc strength due to an increase in the number of the bonds holding the aggregate together (Jarvis *et al.*, 2005). The size and shape of floc micro-particles are also important considerations for floc strength (Leentvaar & Rebhun, 1983).

2.5.2.2   Temperature effects on flocculation

Flocculation and coagulation are known to be affected by water temperature. Temperature affects the water viscosity and the chemistry and rate of the coagulation and flocculation processes. Hanson and Cleasby (1990) have reported that at lower temperatures flocculation is slower and flocs are smaller than at higher temperatures. They also reported that alum flocs at low temperatures were very vulnerable to break up due to fluid shear and that even the weakest ferric floc was stronger than the strongest alum floc. This has implications for both flocculation and filtration. Alum is generally seen to be less effective at low temperatures, which has been attributed to lower density flocs and aggregate size. Conventional jar tests are useful for examining floc formation and settling rates but they do not quantify strength and the re-attachment ability of the flocs (Fitzpatrick *et al.*, 2004). The following conclusions were reached by Fitzpatrick *et al.* (2004):

> ➢ Water temperature affects flocculation, by affecting floc size, strength and ability to re-form after shear break-up. This will affect the clarification and filtration processes, coupled with the effects of viscosity changes due to temperature.
> ➢ Warmer temperatures generally produce bigger flocs that break more easily and re-form less well than at lower temperatures.
> ➢ Aluminium based coagulants produce flocs that vary more with temperature, in size and strength, than ferric sulphate flocs.

The Berg River water temperature, in the region of the Voëlvlei WTP, can vary from approximately 10 ^{o}C in the winter to approximately 20 to 25 ^{o}C in the summer and therefore careful note should be taken of the temperature effects on coagulation and

flocculation when choosing an appropriate treatment strategy of this water (Fitzpatrick *et al.*, 2004).

2.5.2.3 Stirring/Mixing effects on flocculation

Mixing is an important operation in any water treatment process. It facilitates dispersion and homogenisation of added reagents with water and contacts between the particles leading to their combining into readily separable flocs. The efficiency of the water treatment process is, therefore, dependent on the mixing conditions under which the formation of flocculent suspension take place (Polasek, 2007).

Once destabilisation has occurred, floc formation has commenced. It may be speeded up by stirring. Rapid stirring is usually employed at first, followed by a more gentle approach. The overall process is termed tapered flocculation. Approximately 10 to 30 minutes are required for the floc to develop to its full extent.

The normal measure of the intensity of stirring is known as the G value which depicts the velocity gradient. G is not measured directly but is calculated, either using a factor taken from a table or from the formula:

$$G = [P / (\Phi.V)]^{1/2}$$

where

G = velocity gradient, s^{-1}

P = power dissipated, $kg\ m^2\ s^{-3}$

Φ = viscosity of the water, $kg\ m^{-1}\ s^{-1}$

V = volume of reactor, m^3

The effect of G on the time to give a constant turbidity can be directly measured. At high G values (100 or more) the turbidity falls rapidly but the resultant constant turbidity is generally high, while at G values of 20 or 30 it takes longer to get there but the constant turbidity is much lower. Between these limits there is space for more in-between values of G, either stepwise or gradual, giving tapered flocculation starting with high G and ending with low G (Morrison, 2006).

In waterworks design practice, the processes of the reagent dispersion and homogenisation with water and the floc formation take place in two separate chambers under the conditions of rapid and slow mixing.

➢ Rapid mixing is intended for dispersion and homogenisation of added reagent with water. It takes place with a G value of 80 to 100 over a period of 10 to 60 seconds.

➢ Slow mixing is intended for the formation of a flocculent suspension. It takes place with a G value of 20 to 60 over a period of 15 to 30 minutes and even longer.

It follows from the above that the difference between these two mixing conditions is only in the mixing intensity characterised by the velocity gradient (Polasek, 2007).

2.5.2.4   New flocculation technologies.

Several methods are presently used to remove humic acids from natural waters, viz., adsorption on coal and clays, ozonation, membrane filtration and flocculation with synthetic polymers or iron and aluminium salts (Bratskaya *et al.*, 2004). In general, the most popular method of coagulation/flocculation provides colour removal up to 90%, and its effectiveness could be increased up to 95% when mixtures of inorganic coagulants and synthetic polymers are used. Increasing demand for environmentally friendly technologies promotes the interest to natural polyelectrolytes which can replace synthetic flocculants in such fields as water treatment, food and beverage industry, biotechnology and medicine (Bratskaya *et al.*, 2004). Since most of the natural colloids are negatively charged, cationic polyelectrolytes are of particular interest for application as flocculants. The most promising cationic biopolymer for extensive application in this regard is chitosan. Chitosan is well known as a complexing agent for many metal ions, phenolic compounds and natural and synthetic polyanions (Bratskaya *et al.*, 2004).

An electro-coagulation-flotation process has been developed for water treatment (Jiang *et al.*, 2002). In this process, aluminium or iron electrodes are dissolved by electrolysis, forming a range of coagulant species and metal hydroxides, which destabilise and

aggregate the suspended particles or precipitates and adsorb dissolved contaminants (e.g., dissolved organic matter). Metal anode dissolution is accompanied by hydrogen gas evolution at cathodes, the bubbles capturing and floating the suspended solids formed and thus removing contaminants. The water treatment performance of the electro-coagulation-flotation process was found to be superior to that of conventional coagulation and flocculation with aluminium sulphate for treating a model-coloured water, with 20% more dissolved organic carbon (DOC) being removed for the same alum dose. However, for a lowland surface water sample, the two processes achieved a similar performance for DOC and UV absorbance removal (Jiang *et al.*, 2002).

A comparison was made between two technologies viz. electro-flocculation and chemical flocculation, which may be used as a possible pre-treatment step in wastewater treatment (Ofir *et al.*, 2007). Electro-flocculation, a fairly new environmentally friendly process, has been developed with the aim of reducing, or even avoiding altogether, the amount of chemicals required during the pre-treatment process. Zeta potential can be used as an indicator for choosing which process, viz., electro-flocculation or chemical flocculation, should be used and the conditions for running the process (Ofir *et al.*, 2007).

Ballasted flocculation is a new technology that is applied successfully in the water treatment industry, but the concept has not yet been subject to extended experimental studies (Desjardins *et al.*, 2002). This process, trade named ACTIFLO®, was introduced in the 1990s. The weight of the flocs is increased by causing the attachment of grains of high-density micro-sand. The quality of water produced by this process is equal to or better than that of the current conventional treatment and requires less space. Ballasted flocculation is a dynamic physical process which ensures high stability of the quality of settled water undergoing reasonable changes in operational parameters. This is likely due to the use of micro-sand which satisfactorily eliminates the micro-flocs that are most often responsible for degradation in the quality of settled water in conventional clarifiers (Desjardins *et al.*, 2002).

2.5.3 Sedimentation

Sedimentation is the process in which the aggregates that have been formed during coagulation and flocculation are allowed to settle from the water. The flocs collect as sludge at the bottom of the sedimentation tank from where it must be removed on a regular basis. The flocs settle to the bottom of the tank and the clean water leaves the sedimentation tank through collection troughs located at the top of the tank. Generally, the ability of sedimentation tanks to clarify water by letting suspended solids settle down as flocculated particles depends on two aspects (Goula *et al.*, 2008):

➢ The water flow pattern through the tank, which in turn is determined by the configuration of the tank and by operational parameters (e.g., solids concentration, water flow rate and temperature), and

➢ The settling characteristics of the particles as determined by their shape, size and interaction with the water through drag and buoyancy forces (Goula *et al.*, 2008).

Goula *et al.* (2008) researched the effect of influent temperature variations in a sedimentation tank for potable water treatment. Their results indicated that a rise in influent temperature leads to a decrease in the percent removal efficiency for particles of 250 µm from 99.5% to 76.0%, thereby confirming that there is a relationship between the slope of the influent temperature with time and the sedimentation efficiency.

There are a variety of designs available for sedimentation tanks. These include large rectangular tanks in which the water enters at one end and leaves at the other end. This type is normally used at large conventional treatment works. Circular tanks with flat or cone shaped bottoms are also used, especially at smaller works. The design and flow conditions in a sedimentation tank must be such that the minimum amount of floc leaves with the clarified water (Schutte, 2006).

2.6 Jar test procedure

Jar testing is an important tool for the determination of the best chemical dosing regime and operational parameters for a water treatment process. A consistent methodology has been developed for physical-chemical processes such as coagulation, flocculation

and sedimentation (Clark & Stephenson, 1999). The effectiveness of chemical treatment is dependent upon the type of water or wastewater, for example, its strength and specific constituents and type of chemical added (Metcalf & Eddy, 2003). The most suitable chemical for the purpose is often difficult to determine by methods other than trial and error. Jar testing, however, may be an important tool for the determination of the best chemical treatment for a particular works (Szpak *et al.*, 1996).

Jar tests have long been used in water, wastewater and effluent treatment to show the effectiveness of chemical coagulation, flocculation and sedimentation. In addition, they provide guidance on the optimum pH and coagulation/precipitation dose required for treatment (Krasner & Amy, 1995). There are many variables affecting the performance of a chemical during jar tests. Recent research has identified pH, speed of flash mixing, time duration of flash mixing and chemical quantity added as important factors. These factors need to be optimized and standardized before a true chemical comparison can be made (Clark & Stephenson, 1999; Szpak *et al.*, 1996).

2.7 MIEX[®] resin technology

Production of potable water from natural surface waters requires the use of technologies that are likely to provide high removal rates of both bulk natural organic matter (NOM) and trace organic contaminants (Humbert *et al.*, 2008). MIEX[®] resin is a revolutionary product used for the removal of dissolved organic carbon (DOC) and improving potable water quality. This product is ideally suited to treat the highly coloured Cape waters of South Africa and is currently operating at full scale on various plants in Australia, USA and Europe and being tested in other regions of the world. The MIEX[®] resin is a patented high capacity ion exchange resin which includes a magnetized component. This resin is utilized in a continuous ion exchange process designed for the removal of DOC from drinking water supplies and is regenerated with a brine (NaCl) solution where attached organics are substituted for chloride ions, producing a concentrated stream of natural organics (Murray *et al.*, 2005; Sani *et al.*, 2008; Kabsch-Korbutowicz *et al.*, 2008; Drikas *et al.*, 2009).

The combination of MIEX$^®$ plus low ferric dose is an effective solution for the treatment of variable and high organic strength waters. This combination reduces the ferric usage and consequently the sludge produced is also significantly reduced meaning disposal costs are minimized (Fearing *et al.*, 2004). Murray *et al.* (2005) confirmed this in their conclusion that using the MIEX$^®$ resin process, also as a pre-treatment step to conventional water treatment, will improve the quality of the final water whilst significantly reducing conventional chemical consumption and operating costs.

CHAPTER 3

THE VOËLVLEI WTP AND BERG RIVER

3.1 The Voëlvlei water treatment plant

The City of Cape Town treats in excess of 300 000 Megalitres of water to national potable standards each year. It has 10 water treatment plants with a total treatment capacity of 1 650 Megalitres per day (Flower, 2004). The Voëlvlei water treatment plant is one of these plants, and was officially opened on Wednesday, 19 January 1972 by the then Minister of Water Affairs, S. P. Botha. It lies in a natural depression some 64 m above sea level draining into a catchment of about 310 ha. It is situated in the Western Cape about 110 km away from Cape Town. This WTP treats on average about 140-180 ML per day and gets its raw water from the Voëlvlei dam which is situated next to the plant. This dam is nearly 15.3 m high and has a length of 161 m. The Voëlvlei water treatment plant supplies water to the City of Cape Town and surrounding areas. This plant was designed to use ferric sulphate and poly Hi-T flocculants for the purification process of its raw water. The dosage always depends on the variability of raw water. The following unit water treatment processes are used:

➢ Coagulation – The chemical dosing section of the WTP is capable of supplying up to 50 mg/L of ferric sulphate, 50 mg/L of lime slurry and 8 mg/L of chlorine. The raw water is delivered to the flash mixing chamber, dosed with chemicals to pH value of 9.0 to form a ferric hydroxide floc and is then led directly to the inlet manifold and distribution pipe system of four vertical upflow settlement tanks or clarifiers.

➢ Flocculation and sedimentation – Each of the four square clarifiers measures 41 m in length and 5.5 m in height. The treated water enters a flocculation zone near the base of the V-troughs which is situated on the floor of the clarifier, and the floc is carried up with the water flow. The flocculated layer is called the "floc blanket" and under ideal conditions its top surface can be seen through the clear layer of

water above it. The denser floc in the blanket tends to settle to the bottom of the V-troughs and is drawn off periodically through the sludge collector pipe system.

➢ Filtration – The WTP has 24 rapid gravity sand filters, each with an area of 59 m². The filter floor is provided with polystyrene filter nozzles spaced at 150 mm centres to ensure uniform flow of water through the filter medium which consists of a bed of sand one metre in depth with an average grain size of 0.85 mm. Each filter has a rated capacity of 11.5 ML/day. The filters are normally backwashed once a day to remove the accumulated turbid matter which has been retained in the filter bed during its period of operation.

➢ Chlorination and stabilization – The water is chlorinated before the filters as a protection measure, and also after the filters before leaving the WTP to maintain a final residual chlorine concentration of approximately 0.6 to 0.8 mg/L (disinfection). No final lime and carbon dioxide are added after the filters and as a result, the treated water is only partially stabilized. The treated water leaves the WTP with a pH of 9.2 and a total alkalinity of approximately 15 to 20 mg/L as $CaCO_3$.

➢ Treated water pumping plant – Six variable speed centrifugal pumps located in the pump house adjacent to the treated water reservoir can deliver 273 ML/day through a 1.5 m diameter pipeline 84 km in length into the Tygerberg and Plattekloof reservoirs. In addition, pumps are provided for backwashing the filters and for supplying water for use in the plant. Four surge suppression vessels 9 m in height and 3.5 m in diameter have been installed adjacent to the pump house to protect the pipeline against "water hammer". The pressure and volume of air in these air vessels are automatically controlled.

A flow diagram of the water treatment process at the Voëlvlei WTP is shown in Figure 1(b).
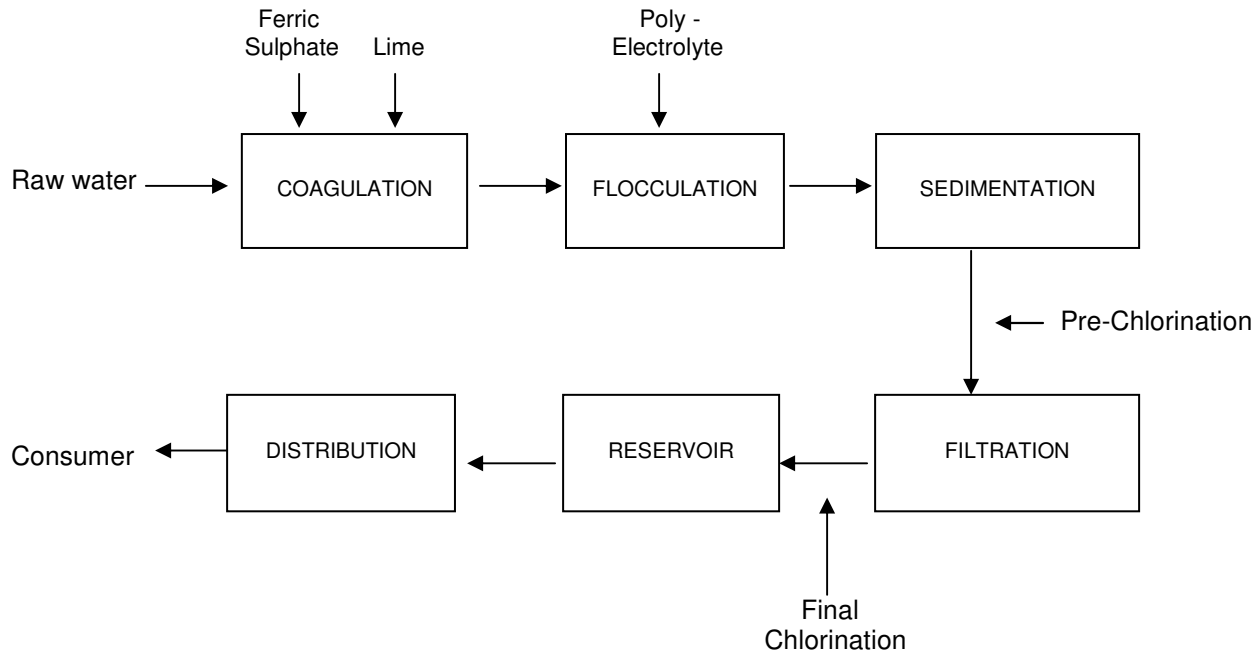
Figure 1(b)   Diagram of the chemical water treatment process at the Voëlvlei WTP.

3.2   The Berg River

The Berg River rises in the Franschhoek and Drakenstein mountains at an altitude of approximately 1 500 m. It flows northwards past Paarl, Wellington, Hermon and Gouda, where it is joined by the Klein Berg and Vier-en-Twintig rivers. The river then flows westwards past Porterville, Piketberg and Velddrif where it finally discharges into St. Helena Bay on the west coast. The Berg River drains an area of approximately 8 980 km^2 and has a total length of about 285 km. It has nine major and seven minor tributaries, six of which were naturally perennial, namely the Franschhoek, Wemmershoek, Dwars, Klein Berg, Vier-en-Twintig and Matjies rivers.

Habitat integrity and water quality in the Berg River deteriorate downstream as a result of alien vegetation encroachment, the interbasin transfer of water and river modification. Urban and agricultural development affects the water quality at Franschhoek (municipal and wine farm effluent). River health is reduced in the tributaries as a result of alien

vegetation infestation and agricultural development (river modification, water abstraction, and runoff). Water quality and habitat integrity in the Berg River and lower reaches of these tributaries are reduced due to urban development (River Health Programme, 2004).

Cultivation of grapes and deciduous fruit is the backbone of the economy in the Berg River catchment. North of Wellington, dry land grain farming and sheep farming predominate. Commercial pine forests occur near the headwaters around Franschhoek. The major industries in the Berg River basin are agriculturally based and include wineries, canneries and other food processing factories. Only the upper catchment of the Vier-en-Twintig River remains in an essentially natural state (River Health Programme, 2004).

The Berg River is an important contributor to the economic and social well-being of the greater Cape Town area. It provides water to towns, cities, rural communities, farmers and recreational users in the area. A large percentage of the country's wheat and wine farming occurs here and contributes towards the economy of the country. Tourism is a growing industry in the Western Cape, relying heavily on the goods and services that the Berg and other rivers provide (River Health Programme, 2004).

CHAPTER 4

MATERIALS AND METHODS

4.1 Introduction

Two of the specific objectives of this research project were to determine if the Berg River water could be treated at the Voëlvlei WTP using the current treatment regime, as well as various mixtures of the Voëlvlei WTP raw water and the Berg River water. One of the most important experimental procedures to be used in reaching these objectives is the Jar test procedure and its results should give a clear indication as to which treatment would be the most suitable. Even though many laboratory analyses were performed on the various raw, intermediate and treated water samples to characterise its physical and chemical composition, the experimental procedure focused mainly on the Jar test which could simulate the initial water treatment process at the Voëlvlei WTP. Since the Voëlvlei WTP uses ferric sulphate as a coagulant and lime for pH control, the laboratory scale Jar test treatment procedure on the Berg River and Voëlvlei WTP raw waters (and their blends) was limited mainly to the use of ferric sulphate as a coagulant and lime for pH control. Some Jar tests were conducted on the Berg River water using aluminium sulphate as a coagulant and these results could give guidance towards an alternative treatment or even pre-treatment strategy of this water. In this study, the Jar test procedure is considered the most important tool (Szpak *et al.*, 1996) used for the determination of the best treatment strategy for the Berg River water at the Voëlvlei WTP.

4.2 Research design

In order to determine the best treatment strategy for the Berg River water at the Voëlvlei WTP, it was important to sample the Berg River at regular intervals over a period of at least a year to determine its quality and the impact of seasonal changes. In the beginning of this study, the Jar test procedure was conducted on the Berg River water using first aluminium sulphate and then ferric sulphate as the coagulant in order to

determine the best treatment strategy in relation to these two coagulants and also the water treatment process used at the Voëlvlei WTP. Subsequent to this, samples were also taken of the Voëlvlei WTP raw water in conjunction with the Berg River water samples and 3 blends, viz., 75:25, 50:50 and 25:75 (Berg River water : Voëlvlei WTP raw water) were prepared for similar Jar test analyses. If the Berg River water could not be treated at the Voëlvlei WTP using the current treatment regime, then various treatment possibilities should be looked at with specific reference to the blending of the two raw waters at the treatment plant. The Jar test results of the various blends, performed over a period of a year, would provide valuable information on the possible treatment or even pre-treatment of the Berg River water at the Voëlvlei WTP. Once all the Jar test analyses have been conducted on the individual raw waters and their blends, the results should conclude which treatment strategy would be the most suitable under the present circumstances.

4.3 Experimental procedure

Various topics are discussed in this section with specific reference to the sampling frequency, Jar tests on the two raw waters and their various blends, the different chemical and physical analyses and also how these analyses were performed.

4.3.1 Sampling

Sampling of the Berg River water and the Voëlvlei WTP raw water commenced in October 2008 and ended in September 2010. Samples of the Berg River were taken at Sonquasdrift which is in close proximity to the Voëlvlei WTP, while samples of the Voëlvlei WTP raw water were taken at the raw water inlet tap situated at the plant. The blending of these two raw waters for Jar test analysis started in January 2010 and ended in September 2010.

The two raw waters were sampled once a week during 2008 and 2009. Jar tests were conducted on the Berg River water during each quarter of 2009. The Jar tests were also conducted on the raw water blends during 2010 with a frequency of at least once a month.

4.3.2 Jar tests

Jar tests were initially only conducted on the Berg River water using aluminium and ferric sulphate as coagulants. These Jar tests were conducted in October 2008 and then in 2009 during the months of February, April, July and October. Jar tests were then conducted on various blends (viz., 75:25, 50:50 and 25:75) of the Berg River water and the Voëlvlei WTP raw water. These Jar tests were conducted at least once a month from January to September 2010. The Jar test procedure was aimed at simulating the initial stages of the water treatment process (viz. coagulation, flocculation and sedimentation) at the Voëlvlei WTP.

4.3.2.1 Reagents

The following reagents, which were used in the Jar test analysis, were supplied by the Bulk Water Branch (Water and Sanitation Department) of the City of Cape Town.

- ➤ Ferric sulphate – containing 134 g/L as Fe^{3+}
- ➤ Aluminium sulphate – containing 7.2% m/m as Al_2O_3
- ➤ Calcium hydrated lime – containing at least 69% m/m Available CaO

4.3.2.2 Preparation of reagents

The reagents were prepared as follows:

- ➤ Ferric sulphate – A 5 000 mg/L Fe^{3+} stock solution was prepared from the ferric sulphate solution containing 134 g/L as Fe^{3+}. This stock solution was further diluted with de-ionized water to form a 500 mg/L Fe^{3+} dosage solution. Adding 1 mL of this dosage solution to 500 mL sample of water represents a ferric sulphate dosage of 1 mg/L as Fe^{3+}.
- ➤ Aluminium sulphate – A 5 000 mg/L Al^{3+} stock solution was prepared from the aluminium sulphate solution containing 7.2% m/m as Al_2O_3. This stock solution was further diluted with de-ionized water to form a 500 mg/L Al^{3+} dosage solution. Adding 1 mL of this dosage solution to 500 mL sample of water represents an aluminium sulphate dosage of 1 mg/L as Al^{3+}.

> Calcium hydrated lime – A saturated lime solution (5 to 10 g/L) was prepared using distilled water. This solution was prepared at least a day before use to allow for settling of any undissolved lime particles. The supernatant lime solution was then filtered through a 0.45 μm filter immediately before use to prevent any undissolved lime particles from taking part in the reaction which could increase the pH with time.

Note! Approximately 10 mL of concentrated HNO_3 was added to the ferric sulphate stock and dosage solutions to convert all Fe^{2+}, formed upon dilution, to Fe^{3+}.

4.3.2.3 Jar test procedure

The Jar test apparatus is shown in Figure 2 (see page 34). The PB-700™ series six-paddle standard Jar tester consists of six stainless steel paddles which are spaced 15 cm apart and are adjustable to a maximum depth of 22.5 cm. An electronic motor control system offers regulated variable speeds of all paddles simultaneously, from 1 to 300 rpm, with the exact speed clearly displayed on a digital readout. A fluorescent lamp floc illuminator is built into the jar tester base to provide soft, diffused lighting of samples being tested.

The following Jar test procedure was based on the actual operations at the Voëlvlei WTP and was standardized for all analyses on the Berg River water, the Voëlvlei WTP raw water and their blends.

(a) The optimum dosage was determined as follows:

> 6 × 500 mL of sample was poured into 6 × 1L beakers and the initial pH of each sample was determined,
> Various dosages of ferric or aluminium sulphate were then added to each of the 500 mL samples (1 dose per sample) after which the pH was again determined,
> Saturated lime solution was then added to obtain the desired coagulation pH specific to ferric and aluminium sulphate (the volume of lime solution was recorded),

- Each solution was then flash mixed at 300 rpm for 2 minutes followed by 30 minutes of slow mixing at 30 rpm,

- Each solution was then allowed to settle for 30 minutes,

- The supernatant was then carefully siphoned off for further physical (e.g., turbidity) and chemical (e.g., UV absorbance, iron, aluminium, manganese, etc.) laboratory analyses.

(b)   The optimum pH was determined as follows:

- 6×500 mL of sample was poured into 6×1L beakers and the initial pH of each sample was determined,

- A specific dosage of ferric or aluminium sulphate [as determined in (a) above] was then added to each of the 500 mL samples after which the pH was again determined,

- Saturated lime solution was then added to obtain different pH values ranging from 4 to 10 (the volume of lime solution was recorded),

- Each solution was then flash mixed at 300 rpm for 2 minutes followed by 30 minutes of slow mixing at 30 rpm,

- Each solution was then allowed to settle for 30 minutes,

- The supernatant was then carefully siphoned off for further physical and chemical laboratory analyses.

Figure 2   The Phipps & Bird PB-700™ Jar test apparatus.

4.3.3 Physical and chemical analyses

All samples were analysed for the following physical and chemical parameters and experimental methods were followed according to standard methods (Standard Methods, 1992) with some modifications.

➢ **pH**

All pH measurements were made using a WTW pH330i pH meter with separate Orion glass and reference electrodes. The pH meter was calibrated each time before use with external certified pH buffer standards.

➢ **Turbidity**

Turbidity measurements were performed on the HACH 2100N turbidimeter. Even though this instrument was checked daily with quality control standards, it was also calibrated at least every three months (or as required) with certified standards.

Alkalinity

The alkalinity was determined via titration of the sample with 0.02M hydrochloric acid using phenolphthalein indicator for the carbonate alkalinity and mixed indicator for the total alkalinity. The titrations were performed manually using a BRAND digital burette. The mixed indicator was prepared by dissolving 0.20 g of methyl red and 1.00 g of bromocresol green in 1 litre of white methylated spirits

UV absorbance

The UV absorbance measurements were performed on a Varian CARY 50 UV/VIS spectrophotometer. The UV absorbance of the samples was measured at 254 and 300 nm in a 40 mm quartz cuvette. This measurement is directly proportional to the organic content (humic acid concentration) of the water.

Colour

The colour of the samples was measured with an Aquakem 250 'Discreet' photometric analyser. This is a photometric determination displaying the results as mg/L Pt. This instrument was calibrated before use.

Sulphate

The sulphate was also determined with the Aquakem 250 'Discreet' photometric analyser. This is also a photometric determination displaying the results as mg/L SO_4^{2-}.

Iron

The iron content of the samples was measured with a Perkin-Elmer Optima 5300 DV inductively coupled plasma optical emission spectrophotometer (ICP-OES). This instrument was also calibrated before use.

> **Aluminium**

The aluminium content of the samples was measured with a Perkin-Elmer Optima 5300 DV inductively coupled plasma optical emission spectrophotometer (ICP-OES).

> **Calcium**

The calcium content of the samples was measured with a Perkin-Elmer Optima 5300 DV inductively coupled plasma optical emission spectrophotometer (ICP-OES).

Note! Various other physical analyses (e.g., conductivity) and chemical analyses (e.g., chloride, potassium, magnesium, etc.) were also performed on the Berg River water and on the Voëlvlei WTP raw water for characterization. These results are shown in Appendices A and C and are discussed in Chapter 5: Results and Discussions.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Introduction

Various raw water samples and combination of samples were analysed using the Jar test procedure and other analytical techniques and the results are presented in this chapter. This chapter is divided under the following sub-headings:

- ➢ Characterization of the Voëlvlei WTP raw water
- ➢ Characterization of the Berg River water
- ➢ Optimum coagulant dose for the Voëlvlei WTP raw water
- ➢ Optimum coagulant pH for the Voëlvlei WTP raw water
- ➢ Optimum coagulant dose for the Berg River water
- ➢ Optimum coagulant pH for the Berg River water
- ➢ Jar test results for Blend 1 (75% Berg River : 25% Voëlvlei WTP raw)
- ➢ Jar test results for Blend 2 (50% Berg River : 50% Voëlvlei WTP raw)
- ➢ Jar test results for Blend 3 (25% Berg River : 75% Voëlvlei WTP raw)

5.2 Characterization of the Voëlvlei WTP raw water.

It is important to know the quality of the raw water before deciding on a treatment option. The aluminium, iron, pH, turbidity, UV absorbance and colour of the Voëlvlei WTP raw water over a period of time are shown in this section.
The detailed results are shown in Appendix A (Tables A1 to A6).

5.2.1 Aluminium and iron concentration of the Voëlvlei WTP raw water as a function of time.

The aluminium and iron concentration of the Voëlvlei WTP raw water as a function of time are shown in Figure 3. The detailed results are shown in Appendix B (Table B1).
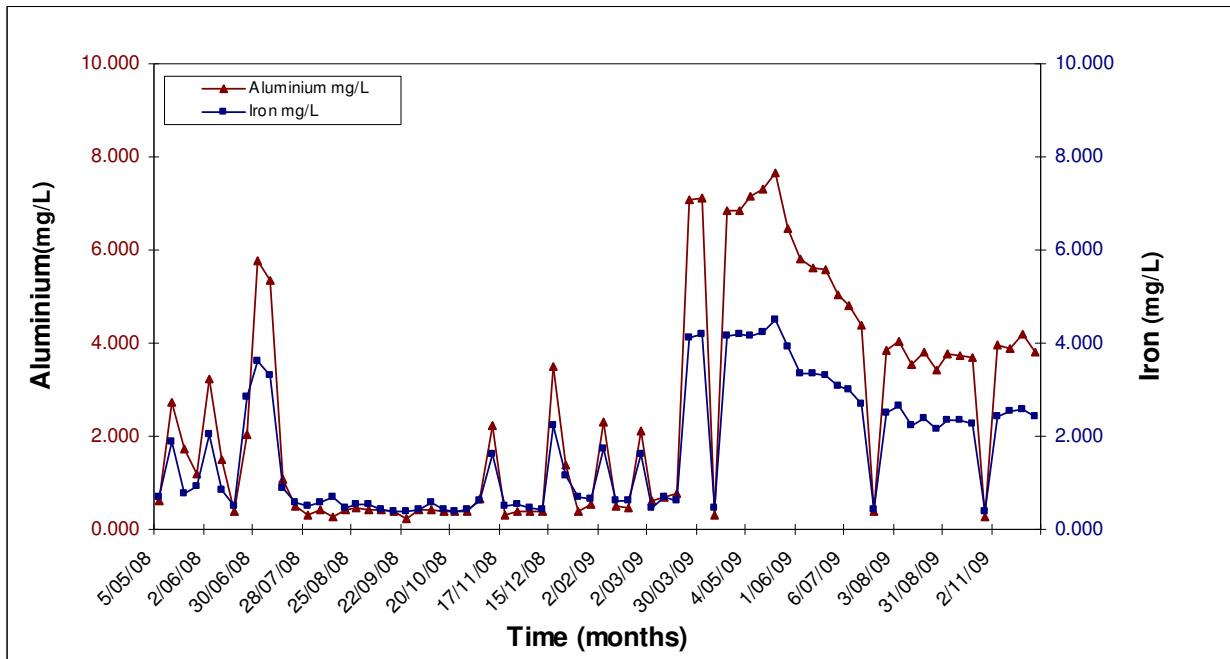
Figure 3   Aluminium and iron concentration of the Voëlvlei WTP raw water as a function of time (May 2008 to December 2009)

The graph in Figure 3 shows a similar profile for both metals during the monitoring period. The aluminium and iron concentrations are consistently low (<1 mg/L) during the summer months with the exception of some sporadic peaks. The graph also clearly indicates an increase in these metal concentrations during the winter months with the aluminium and iron concentrations reaching a maximum of approximately 7.6 and 4.5 mg/L, respectively. It is possible that these high concentrations could be due to the stirring of the river bed as a result of heavy rainfall and strong winds during the winter months and this action could cause the suspension of settled metal deposits in the river. These high aluminium and iron concentrations must be removed from the water during the initial stages of the water treatment process.

5.2.2 pH and turbidity of the Voëlvlei WTP raw water as a function of time.

The pH and turbidity of the Voëlvlei WTP raw water as a function of time are shown in Figure 4. The detailed results are shown in Appendix B (Table B2).
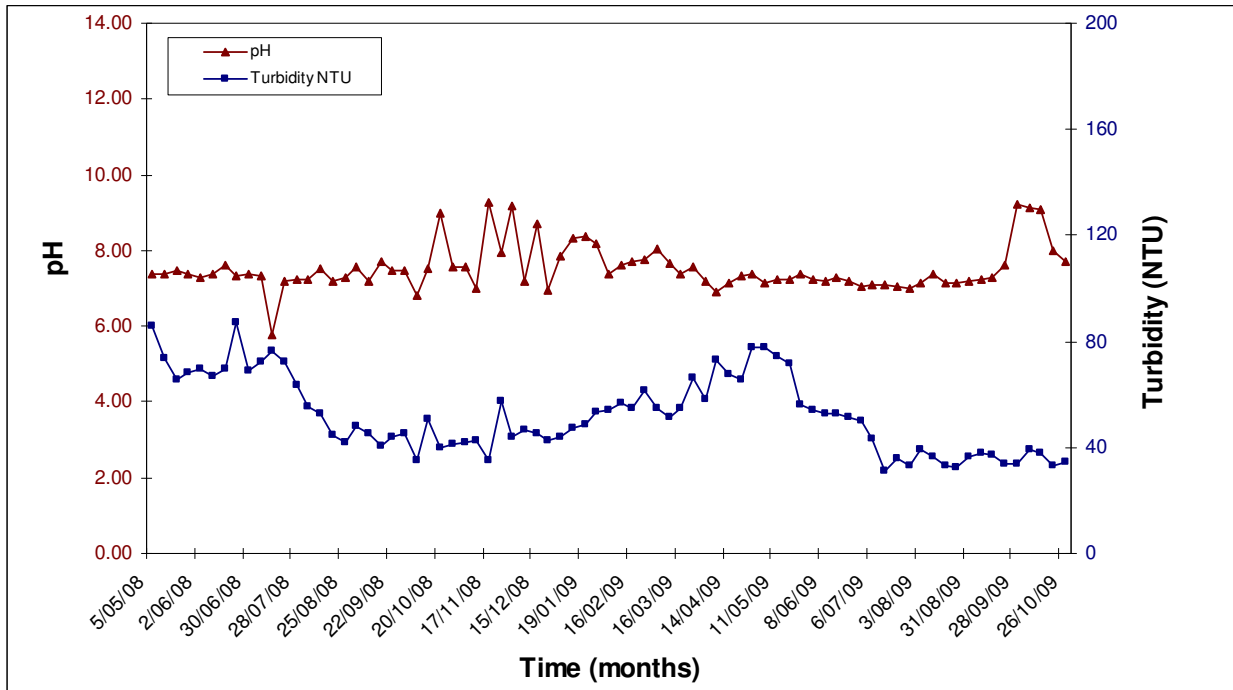
Figure 4   pH and turbidity of the Voëlvlei WTP raw water as a function of time
(May 2008 to December 2009)

The pH of the Voëlvlei WTP raw water remained consistent between 6.8 and 7.8 during the monitoring period with maximum peaks (pH ± 9.0) during the summer months. The pH of the raw water should be constantly monitored as this would have an impact on the coagulation pH of the water treatment process. The Voëlvlei WTP raw water has higher turbidity than other WTP raw waters in the CMA. The Voëlvlei WTP raw water turbidity range from ± 30 NTU's during the summer months to ± 70 to 90 NTU's during the winter months. It is for this reason that the Voelvlei WTP was designed specifically to treat 'turbid' water, instead of 'colour' water. The turbidity of some of the other WTP raw waters in the CMA can reach a maximum of 1 to 2 NTU's, while others can reach a maximum of approximately 20 NTU's. These high turbidities of the Voëlvlei WTP raw water could possibly be due to heavy rainfalls during the winter months and the stirring action of the Voëlvlei Dam caused by strong winds.

5.2.3 UV Absorbance and colour of the Voëlvlei WTP raw water as a function of time.

The UV absorbance and colour of the Voëlvlei WTP raw water as a function of time are shown in Figure 5. The detailed results are shown in Appendix B (Table B3).
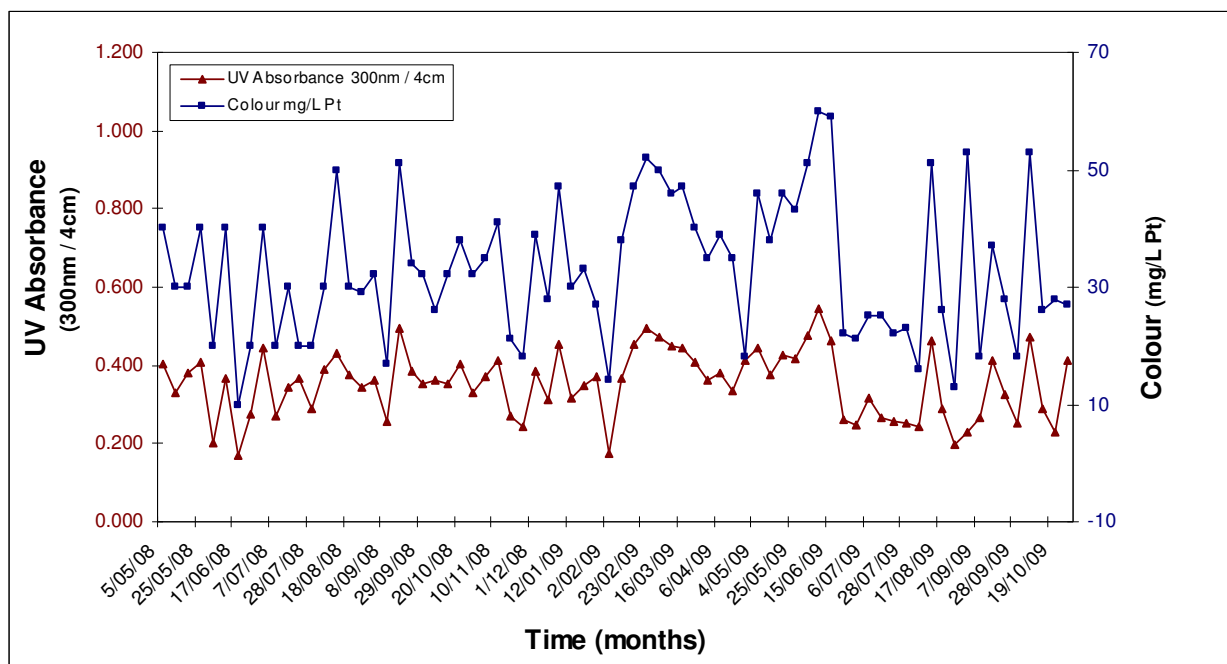
Figure 5   UV absorbance and colour of the Voëlvlei WTP raw water as a function of time (May 2008 to December 2009)

A similar profile for both the UV absorbance and colour of the Voëlvlei WTP raw water over time is evident from Figure 5. The similarity in profiles are expected as the UV absorbance is a measure or indicator of the organic (humic acid) content of the water which gives rise to colour. Therefore, it can be expected that the UV absorbance should be directly proportional to the colour and this is clearly shown in the graphical pattern of both parameters. The colour of the Voëlvlei WTP raw water ranges from 10 to 60 mg/L Pt for the monitoring period with the majority of the colour results ranging from 30 to 50 mg/L Pt. The seasonal variations do not seem to have an impact on the colour and from the graph it can be seen that the maximum colour seems to occur throughout the year. The UV absorbance (measured at 300 nm in a 4 cm quartz cuvette) ranges from 0.171

to 0.545 and, similar to the colour, maximum values are displayed throughout the year indicating minimal impact from seasonal variations. The acceptable limit for UV absorbance (operational parameter) and colour in treated water is <0.100 and <10 mg/L Pt, respectively, according to the SANS 241:2006 Class I Specification for drinking water (SANS 241, 2006).

5.3   Characterization of the Berg River water.

The aluminium, iron, pH, turbidity, UV absorbance and colour of the Berg River water over a period of time are shown in this section.

The detailed results are shown in Appendix C (Tables C1 to C6).

5.3.1   Aluminium and iron concentration of the Berg River water as a function of time.

The aluminium and iron concentration of the Berg River water as a function of time are shown in Figure 6. The detailed results are shown in Appendix D (Table D1).
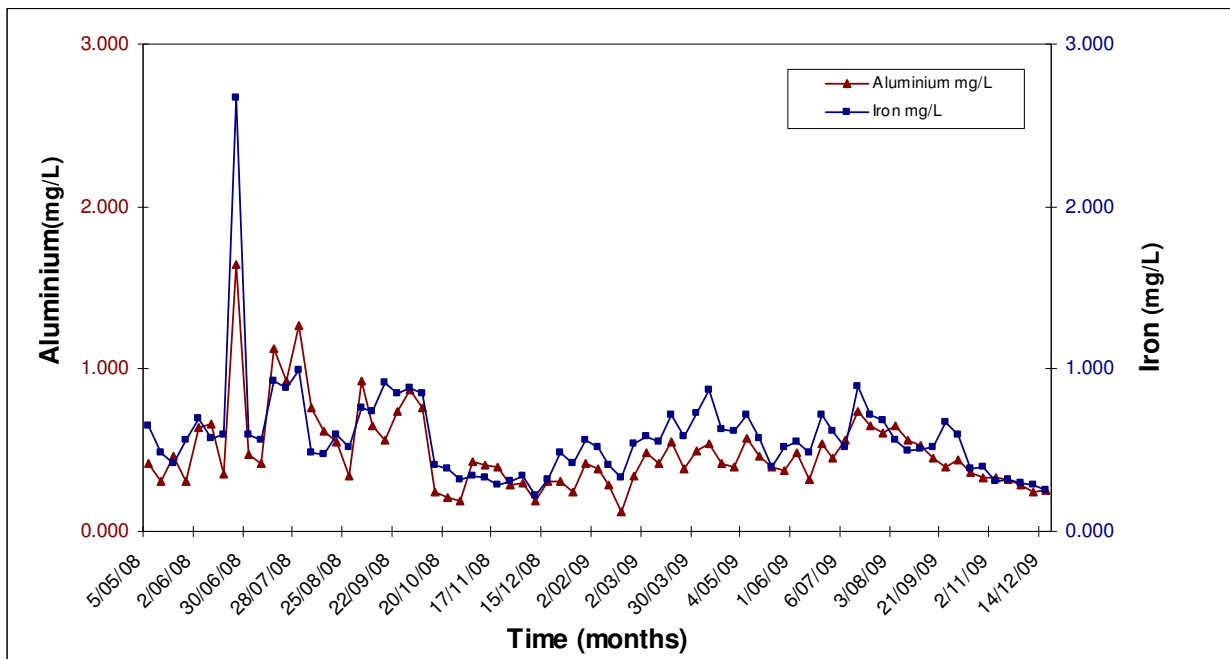
Figure 6   Aluminium and iron concentration of the Berg River water as a function of time (May 2008 to December 2009)

Figure 6 shows a similar profile for the aluminium and iron concentration of the Berg River water from May 2008 to December 2009. The metal results ranged from 0.122 to 1.640 mg/L for aluminium and 0.224 to 2.670 mg/L for iron during the monitoring period. The majority of the results, however, ranged from between 0.400 and 0.600 mg/L for aluminium and between 0.400 and 0.800 mg/L for iron. Generally, the metal concentrations increased during the winter months and this could possibly be due to the stirring of the river bed as a result of heavy rainfall and strong winds. The aluminium and iron concentrations of the Berg River water and the Voëlvlei WTP raw water were similar during the winter of 2008 with results ranging from 0.22 to 2.70 mg/L for both aluminium and iron. There was, however, a significant increase in the aluminium and iron concentrations of the Voëlvlei WTP raw water during the winter of 2009. This could be due to increased run-off as a result of heavy rainfalls and also the stirring action of the Voëlvlei Dam caused by strong winds, which could result in the suspension of any settled metal deposits.

5.3.2 pH and turbidity of the Berg River water as a function of time.

The pH and turbidity of the Berg River water as a function of time are shown in Figure 7. The detailed results are shown in Appendix D (Table D2).
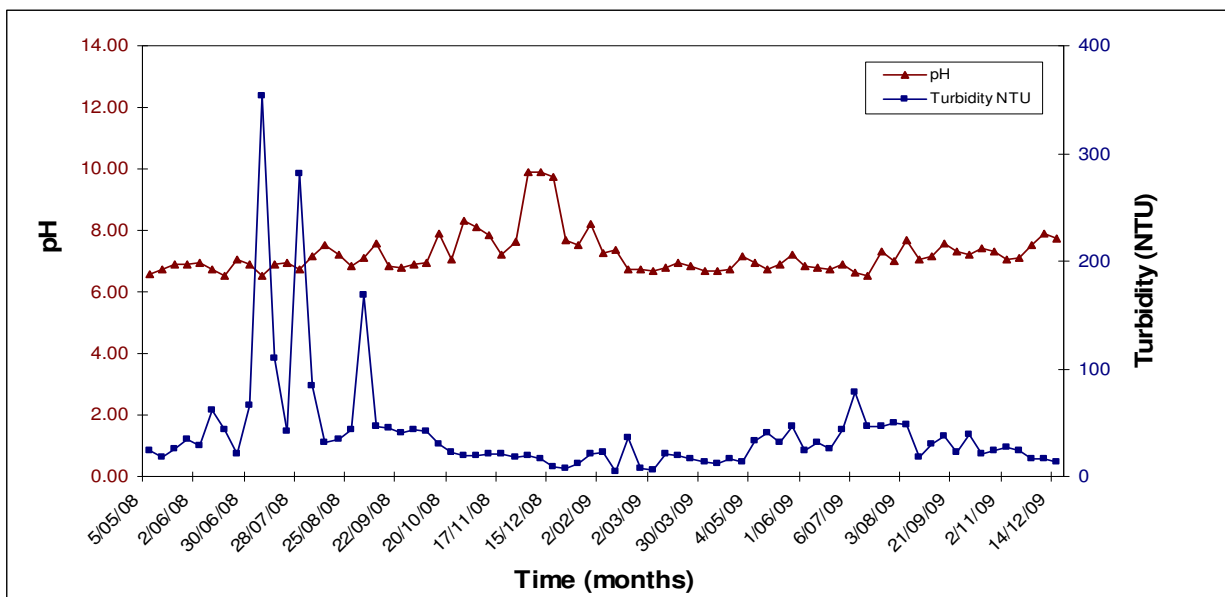
Figure 7   pH and turbidity of the Berg River water as a function of time
(May 2008 to December 2009)

It can be seen from Figure 7 that the pH of the Berg River water ranges from 6.53 to 9.92 during the period May 2008 to December 2009. Most of the pH data, however, ranged from 6.5 to 7.5 during the monitoring period with sharp increases occurring during the summer months which could be due to run-off from farmlands in close proximity to the sampling point. The turbidity ranged from 4 to 354 NTU's with the majority of the turbidities ranging from 15 to 45 NTU's during the monitoring period. As with the aluminium and iron concentrations, the turbidities generally increased during the winter months with notably more significant increases during the winter of 2008 than the winter of 2009. Once again, the high turbidities during the winter months could possibly be due to the stirring of the river bed as a result of heavy rainfall and strong winds.

5.3.3 UV Absorbance and colour of the Berg River water as a function of time.

The UV absorbance and colour of the Berg River water as a function of time are shown in Figure 8. The detailed results are shown in Appendix D (Table D3).
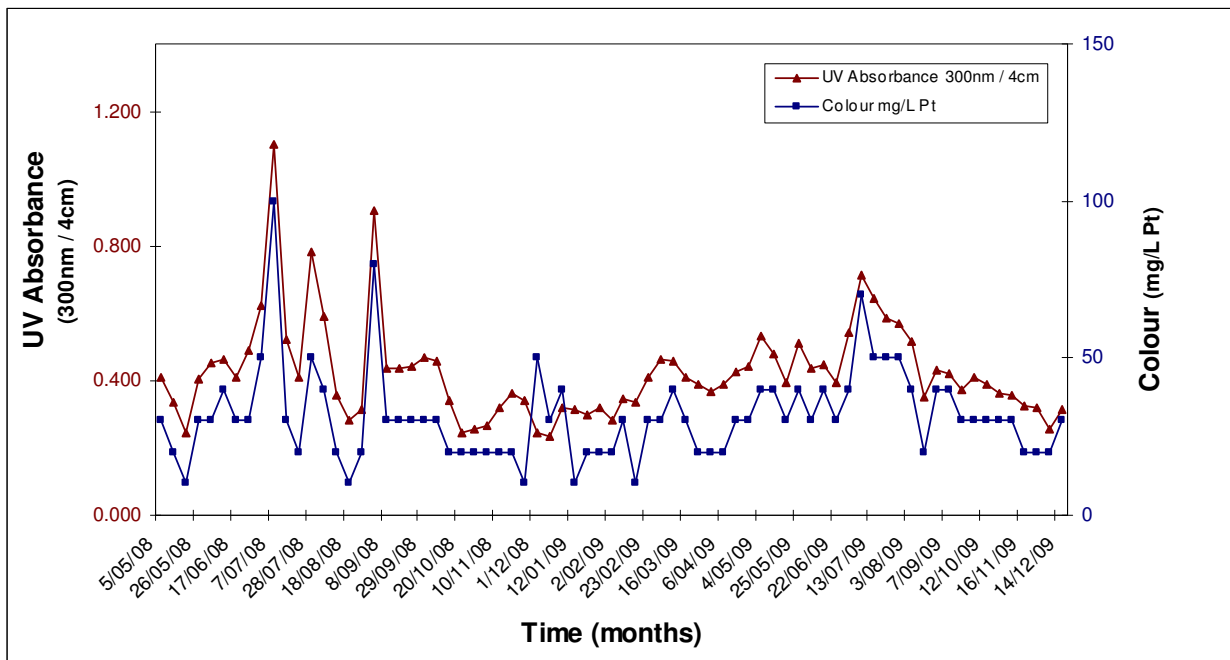
Figure 8   UV absorbance and colour of the Berg River water as a function of time
(May 2008 to December 2009)

As with the Voëlvlei WTP raw water, the UV absorbance and colour of the Berg River water follows a similar graphical pattern (see Figure 8). As mentioned earlier, this is expected due to the direct relationship between the two parameters. The colour ranged from 10 to 100 mg/L Pt with most of the colour ranging from 20 to 50 mg/L Pt during the monitoring period. The UV absorbance (measured at 300 nm in a 4 cm quartz cuvette) ranged from 0.232 to 1.103 with the majority of the absorbance ranging from 0.250 to 0.550 during the monitoring period. Unlike the Voëlvlei WTP raw water (from the Voelvlei Dam), the UV absorbance and colour of the Berg River water showed slight increases during the winter months with significant increases during the winter months of 2008. This could be expected as the heavy rainfall and run-off into the river (as it passes over matter containing humic acids) could increase the colour and UV absorbance of the water. It is important to monitor these two parameters as the calculation for the coagulant dosage concentration used during the water treatment process is based on the UV absorbance of the raw water.

5.4 Optimum coagulant dosage for the Voëlvlei WTP raw water

The focus of this research was mainly to determine a treatment strategy for the Berg River water. Currently, the Voëlvlei WTP uses ferric sulphate as the coagulant, mainly because of its wide coagulation pH range. Aluminium sulphate should be a suitable coagulant for treatment of the Berg River water where a wide pH range for coagulation is not necessary. However, from a health point of view, ferric sulphate would be the preferred coagulant. Therefore, the optimum coagulation conditions for these two coagulants are presented in this section.

5.4.1 Optimum coagulant dosage using ferric sulphate

Jar tests were conducted on the Voëlvlei WTP raw water using ferric sulphate as the coagulant in dosage concentrations of 2.0 to 6.0 mg/L as Fe^{3+} at a constant coagulation pH of 9.2. The turbidity and UV absorbance of the Voëlvlei WTP raw and treated water as a function of the Fe^{3+} dosage at a pH of 9.2 are shown in Figure 9. The detailed results are shown in Appendix E (Table E1).
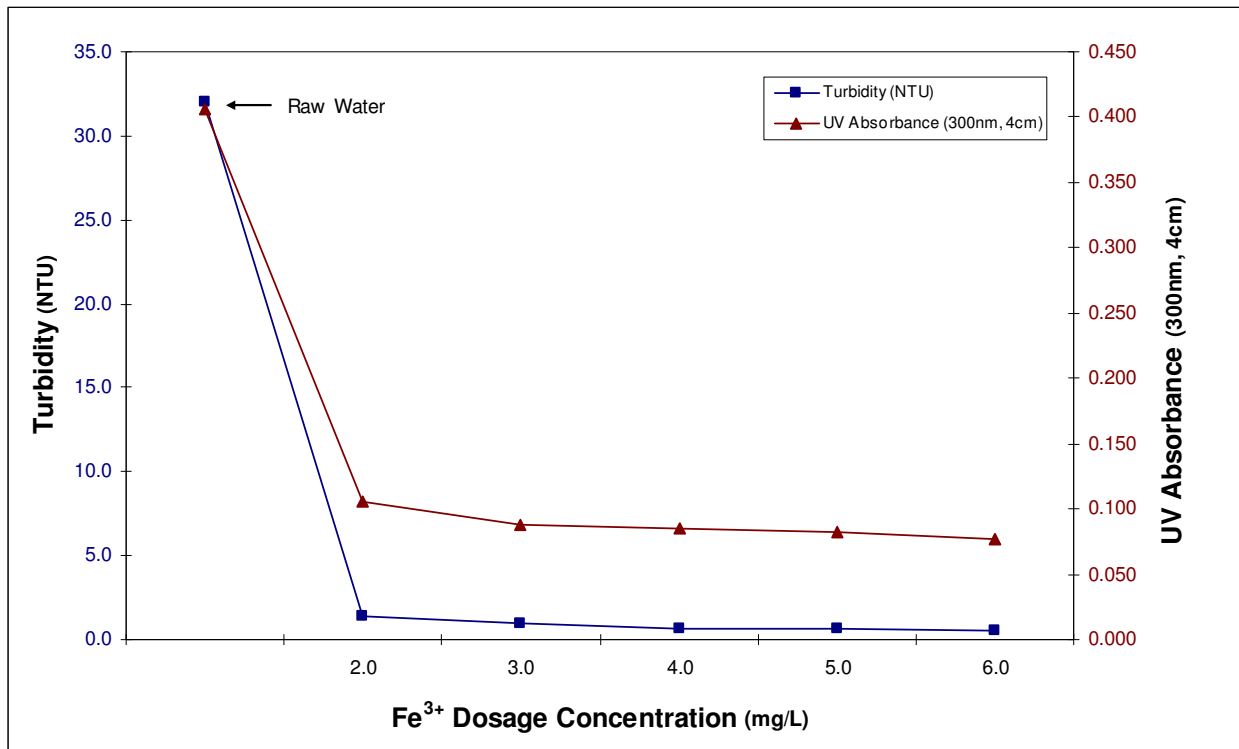
Figure 9   Turbidity and UV absorbance of the Voëlvlei WTP raw and treated water
as a function of the Fe^{3+} dosage at a pH of 9.2

The acceptable limits for treated water is <1 NTU for turbidity (SANS 241, 2006) and <0.100 for UV absorbance at 300 nm in a 4 cm quartz cuvette. It is clearly shown in Figure 9 that the high unacceptable limits of the raw water are reduced to within acceptable limits after a ferric sulphate dosage concentration of 3.0 mg/L as Fe^{3+}. At this dosage concentration the raw water turbidity is reduced from 32 to 0.99 NTU's while the UV absorbance is reduced from 0.406 to 0.088 and therefore a ferric sulphate dosage concentration of between 3.0 and 4.0 mg/L as Fe^{3+} can be confirmed as optimum. Higher dosage concentrations would also work but this would be inefficient and unnecessary from an operational cost perspective.

5.4.2   Optimum coagulant dosage using aluminium sulphate

Jar tests were conducted on the Voëlvlei WTP raw water using aluminium sulphate as the coagulant in dosage concentrations of 0.5 to 3.0 mg/L as Al^{3+} at a constant

coagulation pH of 6.5. The turbidity and UV absorbance of the Voëlvlei WTP raw and treated water as a function of the Al^{3+} dosage at a pH of 6.5 are shown in Figure 10. The detailed results are shown in Appendix E (Table E2).
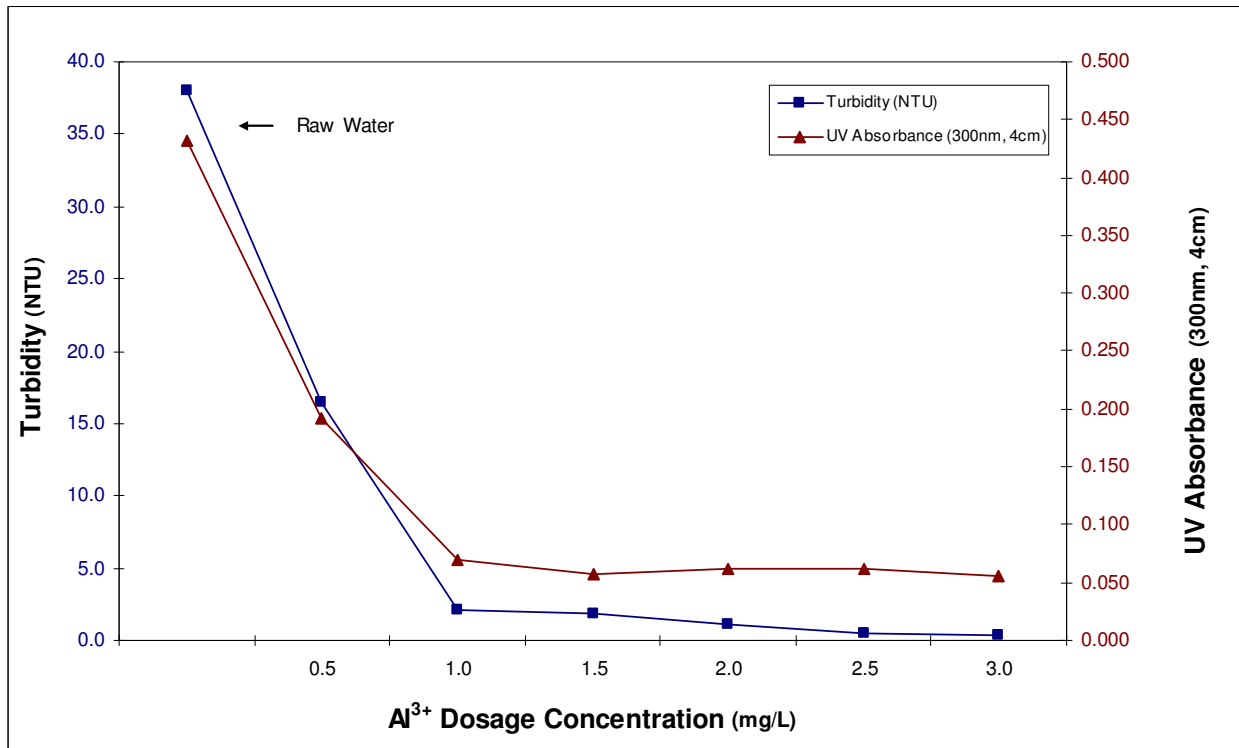
Figure 10   Turbidity and UV absorbance of the Voëlvlei WTP raw and treated water as a function of the Al^{3+} dosage at a pH of 6.5

It is clearly shown in Figure 10 that the raw water turbidity could be reduced from 38 to 0.25 NTU's and the UV absorbance from 0.432 to 0.062 after an aluminium sulphate dosage of 2.5 mg/L as Al^{3+}. This indicates that, should aluminium sulphate be used as the preferred coagulant on the Voëlvlei WTP raw water, its optimum dose would be in the order of 2.5 to 3.0 mg/L as Al^{3+}.

5.5 Optimum coagulation pH for the Voëlvlei WTP raw water

In the previous section the optimum coagulant dosage was determined for the Voëlvlei WTP raw water using ferric sulphate and aluminium sulphate. These optimum coagulant

dosages are used in this section to determine the optimum coagulation pH for the same water using the same two coagulants.

5.5.1 Optimum coagulation pH using ferric sulphate

Jar tests were conducted on the Voëlvlei WTP raw water at various pH values ranging from 3.96 to 9.48, while using a constant ferric sulphate dosage of 4.0 mg/L as Fe^{3+}. The turbidity and UV absorbance of the Voëlvlei WTP raw and treated water as a function of pH at a constant Fe^{3+} dosage of 4.0 mg/L are shown in Figure 11. The detailed results are shown in Appendix F (Table F1).

Figure 11 Turbidity and UV absorbance of the Voëlvlei WTP raw and treated water as a function of pH at a constant Fe^{3+} dosage of 4.0 mg/L

Based on the UV absorbance of the treated water, the wide coagulation pH range for ferric sulphate is confirmed in Figure 11. These results indicate that any coagulation pH from 3.96 to 9.48 would be acceptable. However, the turbidity of the treated water is

unacceptable (i.e. >1 NTU) at the lower coagulation pH values of 3.96 to 6.02 and these turbidities only become acceptable (i.e. <1 NTU) from a pH value of 6.56 and upwards. As a result, it is better to coagulate the Voëlvlei WTP raw water with its relatively high turbidity at a higher pH and therefore the chosen coagulation pH of 9.2 for the Voëlvlei WTP raw water works very well with reference to efficient coagulation, flocculation, sedimentation and stabilization, and also the removal of any manganese present in the water.

5.5.2 Optimum coagulation pH using aluminium sulphate

Jar tests were conducted on the Voëlvlei WTP raw water at various pH values ranging from 4.46 to 9.49 while using a constant aluminium sulphate dosage of 3.0 mg/L as Al^{3+}. The turbidity and UV absorbance of the Voëlvlei WTP raw and treated water as a function of pH at a constant Al^{3+} dosage of 3.0 mg/L are shown in Figure 12. The detailed results are shown in Appendix F (Table F2).
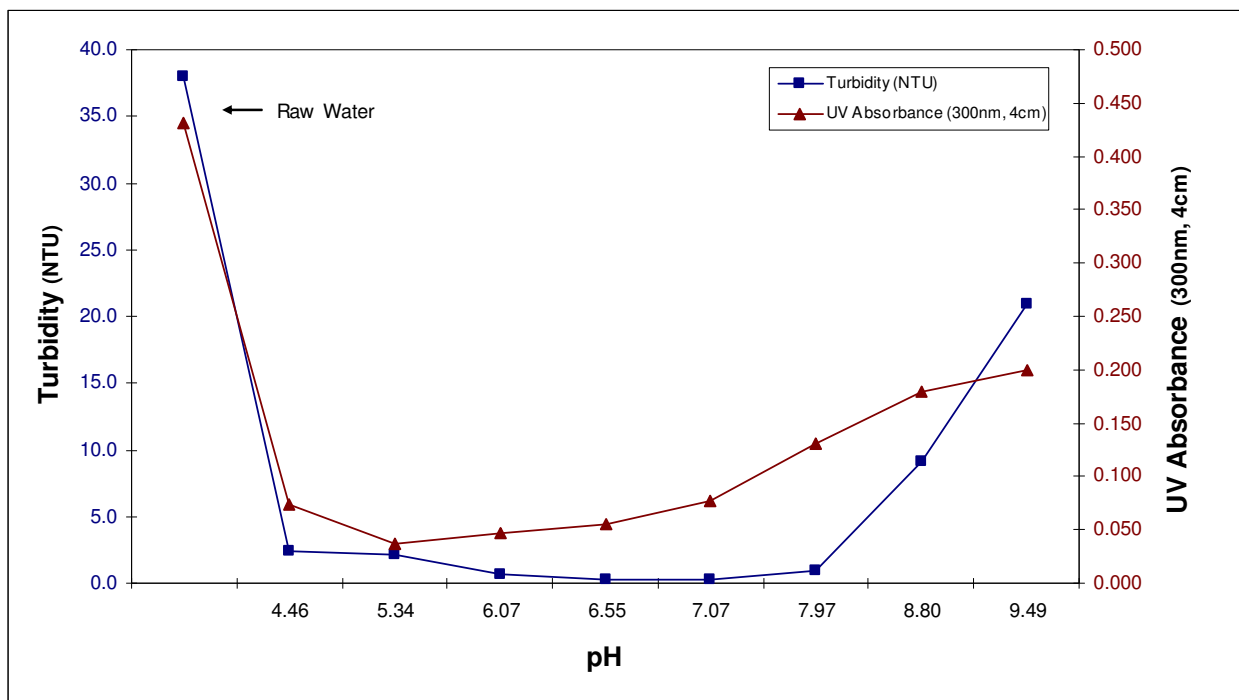
Figure 12 Turbidity and UV absorbance of the Voëlvlei WTP raw and treated water as a function of pH at a constant Al^{3+} dosage of 3.0 mg/L

The narrower coagulation pH range of aluminium sulphate (compared to ferric sulphate) is confirmed in this Jar test experiment. The raw water turbidity of 38 NTU's could be reduced to acceptable limits in the pH range of 6.07 to 7.97 while the raw water UV absorbance is reduced from 0.432 to acceptable limits in the pH range of 4.46 to 7.07. Therefore, these results indicate that the optimum coagulation pH for the Voëlvlei WTP raw water using aluminium sulphate as the coagulant would be in the region of 6.0 to 7.0. The turbidity and UV absorbance of the treated water increase with an increase in coagulation pH beyond 7.07 and therefore at a coagulation pH of approximately 9.2, the turbidity and UV absorbance of the treated water is unacceptable. Aluminium precipitation occurs from a pH range of 5.0 to about 7.0, with minimum solubility occurring at a pH of approximately 6.0. The aluminium solubility increases at a pH greater than 7.0 thereby decreasing coagulation efficiency. As a result the aluminium sulphate would not work as a coagulant at the Voëlvlei WTP considering the plants current optimum coagulation pH of 9.2. Ferric sulphate is therefore the preferred coagulant at the Voëlvlei WTP.

5.6   Optimum coagulant dosage for the Berg River water

The turbidity and UV absorbance of the treated water were used as indicators to determine the optimum coagulant dosage and also the optimum coagulation pH for the treatment of this water. These results are presented in this section.

5.6.1   Optimum coagulant dosage using ferric sulphate

Jar tests were performed on the Berg River water using ferric sulphate as the coagulant in dosage concentrations of 2.0 to 12.0 mg/L as Fe^{3+} at a constant coagulation pH of 5.0. These experiments were performed during October 2008. The turbidity and UV absorbance of the Berg River water as a function of the Fe^{3+} dosage at a pH of 5.0 are shown in Figure 13. The detailed results are shown in Appendix G (Table G1).
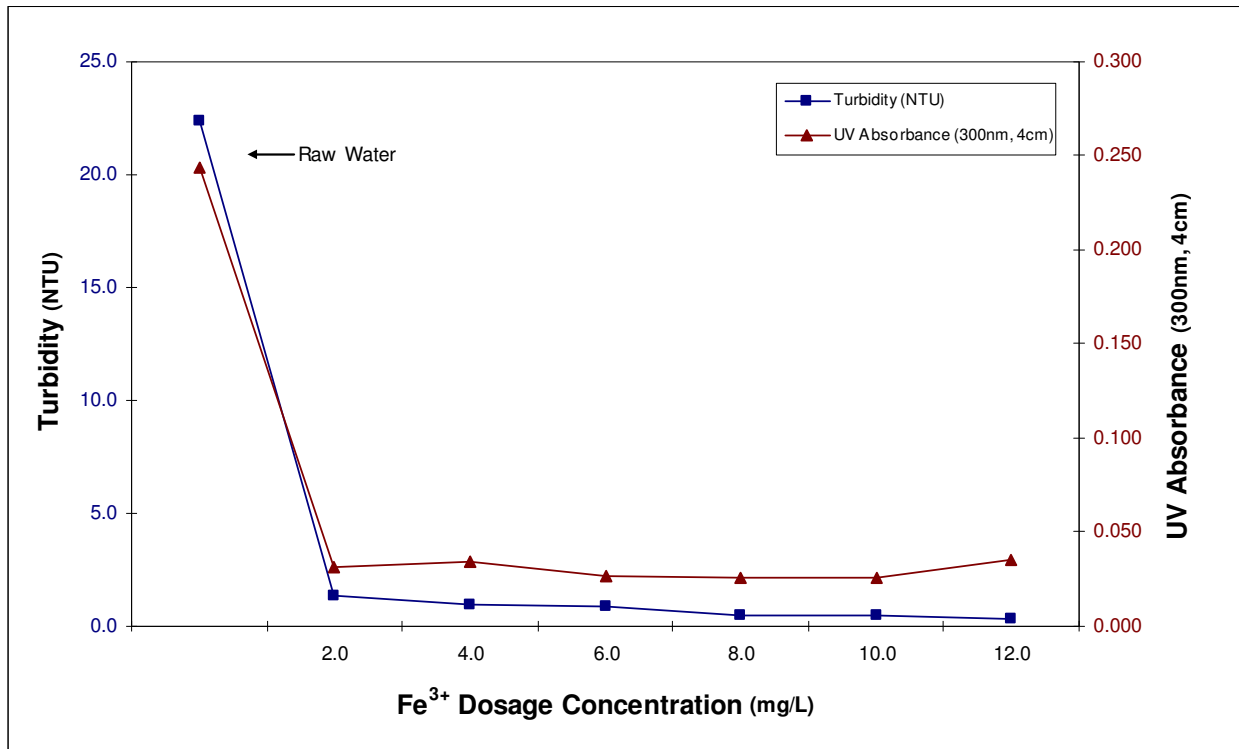
Figure 13 Turbidity and UV absorbance of the Berg River raw and treated water
as a function of the Fe^{3+} dosage at a pH of 5.0

The turbidity of the raw water could be reduced from 22.4 to 0.93 NTU's and the UV absorbance was reduced from 0.244 to 0.034 after a dosage concentration of 4.0 mg/L as Fe^{3+} (see Figure 13). From the graph it can be seen that increased dosages of ferric sulphate would work just as well but this would not be operationally cost effective due to over-dosage. Even though ferric sulphate has a wide coagulation pH range, a pH of 5.0 was estimated as the optimum coagulation pH as ferric sulphate removes more colour (humic acids) at lower pH values. It is shown in Figure 13 that the optimum dosage for ferric sulphate on the Berg River water would be in the region of 4.0 to 6.0 mg/L as Fe^{3+}.

The same Jar tests (i.e. dosage concentrations of 2.0 to 12.0 mg/L as Fe^{3+} at a constant coagulation pH of 5.0) were conducted on the Berg River water during February, April, July and October 2009 and the turbidity and UV absorbance are displayed in Tables 1 and 2.

Table 1   Turbidity of the Berg River raw and treated water as a function of the Fe^{3+} dosage at a constant pH of 5.0

Fe^{3+} Dosage Concentration	Turbidity (NTU)				
(mg/L)	Oct 2008	Feb 2009	Apr 2009	July 2009	Oct 2009
[Raw Water]	22.4	7.4	16.4	46.0	24.4
2.0	1.34	1.08	1.49	1.76	1.28
4.0	0.93	0.92	0.89	1.04	0.88
6.0	0.89	0.68	0.77	0.91	0.74
8.0	0.51	0.57	0.71	0.73	0.68
10.0	0.49	0.52	0.65	0.70	0.51
12.0	0.32	0.39	0.53	0.64	0.45

Table 2   UV absorbance of the Berg River raw and treated water as a function of the Fe^{3+} dosage at a constant pH of 5.0

Fe^{3+} Dosage Concentration	UV Absorbance (300 nm / 4 cm)				
(mg/L)	Oct 2008	Feb 2009	Apr 2009	July 2009	Oct 2009
[Raw Water]	0.244	0.412	0.424	0.642	0.364
2.0	0.031	0.076	0.065	0.089	0.057
4.0	0.034	0.052	0.058	0.072	0.049
6.0	0.027	0.041	0.044	0.068	0.042
8.0	0.026	0.039	0.041	0.055	0.038
10.0	0.026	0.040	0.045	0.055	0.041
12.0	0.035	0.041	0.044	0.054	0.040

From Table 1 it can be seen that the turbidity of the raw water was reduced to acceptable levels (i.e. <1 NTU) at a ferric sulphate dosage of 4.0 mg/L as Fe^{3+} for all the months concerned with the exception of July 2009 where it was just over the acceptable limit (viz., 1.04 NTU). The UV absorbance (see Table 2) of the raw water was reduced to acceptable levels (<0.100) at the same dosage concentration. As a result, the optimum ferric sulphate dosage for the Berg River water remained the same throughout the year at 4.0 to 6.0 mg/L as Fe^{3+} except for the winter months where it moved closer to 6.0 mg/L as Fe^{3+} possibly due to the higher turbidities encountered in the river water during the winter season.

5.6.2 Optimum coagulant dosage using aluminium sulphate

Jar tests were conducted on the Berg River water using aluminium sulphate as the coagulant in dosage concentrations of 1.0 to 6.0 mg/L as Al^{3+} at a constant coagulation pH of 6.0. These experiments were performed during October 2008. The turbidity and UV absorbance of the Berg River water as a function of the Al^{3+} dosage at a constant pH of 6.0 are shown in Figure 14. The detailed results are shown in Appendix G (Table G2).
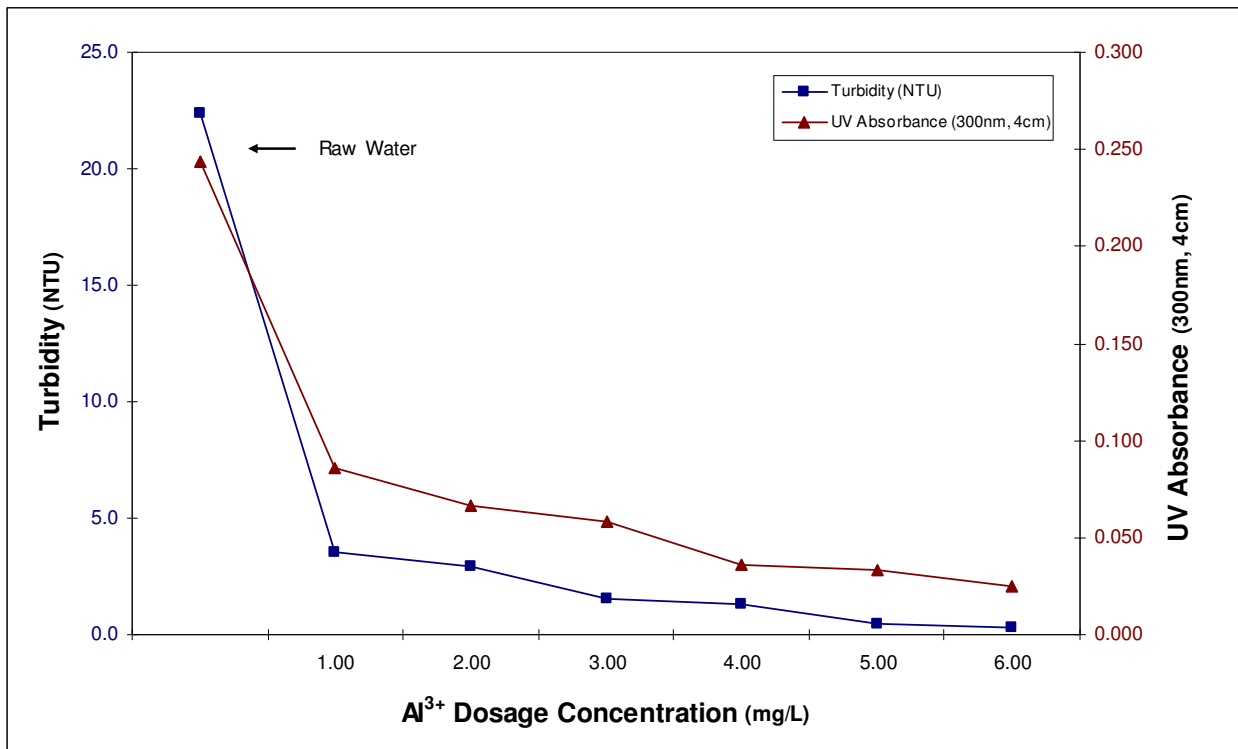
Figure 14 Turbidity and UV absorbance of the Berg River raw and treated water as a function of the Al^{3+} dosage at a pH of 6.0

Even though the UV absorbance of the raw water was reduced from 0.244 to within acceptable limits (i.e. <0.100) across the entire dosage concentration range (see Figure 14) the turbidity of the raw water was only reduced from 22.4 NTU's to below 1 NTU at a dosage concentration of 5.0 mg/L as Al^{3+}. The results in Figure 14 confirm that the optimum dosage for aluminium sulphate on the Berg River water would be approximately 5.0 mg/L as Al^{3+}.

The same Jar tests (i.e. dosage concentrations of 1.0 to 6.0 mg/L as Al^{3+} at a constant coagulation pH of 6.0) were conducted on the Berg River water during February, April, July and October 2009 and the turbidity and UV absorbance are displayed in Tables 3 and 4.

Table 3   Turbidity of the Berg River raw and treated water as a function of the Al^{3+} dosage at a constant pH of 6.0

Al^{3+} Dosage Concentration	Turbidity (NTU)				
(mg/L)	Oct 2008	Feb 2009	Apr 2009	July 2009	Oct 2009
[Raw Water]	22.4	7.4	16.4	46.0	24.4
1.0	3.57	2.13	2.45	4.34	2.87
2.0	2.94	1.67	1.69	2.16	2.25
3.0	1.53	1.32	1.25	1.54	1.31
4.0	1.29	1.03	0.99	1.26	0.86
5.0	0.46	0.53	0.57	0.79	0.55
6.0	0.29	0.27	0.36	0.54	0.39

Table 4   UV absorbance of the Berg River raw and treated water as a function of the Al^{3+} dosage at a constant pH of 6.0

Al^{3+} Dosage Concentration	UV Absorbance (300 nm / 4 cm)				
(mg/L)	Oct 2008	Feb 2009	Apr 2009	July 2009	Oct 2009
[Raw Water]	0.244	0.412	0.424	0.642	0.364
1.0	0.086	0.093	0.091	0.106	0.094
2.0	0.066	0.068	0.079	0.095	0.077
3.0	0.058	0.063	0.062	0.078	0.061
4.0	0.036	0.057	0.059	0.063	0.053
5.0	0.033	0.058	0.061	0.067	0.056
6.0	0.025	0.055	0.052	0.058	0.039

The turbidity of the raw water was reduced to acceptable levels (i.e. <1 NTU) at an aluminium sulphate dosage of 5.0 mg/L as Al^{3+} for all the months concerned. The UV absorbance of the raw water was reduced to acceptable levels (<0.100) at the same concentration. As a result, the optimum aluminium sulphate dosage for the Berg River water should remain the same throughout the year at approximately 5.0 mg/L as Al^{3+}.

5.7 Optimum coagulation pH for the Berg River water

In the previous section the optimum coagulant dosages were determined for the Berg River water using ferric sulphate and aluminium sulphate as coagulants. This determination was performed during different months of the year to monitor the impact of seasonal variations. These optimum coagulant dosages are now used in this section to determine the optimum coagulation pH for the same water using the same two coagulants.

5.7.1 Optimum coagulation pH using ferric sulphate

Jar tests were conducted on the Berg River water at various pH values ranging from 3.53 to 12.01 while using a constant ferric sulphate dosage of 4.0 mg/L as Fe^{3+}. These experiments were performed during October 2008. The turbidity and UV absorbance of the Berg River raw and treated water as a function of pH at a constant Fe^{3+} dosage of 4.0 mg/L are shown in Figure 15. The detailed results are shown in Appendix H (Table H1).
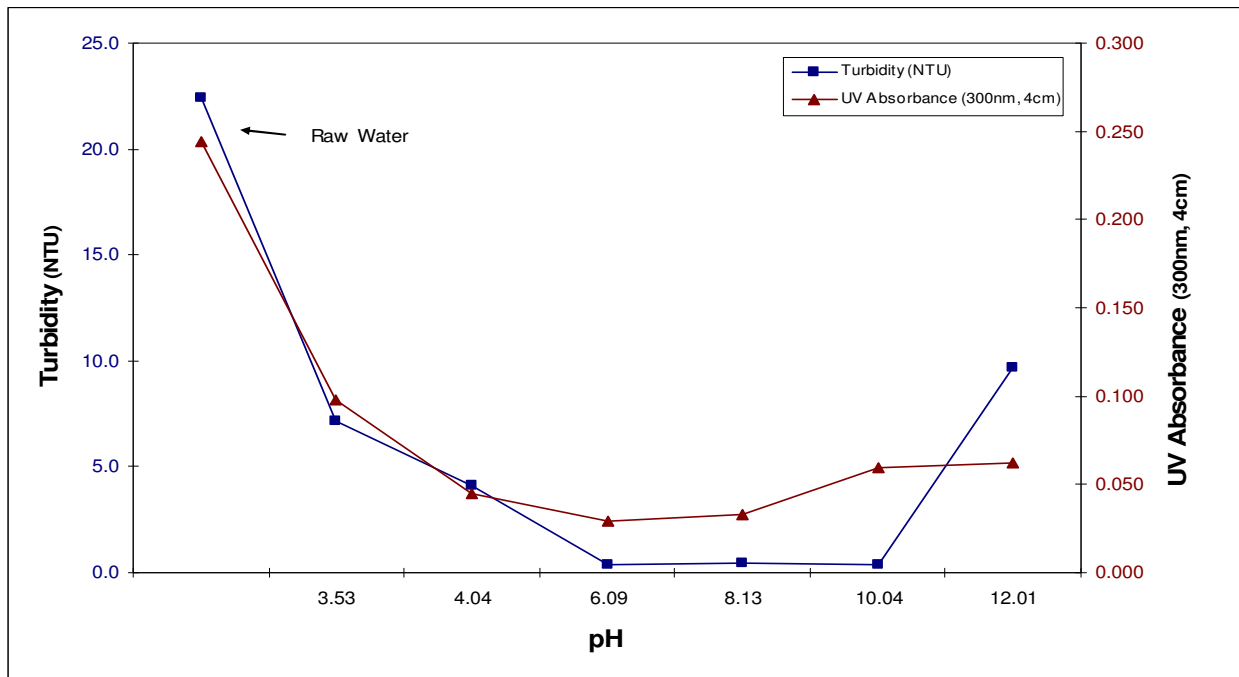
Figure 15 Turbidity and UV absorbance of the Berg River raw and treated water as a function of pH at a constant Fe^{3+} dosage of 4.0 mg/L

The UV absorbance (see Figure 15) of the raw water was reduced from 0.244 to within acceptable limits across the entire pH range. The turbidity of the raw water, however, was only reduced from 22.4 NTU's to below 1 NTU at a coagulation pH of 6.09. Even though the turbidities are unacceptable (i.e. >1 NTU) at a coagulation pH of 4.04, they are well within the acceptable limits at a coagulation pH of 6.09. It can therefore be assumed that the optimum coagulation pH is approximately 5.0 but this needs to be verified with similar Jar tests in the pH range of 4.0 to 6.0 with 0.1 pH increments. The wide coagulation pH range for ferric sulphate can be seen in Figure 15 ranging from pH 5.0 to 10.0 with the turbidity of the treated water rising above 1 NTU at pH >10, which is mainly due to the increased iron solubility at these high pH values.

The same Jar tests (i.e. dosage concentration of 4.0 mg/L as Fe^{3+} at various pH values, ranging from 3.5 to 12.0) were conducted on the Berg River water during February, April, July and October 2009 and the turbidity and UV absorbance results are shown in Tables 5 and 6.

Table 5   Turbidity of the Berg River raw and treated water as a function of pH at a constant Fe^{3+} dosage of 4.0 mg/L

Fe^{3+} Dosage Concentration	pH	Turbidity (NTU)				
(mg/L)		Oct 2008	Feb 2009	Apr 2009	July 2009	Oct 2009
[Raw Water]		22.4	7.4	16.4	46.0	24.4
4.0	3.5	7.14	3.16	3.89	6.67	5.94
4.0	4.0	4.12	1.24	1.78	2.09	2.57
4.0	6.0	0.39	0.54	0.48	0.67	0.61
4.0	8.0	0.47	0.48	0.45	0.55	0.49
4.0	10.0	0.40	0.63	0.49	0.51	0.43
4.0	12.0	9.67	2.07	3.18	4.88	3.21

Table 6   UV absorbance of the Berg River raw and treated water as a function of pH
at a constant Fe^{3+} dosage of 4.0 mg/L

Fe^{3+} Dosage Concentration	pH	UV Absorbance (300 nm / 4 cm)				
(mg/L)		Oct 2008	Feb 2009	Apr 2009	July 2009	Oct 2009
[Raw Water]		0.244	0.412	0.424	0.642	0.364
4.0	3.5	0.098	0.104	0.087	0.118	0.096
4.0	4.0	0.045	0.089	0.069	0.075	0.056
4.0	6.0	0.029	0.041	0.046	0.058	0.039
4.0	8.0	0.033	0.057	0.050	0.066	0.048
4.0	10.0	0.059	0.055	0.056	0.067	0.053
4.0	12.0	0.062	0.067	0.059	0.069	0.061

The turbidity of the raw water was reduced to <1 NTU at a coagulation pH of 6.0 for all the months concerned. The UV absorbance of the raw water was reduced to acceptable levels (<0.100) at the same coagulation pH. As a result, the optimum coagulation pH for ferric sulphate on the Berg River water remained the same throughout the year at approximately 5.0 to 6.0. As mentioned earlier, the turbidities of the treated water are above the acceptable limit at pH 4.0 but well within the limit at pH 6.0 and therefore the optimum coagulation pH can be assumed to be approximately 5.0. This, however, needs to be verified with further Jar tests in the pH range of 4.0 to 6.0 with 0.1 pH increments.

5.7.2 Optimum coagulation pH using aluminium sulphate

Jar tests were conducted on the Berg River water at various pH values ranging from 4.0 to 9.0 while using a constant aluminium sulphate dosage of 5.0 mg/L as Al^{3+}. These experiments were performed during October 2008.

The turbidity and UV absorbance of the Berg River raw and treated water as a function of pH at a constant Al^{3+} dosage of 5.0 mg/L are shown in Figure 16. The detailed results are shown in Appendix H (Table H2).
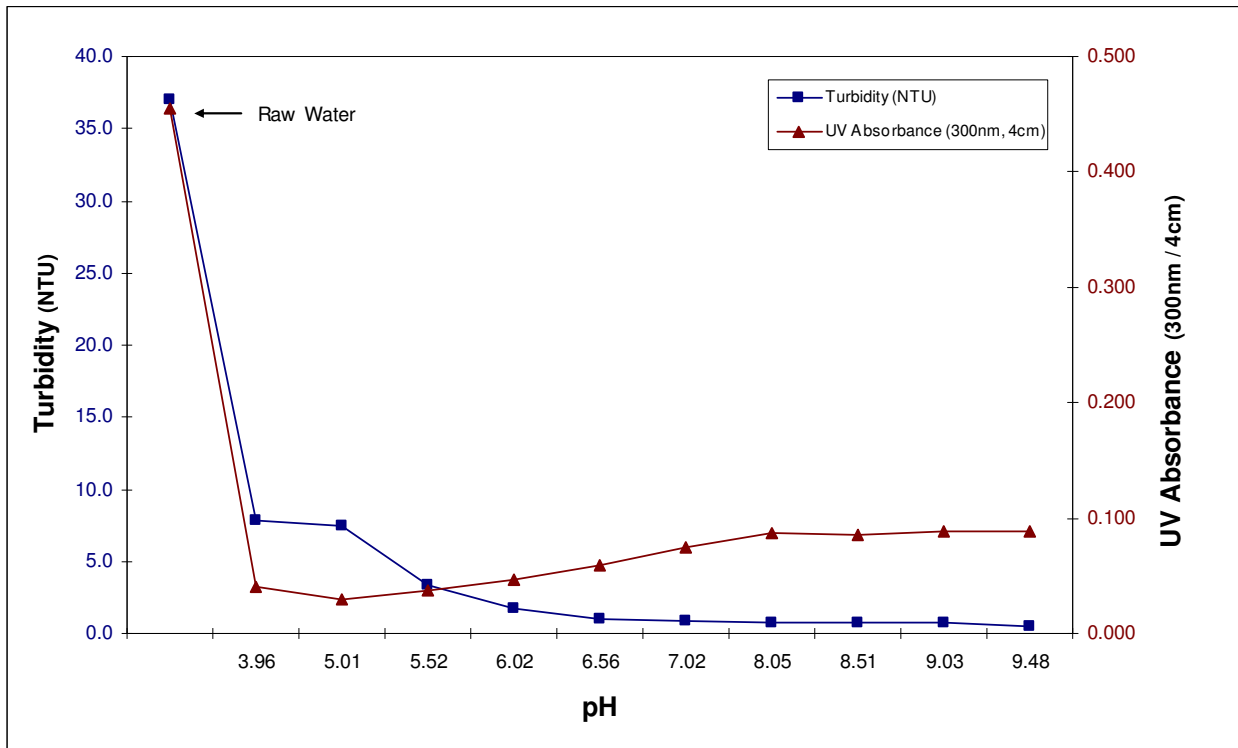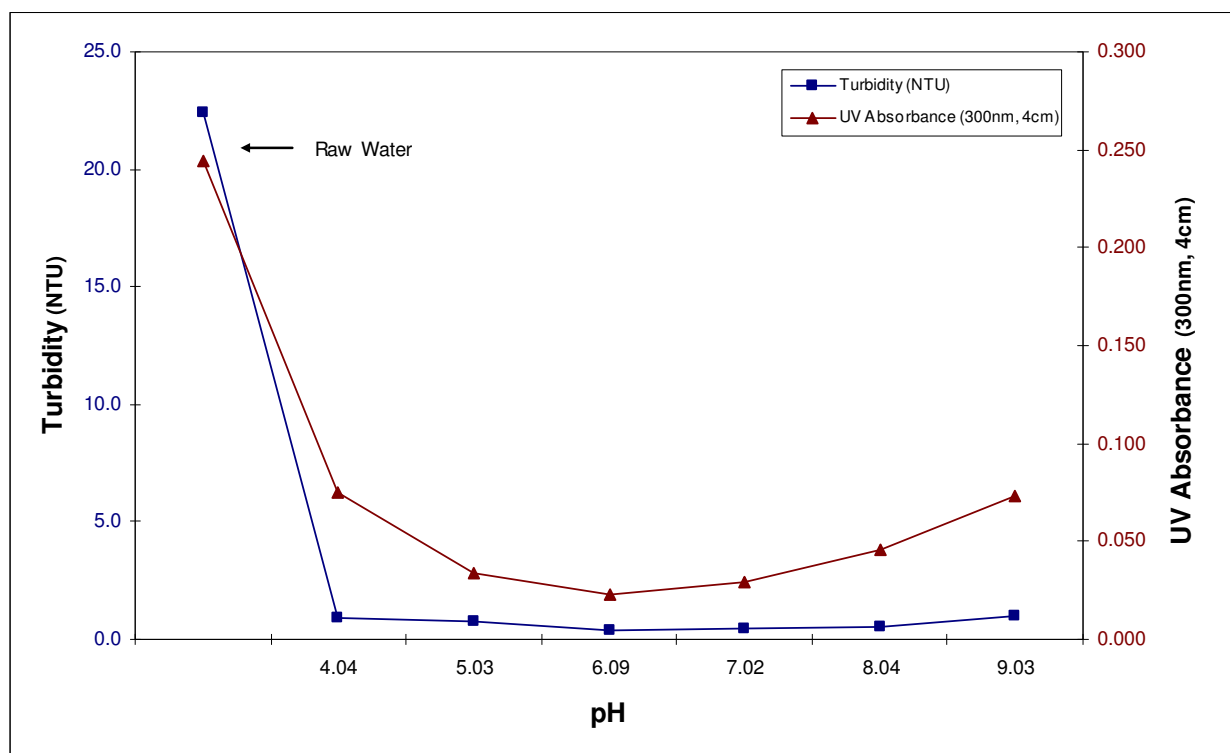
Figure 16 Turbidity and UV absorbance of the Berg River raw and treated water
as a function of pH at a constant Al^{3+} dosage of 5.0 mg/L

According to Figure 16, the turbidity and UV absorbance of the raw water were reduced to acceptable levels across the entire pH range at an aluminium sulphate dosage of 5.0 mg/L as Al^{3+}. However, the lowest turbidity (0.38 NTU's) and UV absorbance (0.023) of the treated water were obtained at pH 6.0 and therefore this pH can be considered to be the optimum coagulation pH. The treated water was also tested for aluminium and iron and the lowest readings were obtained at this pH which confirms 6.0 as the optimum coagulation pH for the Berg River water using aluminium sulphate as the coagulant.

The same Jar tests (i.e. dosage concentration of 5.0 mg/L as Al^{3+} at various pH values, ranging from 4.0 to 9.0) were conducted on the Berg River water during February, April, July and October 2009 and the turbidity and UV absorbance results are shown in Tables 7 and 8.

Table 7   Turbidity of the Berg River raw and treated water as a function of pH at a constant Al^{3+} dosage of 5.0 mg/L

Al^{3+} Dosage Concentration	pH	Turbidity (NTU)				
(mg/L)		Oct 2008	Feb 2009	Apr 2009	July 2009	Oct 2009
[Raw Water]	[7.06]	22.4	7.4	16.4	46.0	24.4
5.0	4.0	0.89	0.93	0.88	1.21	0.92
5.0	5.0	0.76	0.89	0.61	0.94	0.76
5.0	6.0	0.38	0.57	0.44	0.65	0.41
5.0	7.0	0.45	0.65	0.58	0.68	0.55
5.0	8.0	0.52	0.68	0.63	0.73	0.59
5.0	9.0	0.96	0.79	0.65	0.79	0.60

Table 8   UV absorbance of the Berg River raw and treated water as a function of pH at a constant Al^{3+} dosage of 5.0 mg/L

Al^{3+} Dosage Concentration	pH	UV Absorbance (300 nm / 4 cm)				
(mg/L)		Oct 2008	Feb 2009	Apr 2009	July 2009	Oct 2009
[Raw Water]	[7.06]	0.244	0.412	0.424	0.642	0.364
5.0	4.0	0.075	0.088	0.090	0.097	0.085
5.0	5.0	0.034	0.059	0.057	0.059	0.062
5.0	6.0	0.023	0.043	0.040	0.037	0.043
5.0	7.0	0.029	0.048	0.042	0.045	0.048
5.0	8.0	0.046	0.059	0.055	0.049	0.059
5.0	9.0	0.073	0.064	0.061	0.067	0.070

The turbidities of the raw water were reduced to below 1 NTU across the entire pH range for all the months concerned except for July 2009 which displayed a turbidity of 1.21 NTU for the treated water at a coagulation pH of 4.0. The UV absorbance of the raw water was also reduced to acceptable limits across the entire pH range with no exceptions. However, as shown in Figure 16, the lowest turbidity and UV absorbance for the treated water were obtained at pH 6.0. This once again confirms pH 6.0 as being the optimum coagulation pH for the Berg River water using aluminium sulphate as the coagulant.

5.8 Treatment of raw water blends using ferric sulphate

It was shown in the previous sections of this chapter that when compared to each other, there is a distinct difference between the quality and the optimum treatment parameters of the Voëlvlei WTP raw water and the Berg River water. Based on the Jar test results it seems that these two raw waters should be treated separately from each other especially when using ferric sulphate as the coagulant. As a result of this finding, these two raw waters were then blended together in different proportions to determine the effect of blending on the optimum treatment conditions. The Voëlvlei WTP raw water and the Berg River water were blended in the following proportions:

(a) Blend 1 - Berg River water 75% : Voëlvlei WTP raw water 25% (BR75:VV25)

(b) Blend 2 - Berg River water 50% : Voëlvlei WTP raw water 50% (BR50:VV50)

(c) Blend 3 - Berg River water 25% : Voëlvlei WTP raw water 75% (BR25:VV75)

Jar tests were conducted on these blends using ferric sulphate as the coagulant at a concentration of 5.0 mg/L as Fe^{3+} and at an optimum coagulation pH of 5.0 as determined in section 5.7.1. These tests were conducted from February 2010 to September 2010. Jar tests were conducted on the blends at least once a month and in some cases more than once a month.

The following physical and chemical parameters were used to determine the efficiency of the treatment process (coagulation, flocculation and sedimentation) on the blended waters:

♦ Turbidity (NTU)

♦ UV absorbance (at 300 nm in a 4 cm cell)

♦ Iron (mg/L as Fe)

♦ Aluminium (mg/L as Al)

♦ Manganese (mg/L as Mn)

The Jar test results and the findings of the investigation for the blends are presented in sections 5.8.1, 5.8.2 and 5.8.3.

5.8.1 Treatment of Blend 1 (BR75:VV25)

The turbidity, UV absorbance, iron, aluminium and manganese content of the raw and treated water for Blend 1 are shown in Table 9.

Table 9   Turbidity, UV absorbance, iron, aluminium and manganese content of the raw and treated water for Blend 1

Date	Blend 1 (Berg River water 75% : Voëlvlei WTP raw water 25%)									
	Raw					Treated				
	Turb	UV Abs	Fe	Al	Mn	Turb	UV Abs	Fe	Al	Mn
Months	NTU	300nm 4cm	mg/L	mg/L	mg/L	NTU	300nm 4cm	mg/L	mg/L	mg/L
24/02/2010	37.4	0.269	1.377	1.760	0.068	0.63	0.053	0.334	0.022	0.057
09/03/2010	40.5	0.331	0.970	0.295	0.066	0.59	0.059	0.378	0.005	0.020
16/03/2010	42.5	0.308	N/R	N/R	N/R	0.64	0.059	0.530	0.010	0.035
24/03/2010	38.4	0.287	0.847	0.244	0.056	0.92	0.055	0.437	0.048	0.024
31/03/2010	36.9	0.249	1.700	2.250	0.074	0.69	0.073	0.452	0.002	0.022
15/04/2010	33.3	0.218	1.050	1.150	0.042	1.00	0.046	0.472	0.004	0.039
06/05/2010	34.8	0.264	1.210	1.600	0.034	1.02	0.060	0.497	0.049	0.021
14/06/2010	30.8	0.204	1.290	1.580	0.039	1.69	0.054	0.515	0.105	0.024
23/07/2010	25.5	0.249	1.210	1.410	0.038	1.07	0.055	0.405	0.041	0.022
24/08/2010	27.7	0.182	1.660	1.640	0.044	1.05	0.036	0.197	0.040	0.024
14/09/2010	21.8	0.249	1.210	1.350	0.064	1.28	0.049	0.407	0.022	0.075
22/09/2010	12.2	0.234	0.738	0.427	0.033	0.81	0.056	0.414	0.008	0.033

Turb = Turbidity,   UV Abs = UV Absorbance,   Fe = Iron,   Al = Aluminium,   Mn = Manganese,   N/R = No Result

The turbidity and UV absorbance of the raw and treated water for Blend 1 as a function of time are shown in Figures 17 and 18, respectively.
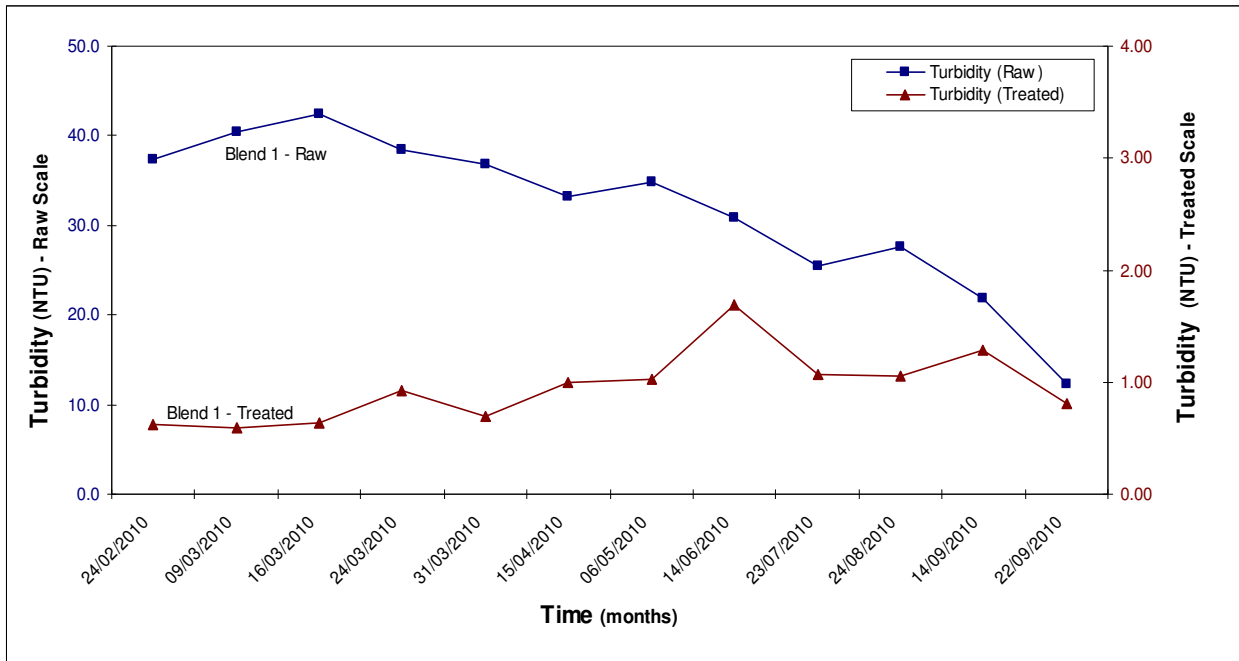
Figure 17   Turbidity of the raw and treated water for Blend 1 as a function of time (Fe^{3+} dose 5.0 mg/L, pH 5)
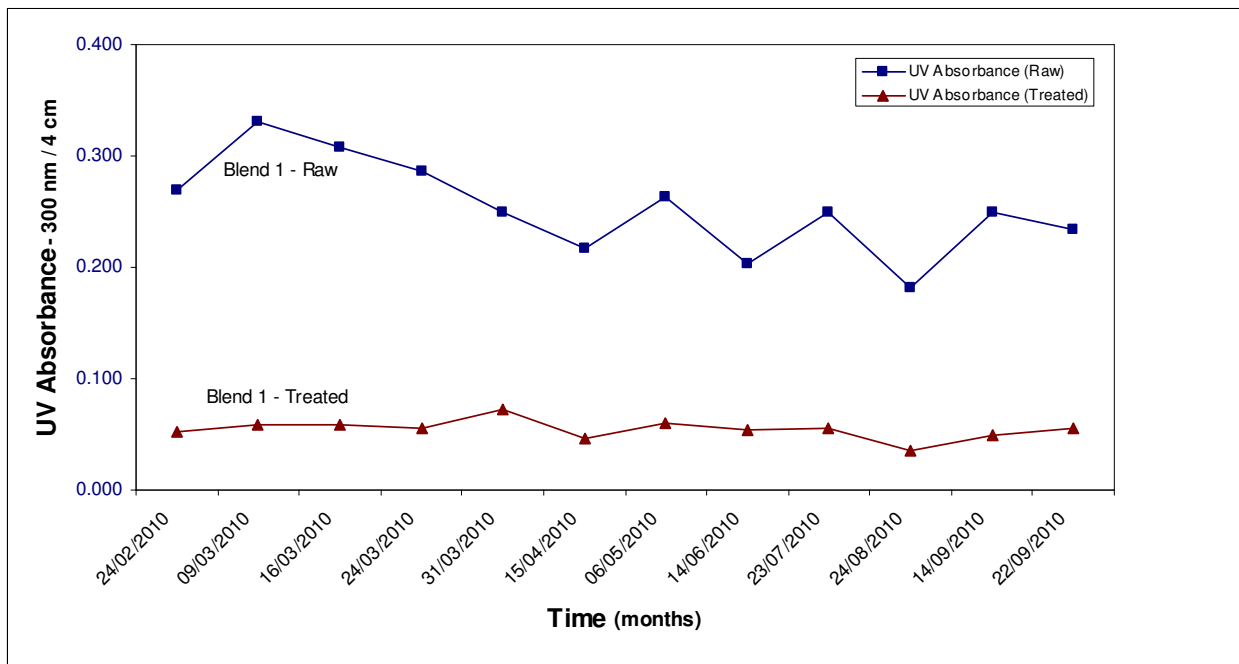
Figure 18   UV absorbance of the raw and treated water for Blend 1 as a function of time (Fe^{3+} dose 5.0 mg/L, pH 5)

The turbidity of the Blend 1 raw water ranges from 12.2 NTU's to 42.5 NTU's while the treated water turbidity ranges from 0.59 NTU's to 1.69 NTU's. Some of the results are consistently above 1NTU which is not acceptable based on the SANS 241:2006 Specification of <1 NTU for a Class I water. The UV absorbance of Blend 1 raw water ranges from 0.182 to 0.331 while the treated water ranges from 0.036 to 0.073. The results for the treated water are acceptable. Another concern is also the consistently high iron concentrations in the treated water which ranges from 0.197 to 0.530 mg/L as Fe with most of the results being greater than the maximum limit of 0.200 mg/L. The aluminium and manganese concentrations of the treated water are within the acceptable limits of 0.300 mg/L and 0.100 mg/L, respectively. The selected coagulation parameters did not give the desired results. Further investigation is necessary to determine the optimum coagulation parameters.

5.8.2 Treatment of Blend 2 (BR50:VV50)

The turbidity, UV absorbance, iron, aluminium and manganese content of the raw and treated water for Blend 2 are shown in Table 10.

Table 10   Turbidity, UV absorbance, iron, aluminium and manganese content of the raw and treated water for Blend 2

Date	Blend 2 (Berg River water 50% : Voëlvlei WTP raw water 50%)									
	Raw					Treated				
	Turb	UV Abs	Fe	Al	Mn	Turb	UV Abs	Fe	Al	Mn
Months	NTU	300nm 4cm	mg/L	mg/L	mg/L	NTU	300nm 4cm	mg/L	mg/L	mg/L
24/02/2010	53.7	0.282	2.177	3.390	0.064	0.61	0.053	0.294	0.025	0.043
09/03/2010	57.8	0.286	3.923	5.950	0.068	0.74	0.054	0.363	0.001	0.019
16/03/2010	62.1	0.298	N/R	N/R	N/R	0.81	0.052	0.395	0.007	0.047
24/03/2010	57.5	0.261	0.888	0.338	0.050	0.89	0.052	0.341	0.005	0.021
31/03/2010	53.0	0.186	3.440	5.630	0.065	0.42	0.048	0.236	0.002	0.032
15/04/2010	54.4	0.197	2.210	3.290	0.045	0.71	0.066	0.241	0.022	0.025
06/05/2010	54.5	0.239	2.360	3.750	0.039	1.18	0.040	0.588	0.060	0.074
14/06/2010	47.0	0.178	2.250	3.320	0.041	1.56	0.044	0.399	0.081	0.024
23/07/2010	35.5	0.272	1.720	2.360	0.037	1.40	0.065	0.405	0.072	0.023
24/08/2010	38.3	0.163	2.080	2.790	0.042	1.59	0.037	0.220	0.012	0.024
14/09/2010	29.7	0.252	1.720	2.360	0.052	1.71	0.047	0.587	0.118	0.063
22/09/2010	13.8	0.254	0.659	0.379	0.030	0.85	0.054	0.387	0.009	0.030

Turb = Turbidity,   UV Abs = UV Absorbance,   Fe = Iron,   Al = Aluminium,   Mn = Manganese,   N/R = No Result

The turbidity and UV absorbance of the raw and treated water for Blend 2 as a function of time are shown in Figures 19 and 20, respectively.
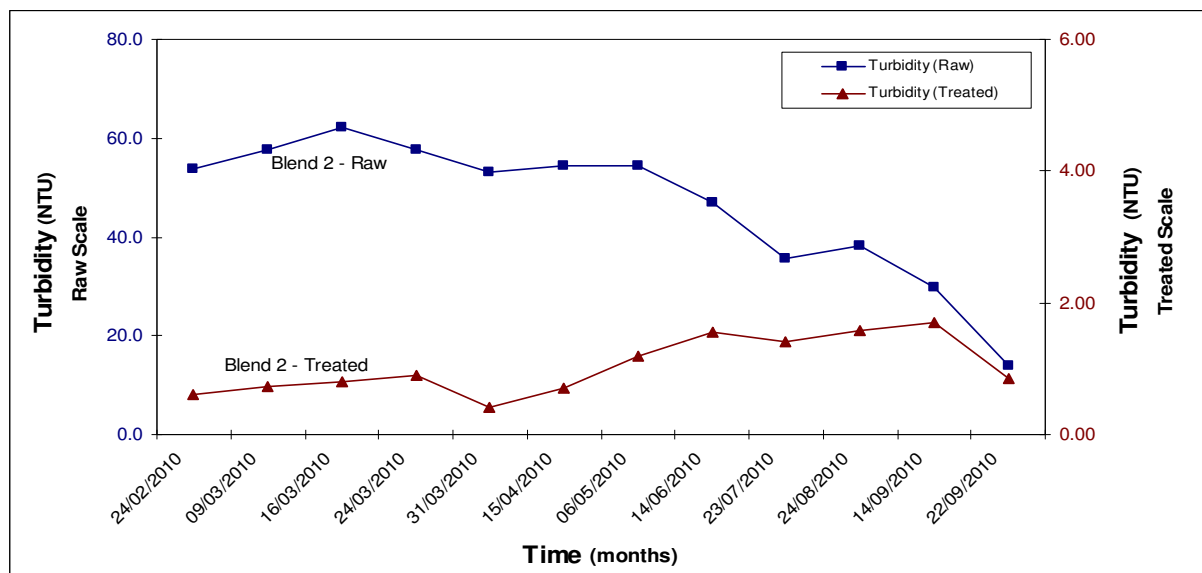
Figure 19   Turbidity of the raw and treated water for Blend 2 as a function of time
(Fe^{3+} dose 5.0 mg/L, pH 5)
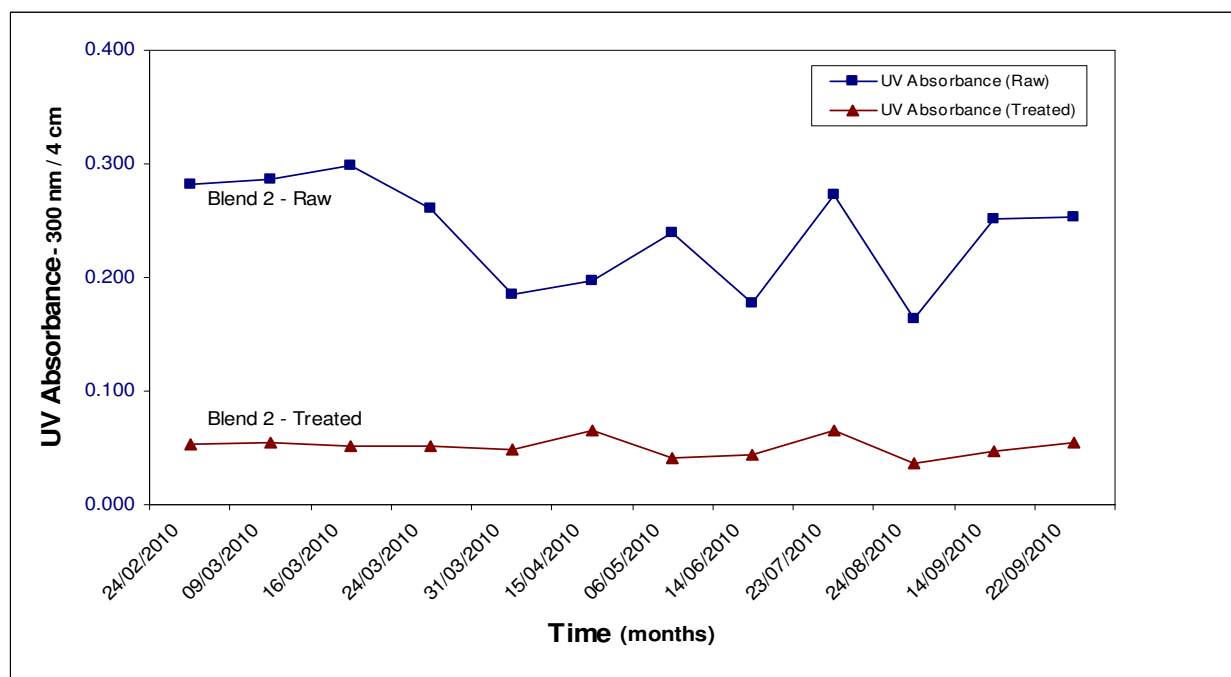
Figure 20   UV absorbance of the raw and treated water for Blend 2 as a function of time
(Fe^{3+} dose 5.0 mg/L, pH 5)

The turbidity of the Blend 2 raw water ranges from 13.8 NTU's to 62.1 NTU's while the treated water turbidity ranges from 0.61 NTU's to 1.71 NTU's. Contrary to the UV absorbance, the turbidities of the raw and treated water are slightly higher than those obtained for Blend 1. This is expected as the Voëlvlei WTP raw water which generally has a higher turbidity than the Berg River water was blended in a larger proportion. The UV absorbance of Blend 2 raw water ranges from 0.163 to 0.298 while the treated water ranges from 0.037 to 0.066. The iron concentration of the treated water is consistently above the specified value of <0.200 mg/L. The aluminium and manganese concentrations of the treated water are within the acceptable limit of 0.300 mg/L and 0.100 mg/L, respectively. As with Blend 1 the selected coagulation parameters did not give the desired results and further investigation is necessary to determine the optimum coagulation parameters for Blend 2.

5.8.3 Treatment of Blend 3 (BR25:VV75)

The turbidity, UV absorbance, iron, aluminium and manganese content of the raw and treated water for Blend 3 are shown in Table 11.

Table 11   Turbidity, UV absorbance, iron, aluminium and manganese content of the raw and treated water for Blend 3

Date	Blend 3 (Berg River water 25% : Voëlvlei WTP raw water 75%)									
	Raw					Treated				
	Turb	UV Abs	Fe	Al	Mn	Turb	UV Abs	Fe	Al	Mn
Months	NTU	300nm 4cm	mg/L	mg/L	mg/L	NTU	300nm 4cm	mg/L	mg/L	mg/L
24/02/2010	70.1	0.213	0.951	1.520	0.030	0.53	0.049	0.270	0.031	0.016
09/03/2010	75.8	0.239	1.394	0.847	0.056	0.71	0.049	0.292	0.003	0.017
16/03/2010	82.6	0.222	N/R	N/R	N/R	0.59	0.049	0.349	0.003	0.027
24/03/2010	77.2	0.248	1.035	0.474	0.051	1.06	0.047	0.261	0.004	0.019
31/03/2010	73.9	0.161	2.450	3.910	0.069	0.38	0.045	0.613	0.009	0.024
15/04/2010	71.0	0.210	3.290	5.220	0.047	0.47	0.041	0.661	0.362	0.042
06/05/2010	74.3	0.254	3.510	5.540	0.065	1.04	0.034	0.616	0.027	0.018
14/06/2010	66.7	0.232	3.230	5.160	0.044	1.25	0.044	0.362	0.041	0.023
23/07/2010	44.0	0.256	2.340	3.610	0.035	1.04	0.036	0.325	0.049	0.021
24/08/2010	48.6	0.220	2.600	3.630	0.041	1.45	0.036	0.248	0.056	0.025
14/09/2010	38.1	0.294	2.280	3.140	0.074	1.59	0.041	0.372	0.021	0.037
22/09/2010	17.3	0.273	0.799	0.440	0.042	0.82	0.076	0.408	0.010	0.030

Turb = Turbidity,   UV Abs = UV Absorbance,   Fe = Iron,   Al = Aluminium,   Mn = Manganese,   N/R = No Result

The turbidity and UV absorbance of the raw and treated water for Blend 3 as a function of time are shown in Figures 21 and 22, respectively.
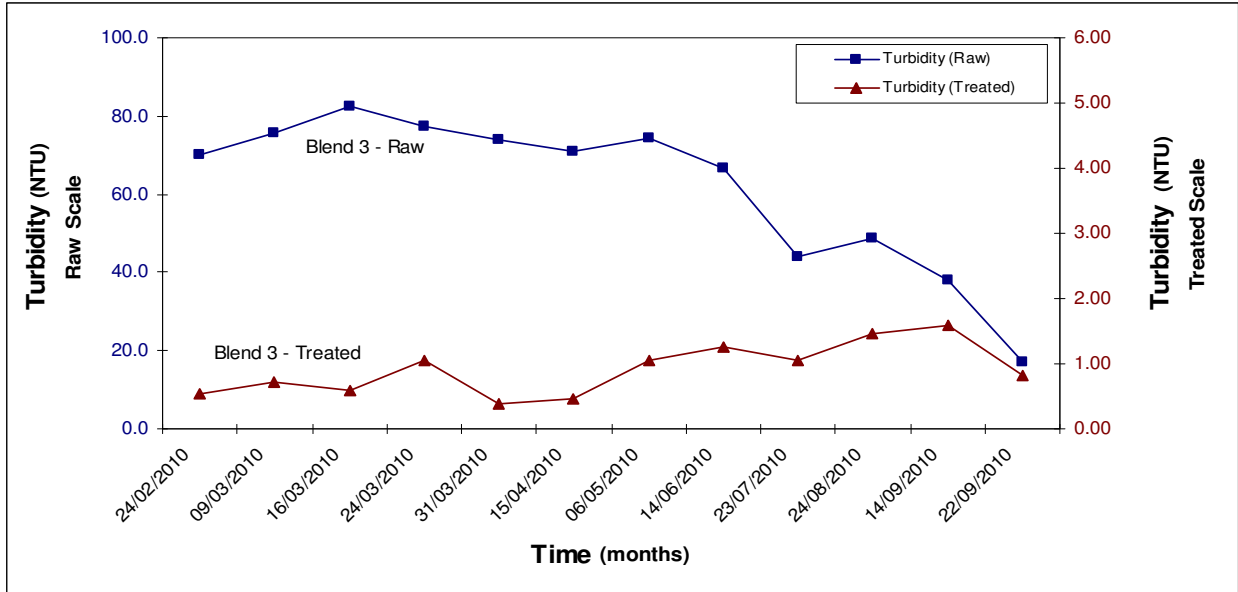
Figure 21   Turbidity of the raw and treated water for Blend 3 as a function of time (Fe^{3+} dose 5.0 mg/L, pH 5)
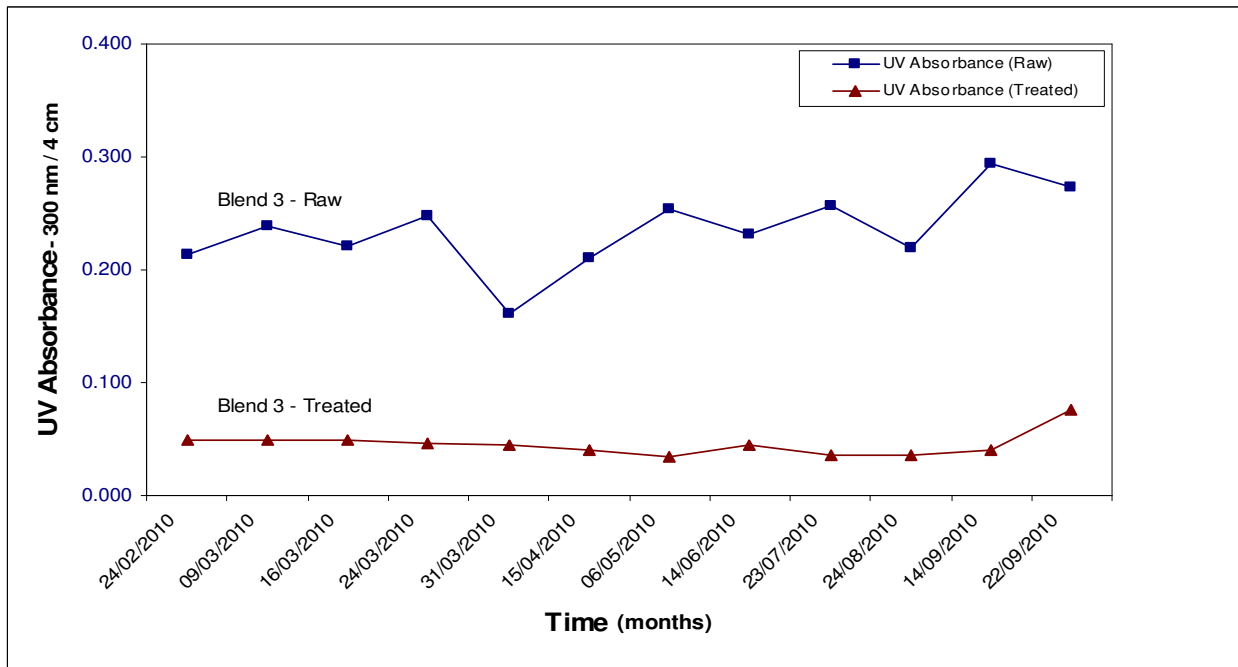
Figure 22   UV absorbance of the raw and treated water for Blend 3 as a function of time (Fe^{3+} dose 5.0 mg/L, pH 5)

The turbidities are expectedly higher than those obtained for Blends 1 and 2 and ranges from 17.3 NTU's to 82.6 NTU's for the raw water and 0.38 NTU's to 1.59 NTU's for the treated water. As with Blends 1 and 2 not all the treated water turbidities comply with the SANS 241:2006 Specification and the iron concentrations are also greater than the specified value. Since the majority of Blend 3 is made up of Voëlvlei WTP raw water (i.e., BR25:VV75), it could be expected that the UV absorbance would be slightly lower than the first two blends and this is confirmed in Table 11 which displays a UV absorbance range of 0.161 to 0.273 for the raw water and 0.034 to 0.076 for the treated water. As with Blends 1 and 2 the selected coagulation parameters did not give the desired results and further investigation is necessary to determine the optimum coagulation parameters for Blend 3.

5.9 Treatment of the raw water blends with the Voëlvlei WTP treatment parameters.

The Jar test results for the treatment of the Berg River water using ferric sulphate as the coagulant clearly indicates the optimum coagulation pH as 5.0 and the optimum coagulant dose as 5.0 mg/L as Fe^{3+} (see sections 5.6.1 and 5.7.1). These optimum treatment parameters might work well for the Berg River water only, but loses efficiency once this water is blended with the Voëlvlei WTP raw water. This is not surprising as the characteristics of the two raw waters are totally different (see sections 5.2 and 5.3) with the Berg River water having more colour than the Voëlvlei WTP raw water but far less turbidity. Since the two raw waters have their own optimum treatment parameters which are different to each other, more Jar tests should be conducted on each raw water blend to determine its optimum treatment parameters.

It would be logical to treat the raw water blends with the Voëlvlei WTP optimum treatment parameters as the Berg River water would be blended with the Voëlvlei WTP raw water and treated at the water treatment plant itself. Based on the results obtained in sections 5.8.1, 5.8.2 and 5.8.3, it appears that the Voëlvlei WTP optimum treatment parameters might not be efficient for the treatment of the raw water blends. Nevertheless, the Voëlvlei WTP optimum treatment parameters were used to treat the

raw water blends (optimum coagulation pH of 9.2 and an optimum ferric sulphate dosage of 3.5 mg/L as Fe^{3+}). The turbidity, UV absorbance and alkalinity of the raw and treated water blends are shown in Table 12.

Table 12 Turbidity, UV absorbance and alkalinity of the raw and treated water blends with the Voëlvlei WTP treatment parameters (Fe^{3+} dose 3.5 mg/L, pH 9.2)

Blend	Raw			Treated		
	Turb	UV Absorbance	Alkalinity	Turb	UV Absorbance	Alkalinity
	NTU	300nm 4cm	mg/L as $CaCO_3$	NTU	300nm 4cm	mg/L as $CaCO_3$
Blend 1 (BR75 : VV25)	27.4	0.188	22.6	1.29	0.129	26.7
Blend 2 (BR50 : VV50)	51.0	0.202	19.4	2.12	0.117	24.3
Blend 3 (BR25 : VV75)	66.9	0.213	15.1	1.97	0.105	18.3

Turb = Turbidity

The turbidity and UV absorbance of the raw and treated water blends with the Voëlvlei WTP treatment parameters are shown in Figures 23 and 24, respectively.
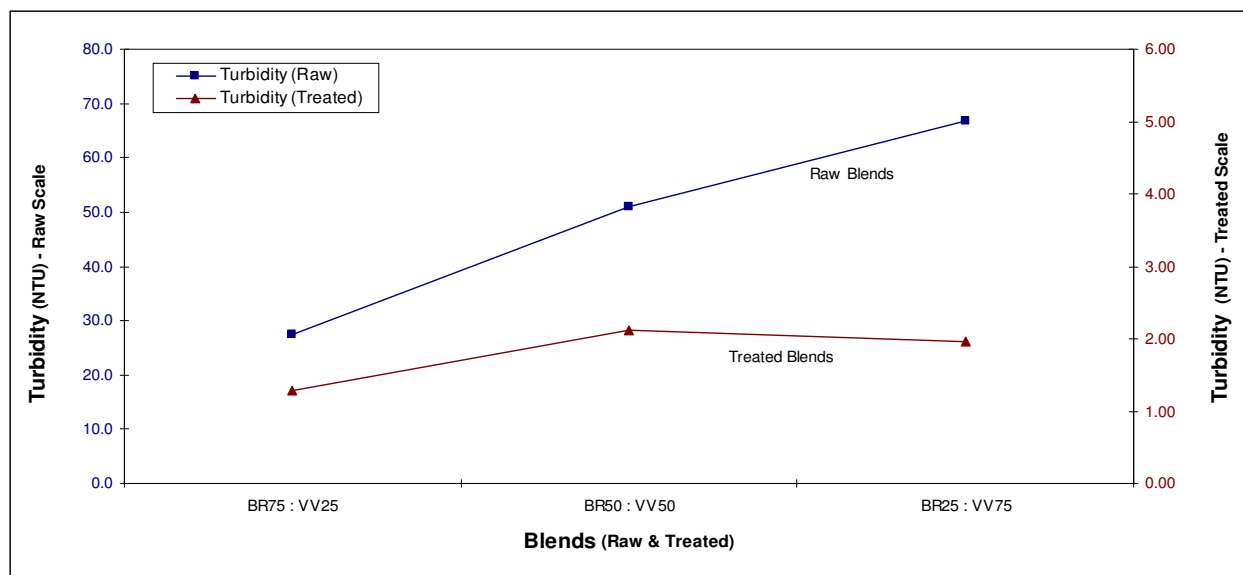
Figure 23 Turbidity of the raw and treated water blends with the Voëlvlei WTP treatment parameters (Fe^{3+} dose 3.5 mg/L, pH 9.2)
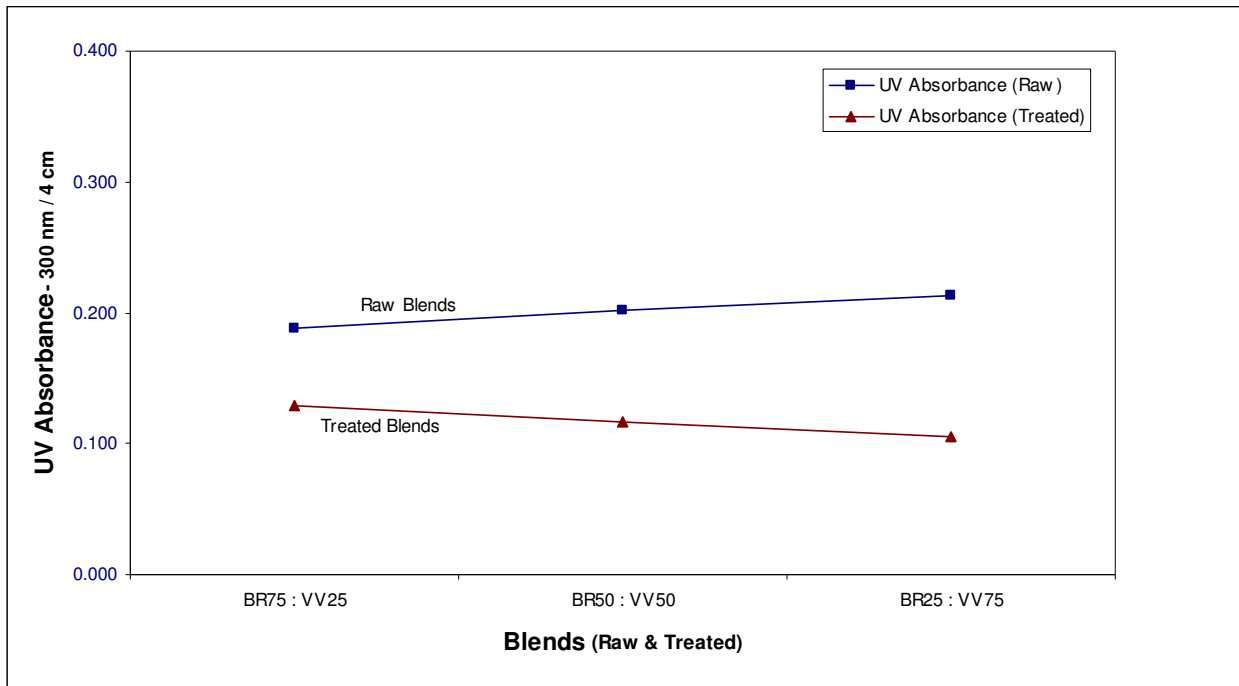
Figure 24   UV absorbance of the raw and treated water blends with the Voëlvlei WTP treatment parameters (Fe^{3+} dose 3.5 mg/L, pH 9.2)

The Voëlvlei WTP raw water generally has a higher turbidity than the Berg River water and since Blend 3 is mainly compiled of the Voëlvlei WTP raw water (i.e. 75 %) it is expected that this raw water blend should have the highest turbidity when compared to the other two blends. This expectation is confirmed in Table 12 and Figure 23 with the raw water blend turbidity increasing from Blend 1 to Blend 3. Even though treatment of the raw water blends at the Voëlvlei WTP treatment parameters had significantly reduced the raw water UV absorbance and turbidities, the treated water is still unacceptable with turbidities being greater than the specification of <1 NTU for a Class I water. The UV absorbance is also greater than the operational specification of 0.100 at 300 nm in a 4 cm cell (see Figures 23 & 24). It must be noted that the UV absorbance of the treated blended water is approximately 3 to 4 times higher than the UV absorbance of the Voëlvlei WTP treated water.

The results in this chapter have shown that only the Voëlvlei WTP raw water can be treated at the Voëlvlei WTP with its current treatment parameters. It is possible to treat the blended Berg River water at the Voëlvlei WTP, but the Voëlvlei WTP treatment parameters would have to be changed or the Berg River water would have to be pre-treated before entering the Voëlvlei WTP. It would not be practical to change the Voëlvlei WTP treatment parameters as this would compromise the quality of the Voëlvlei WTP treated water and the plants design and treatment strategy would also have to be adjusted to accommodate these changes. The Voëlvlei WTP operates at an optimum coagulation pH of 9.2 for the following reasons, amongst others:

➢ The Voëlvlei WTP raw water has a high turbidity when compared to the other 'soft' Western Cape coastal raw waters. This turbidity is more effectively removed at a higher coagulation pH.

➢ Due to the 'soft' nature (i.e. low alkalinity, low hardness) of the Western Cape coastal raw waters, the treated water pH should be adjusted to 9.2 in order to sufficiently stabilize the water for buffering capacity and also to protect the City's vast and complex water distribution network and infrastructure. The Voëlvlei WTP does not add lime (for final pH adjustment) and CO_2 (for stabilization) after the filtration stage of the water treatment process and therefore this desired treated pH of 9.2 has to be attained during the initial stages of coagulation and flocculation.

➢ The Voëlvlei WTP raw water has relatively high manganese content when compared to the other Western Cape raw waters. The manganese content can range from as low as 0.010 mg/L Mn to as high as 0.100 to 0.200 mg/L Mn. This metal is more effectively removed at a higher pH as MnO_2 and settles out during the sedimentation stage of the water treatment process.

Therefore, if the treatment parameters of the Voëlvlei WTP are adjusted to accommodate the Berg River water or even the raw water blends, the Voëlvlei WTP would produce low quality treated water and would probably not comply with the accepted drinking water standards. This treated water will have a higher UV

absorbance, colour, turbidity and manganese concentration. It would also have a lower pH value rendering the water more unstable and corrosive. The higher manganese concentration could increase the turbidity of the treated water and could also stain clothing when oxidized to MnO_2 during the washing process, both of which can lead to a public outcry. It therefore seems better to pre-treat the Berg River water instead of adjusting the design, structure and treatment strategy of the Voëlvlei WTP in order to accommodate this water.

5.10 Pre-treatment of the Berg River water.

There are various ways to pre-treat the Berg River water considering all the different treatment processes available and also new emerging technologies. The choice of the most appropriate and effective pre-treatment process should be based on various factors e.g., the desired treated water quality, the nature and availability of the treatment chemical(s), the volume and availability of raw water, cost effectiveness, etc.

5.10.1 Previous experimental work

Experiments were performed during August 2001 for the City of Cape Town on the Berg River water to determine its optimum treatment conditions, possible treatment at the Voëlvlei WTP and also pre-treatment options if required (Pieterse and Mxeli, 2001). Ferric sulphate was used as the coagulant in conjunction with various polymers to assist with coagulation and flocculation. Based on the experimental work, the following conclusions were made:

➢ "The Berg River water contains about 10% more humic materials than that from the Theewaterskloof Dam while at the same time having an alkalinity much higher than any of the existing Cape Town supplies. This complicates the treatment as it makes the use of the optimum pH for removal of organic matter more difficult to achieve".

➢ "It should be possible to treat the river water at the Voëlvlei WTP, with much the same quantities of chemicals, provided that facilities for the addition of lime for

stabilization are added between the settling tanks and filters. Sludge handling facilities and filters may need to be reviewed and overhauled".

➢ "The same treatment can probably be used for water from the Voëlvlei Dam and mixtures with river water".

➢ "The treated water quality will not be as good as that of the present water, having a greater salt and organic content, and hardness".

➢ "The average domestic wastewater content of the river during the winter, estimated to be about 2%, is of moderate concern. Refurbishment of the Voëlvlei WTP filters and dosing of powdered activated carbon when the river supply is in use, are advisable" (Pieterse and Mxeli, 2001).

5.10.2   Possible pre-treatment with ferric sulphate and aluminium sulphate

The results obtained in sections 5.6 and 5.7 indicated that both ferric sulphate and aluminium sulphate could be used to treat the Berg River water with ferric sulphate being the preferred choice given its wide coagulation pH range, its ability to effectively remove turbidity and organic matter and is also the coagulant being used at the Voëlvlei WTP. The pre-treatment of the Berg River water could be incorporated into the Voëlvlei WTP but this would not be easy and would require changes to the existing WTP, e.g., the coagulation and flocculation units would have to be rebuilt and lime would have to be added to the water between the settling tanks and the filters for stabilization. The lime should also be added in a channel or a series of stirred chambers, with facilities for removal of sediments. Lime storage silos and dosing equipment would be required. The additional head loss caused by this process would have to be taken into account and kept as low as possible in order not to reduce the flow to the filters below the design value or otherwise pumping may be required (Pieterse and Mxeli, 2001). Further research and investigation is necessary to determine what the best option would be, either building a small pre-treatment plant for the Berg River water or incorporating this pre-treatment into the present Voëlvlei WTP facility.

5.10.3 Possible pre-treatment with MIEX®

Some experimental work was conducted by B. Murray *et al.* (2005) to investigate the possible treatment of the 'soft' Western Cape coastal waters using MIEX®. The MIEX® resin (produced by Orica WaterCare) is a type 1 Strong Base Anion (SBA) resin in the chloride form and it is constituted by a macroporous structure poly-acrylic matrix with a dispersed magnetic component (Sani *et al.*, 2008). The MIEX® resin process is a continuous ion exchange process designed for the removal of DOC, UV absorbance and true colour from water supplies. The application of MIEX® resin technology in water treatment has the following advantages (Murray *et al.*, 2005):

- ➢ "Improved final water quality and reduced THM formation"
- ➢ "Improved floc formation and settlement in downstream coagulation"
- ➢ "Increased treatment plant capacity"
- ➢ "Reduced conventional chemical consumption"
- ➢ "Improved safety and risk management achieved through reduced chemical handling"
- ➢ "Reduced metal residuals (i.e. aluminium, iron and manganese) in the final water"
- ➢ "Reduced sludge production, reduced bacterial re-growth", and
- ➢ "Other associated benefits".

Murray *et al.* (2005) concluded that the MIEX® resin technology is very efficient for treatment of the highly coloured raw waters throughout the Cape region of South Africa. The results also indicated that using MIEX® DOC resin as a pre-treatment step would improve the quality of the final water whilst significantly reducing conventional chemical consumption.

The MIEX® resin technology could be used in the pre-treatment of the Berg River water but further research and investigation is necessary to confirm its application and treatment efficiency on this type of water.

5.11 Summary

The results presented in this chapter have shown the quality of the Voëlvlei WTP raw water and also the Berg River water. These results play an important role in deciding which treatment strategy to use in treating these two raw waters and their various blends. The Jar test results have indicated the optimum coagulation conditions for the treatment of both raw waters using either ferric sulphate or aluminium sulphate.

These results also confirmed that ferric sulphate would be the coagulant of choice to treat the Voëlvlei WTP raw water, while either ferric sulphate or aluminium sulphate could be used to treat the Berg River water.

Various blends of the two raw waters were also tested at these optimum coagulation conditions with ferric sulphate using the Jar test procedure. These results showed a reduction in treatment efficiency with some of the treated results failing to comply with operational and drinking water specifications. It is recommended that further Jar tests be conducted on these blends to determine their own optimum treatment parameters. These blends were also tested at the Voëlvlei WTP treatment parameters, but produced lower quality treated water that failed to meet the UV absorbance and turbidity specifications.

It is suggested that the Berg River water be pre-treated at the Voëlvlei WTP and possibly blended with the Voëlvlei WTP treated water. However, other treatment processes and technologies should also be investigated before a final decision is made.

CHAPTER 6

COST EVALUATION

6.1 Introduction

The results presented in the previous chapter have shown that the Berg River water cannot be treated efficiently with the Voëlvlei WTP treatment parameters. When the Berg River water was blended with the Voëlvlei WTP raw water in various proportions, treatment with the WTP treatment parameters was also problematic and it was concluded that these blends should be treated with its own optimum parameters which need to be determined through future investigation and research. It is possible to treat the Berg River water at the Voëlvlei WTP provided some design and treatment changes are made to the plants current operation but this also depends on the blending ratio of the raw waters. It is difficult to compare the costs of the various treatments and pre-treatments as there are many different factors and variables to consider. In this chapter, the monthly chemical usage operating costs of the Voëlvlei WTP are evaluated, while cost estimations are made for the pre-treatment of the Berg River water using conventional water treatment (with ferric sulphate as the coagulant) and also the MIEX$^{®}$ treatment technology. It is also difficult to estimate the cost of treatment of the raw water blends at the Voëlvlei WTP as this would depend on the changes that need to be made at the plant to accommodate the Berg River water. Since these changes still have to be investigated through future research, it is not possible to estimate a cost for this treatment option in this study. This chapter therefore only focuses on the monthly chemical usage operating costs at the Voëlvlei WTP and on the comparative pre-treatment costs of the Berg River water using conventional treatment with ferric sulphate and the MIEX$^{®}$ treatment technology.

6.2 Monthly chemical usage operating costs at the Voëlvlei WTP.

The monthly chemical usage operating costs at the Voëlvlei WTP, assuming the plant treats 3 000 ML of raw water per month (i.e. 100 ML/day for a 30 day month), are shown in Table 13.

Table 13   Monthly chemical usage operating costs at the Voëlvlei WTP
(assuming the plant treats 3 000 ML of raw water per month)

Chemical used	Current Dose (mg/L)	Mass of Product used (Tons)	Product Cost (ZAR/Ton)	Treatment Cost (ZAR)
Ferric Sulphate	3.50	10.5	8 850	92 925
Total Lime	6.58	19.74	985	19 444
Chlorine – Pre & Final	2.25	6.75	8 310	56 093
Poly – Electrolyte	1.69	5.07	10 230	17 289
Total monthly treatment cost per 3000 ML				185 751
Total monthly treatment cost per ML				61.92

ZAR = Zuid Afrikaanse Rand (South African Rand)

The data in Table 13 only indicates the WTP monthly operating costs with reference to the chemicals used for treatment and does not include other monthly operating costs e.g., maintenance and repairs of equipment and fittings, vehicle maintenance and operating costs, etc. The Voëlvlei WTP also uses powdered activated carbon, when necessary, in its treatment process to remove any undesirable taste and odour compounds which could occur in the Voëlvlei WTP raw water and this usage will therefore also increase the monthly operating costs. This monthly cost is not fixed and will vary depending on the chemical dosages and the quality of the raw water. The information in Table 13 gives a good indication of the amount of chemicals used per month and its relative costs.

6.3 Pre-treatment with Ferric Sulphate and MIEX®.

The monthly chemical usage operating costs were considered for the pre-treatment of the Berg River water using ferric sulphate, lime and chlorine, in comparison to the cost of the same pre-treatment but with the MIEX® resin. The poly-electrolyte used by the Voëlvlei WTP as a flocculant aid was not considered as it was not included in this study.

The approximate monthly chemical usage operational costs for the pre-treatment of the Berg River water, assuming that the plant treats 30 ML of river water per month (i.e., 1 ML/day for a 30 day month), are shown in Table 14. This table also indicates the estimated operational cost savings when using the MIEX® resin technology in conjunction with ferric sulphate, lime and chlorine.

Table 14 Monthly chemical usage operating costs of the Berg River water pre-treatment (assuming the plant treats 30 ML of river water per month)

Chemical used	Current Dose (mg/L)	Mass of Product used (Tons)	Product Cost (ZAR/Ton)	Pre-Treatment Cost (ZAR)	* Potential Saving with MIEX® resin Pre-treatment (%)	Potential Cost Saving (ZAR/month)
Ferric Sulphate	3.50	0.105	8 850	929	90	836
Total Lime	6.58	0.197	985	194	80	155
Chlorine – Pre & Final	2.25	0.068	8 310	565	30	169
Total monthly treatment cost (per 30 ML)				1 688		1 160
Total monthly treatment cost (per ML)				56.27		

ZAR = Zuid Afrikaanse Rand (South African Rand)

* The percentages for the potential saving with the MIEX® resin were quoted from Murray *et al.* (2005) except for the ferric sulphate percentage which was assumed to be the same as for aluminium sulphate.

Although the application of the MIEX® resin technology indicates a potential cost saving of 1160 ZAR per month, this figure does not include the cost of the resin regeneration. The exact operating cost saving is unique to each WTP and varies according to the raw water quality, coagulant demand, resin loss rates, plant operation and desired final water quality. Resin cost is a function of many variables, including raw water quality, plant design, existing infrastructure and plant operation. As a guide, the resin cost is approximately 80 to 120 ZAR/ML of treated water (Murray *et al.*, 2005). Even though the information in Table 14 gives a good indication of the pre-treatment operational costs involved, much more investigation and research is necessary and more factors and variables should be considered before these estimated values can become definite.

6.4 Summary

It is difficult to choose the best treatment strategy for the Berg River water based on the cost estimations presented in this chapter as the Voëlvlei WTP treatment and Berg River water pre-treatment chemical usage operating costs per ML are similar to each other (see Tables 13 & 14). Pre-treating the Berg River water at a separate pre-treatment plant using conventional water treatment with ferric sulphate, lime and chlorine seems to be the better option especially when used in conjunction with the MIEX® resin technology. Treating the Berg River water at the Voëlvlei WTP by blending it with the Voëlvlei WTP raw water would require design and treatment changes at the WTP which could result in significant capital costs. The treatment of the Berg River water at the Voëlvlei WTP could also increase the chemical dosage per month. The chemical treatment data in Chapter 5 also indicated that pre-treatment of the Berg River water would be the better option. This option seems more viable if the pre-treatment is performed in conjunction with the MIEX® resin technology. Further research and investigation is necessary to determine the exact costs involved and this should include all operating and capital costs.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The main objective of this study was to determine a treatment strategy for the Berg River water at the Voëlvlei WTP, while the specific objectives were:

a) Characterisation of the Voëlvlei WTP raw water
b) Characterisation of the Berg River water
c) Treatment of the Voëlvlei WTP raw water
d) Treatment of the Berg River water
e) Treatment of raw water blends
f) Treatment of raw water blends with the Voëlvlei WTP parameters
g) Preliminary cost evaluations
h) Evaluation of treatment strategies to determine the best treatment option

CONCLUSIONS

7.1 Characterization of the Voëlvlei WTP raw water.

The Voëlvlei WTP raw water was sampled and analysed weekly for the period May 2008 to December 2009.

a) The aluminium and iron concentrations were consistently low (<1.0 mg/L) during the summer months with maximum values of 7.654 and 4.494 mg/L, respectively, during the winter months.
b) The pH remained consistent between 6.8 and 7.8 during the monitoring period with maximum peaks (pH ± 9.0) during the summer months.
c) The turbidities ranged from ± 30 NTU's during the summer months to ± 70 to 90 NTU's during the winter months.
d) The UV absorbance (300 nm / 4 cm) ranged from 0.171 to 0.545 with maximum values throughout the year indicating minimal impact from seasonal variations.

e) The colour ranged from 10 to 60 mg/L Pt with the majority of the results between 30 and 50 mg/L Pt. There was no significant impact from seasonal variations.

7.2 Characterization of the Berg River water.

The Berg River water was also sampled and analysed weekly for the period May 2008 to December 2009.

a. The aluminium concentrations ranged from 0.122 to 1.640 mg/L with the majority of the results between 0.400 and 0.600 mg/L. The aluminium concentrations generally increased during the winter months.

b. The iron concentrations ranged from 0.224 to 2.670 mg/L with the majority of the results between 0.400 and 0.800 mg/L. Like the aluminium concentrations, the iron concentrations also increased during the winter months.

c. The pH ranged from 6.5 to 9.9 with most of the pH's between 6.5 and 7.5. The pH generally increased during the summer months.

d. The turbidities ranged from 4 to 354 NTU's with most of the results between 15 and 45 NTU's. The turbidities also increased during the winter months.

e. The UV absorbance (300 nm / 4 cm) ranged from 0.232 to 1.103 with the majority of the readings between 0.250 and 0.550. Unlike the Voëlvlei WTP raw water, there were slight increases in the UV absorbance during the winter months.

f. The colour ranged from 10 to 100 mg/L Pt with the majority of the results between 20 and 50 mg/L Pt. Like the UV absorbance, there were also slight increases in the colour during the winter months.

The above-mentioned physical and chemical results for these two raw waters play an important part in deciding which treatment strategy to use for the Berg River water. The seasonal fluctuations should also be considered with most of the concentrations increasing during the winter months with the exception of the pH which increased during the summer months.

7.3 Treatment of the Voëlvlei WTP raw water.

a. The optimum dosage concentration for ferric sulphate was determined to be between 3.0 and 4.0 mg/L as Fe^{3+} with an optimum coagulation pH range from 6.56 to 9.48. The Voëlvlei WTP coagulates at a pH of 9.2, not only because it falls within the optimum range, but also to remove turbidity and any manganese (as MnO_2) that might be present in the raw water. Ferric sulphate is therefore the preferred coagulant mainly because of its wide coagulation pH range.

b. The optimum dosage concentration for aluminium sulphate was determined to be between 2.5 and 3.0 mg/L as Al^{3+} with an optimum coagulation pH range from 6.0 to 7.0. Any manganese that might be present in the raw water would not be removed at this pH range and therefore aluminium sulphate is not the preferred coagulant at the Voëlvlei WTP.

7.4 Treatment of the Berg River water.

a. The optimum dosage concentration for ferric sulphate was determined to be between 4.0 and 6.0 mg/L as Fe^{3+} with an optimum coagulation pH range from 5.0 to 10.0 with the range 5.0 to 6.0 being the most effective for this water.

b. The optimum dosage concentration for aluminium sulphate was determined to be between 4.0 and 5.0 mg/L as Al^{3+} with an optimum coagulation pH of 6.0.

It must be remembered that even though this optimum coagulation pH is effective for removing colour, turbidity and organic matter, it would not remove the manganese from the Berg River water. Manganese is removed at higher pH values and therefore ferric sulphate would be the preferred coagulant because of its wide coagulation pH range.

7.5 Treatment of raw water blends.

The Jar test was conducted on all 3 raw water blends viz. Blend 1 (BR75:VV25), Blend 2 (BR50:VV50) and Blend 3 (BR25:VV75) at a coagulation pH of 5.0 and a ferric sulphate dosage concentration of 5.0 mg/L as Fe^{3+}.

The results obtained for all 3 blends were similar to each other. The UV absorbance of the treated water was consistently below the operational specification of <0.100, while the turbidities were inconsistent and did not always comply with the SANS 241:2006 Specification (Class I) for drinking water which is <1 NTU. The iron concentrations of the treated water were also consistently above the specified value of <0.200 mg/L. These treatment parameters were therefore not effective in treating the raw water blends and further investigation and research is necessary to determine its optimum treatment parameters.

7.6 Treatment of raw water blends with the Voëlvlei WTP treatment parameters.

The Jar tests were also conducted on all 3 raw water blends with the Voëlvlei WTP treatment parameters i.e., at a coagulation pH of 9.2 and a ferric sulphate dosage concentration of 3.5 mg/L as Fe^{3+}.

The results obtained for all 3 blends were once again similar to each other. The UV absorbance of the treated water was consistently above the maximum operational specification of 0.100, while the turbidities were also consistently above the SANS 241:2006 Specification of <1 NTU. These results therefore indicate that the raw water blends cannot be effectively treated with the Voëlvlei WTP treatment parameters and, as mentioned in 7.5 above, further investigation and research is necessary to determine its optimum treatment parameters.

7.7 Preliminary cost evaluations

The preliminary cost evaluations, which focused only on chemical treatment costs, indicate that the pre-treatment costs (approximately ZAR 56.27 per ML) of the Berg River water using ferric sulphate, lime and chlorine are similar to the present treatment costs (approximately ZAR 61.92 per ML) of the Voëlvlei WTP raw water using the same chemicals. If the MIEX® treatment technology is used in conjunction with ferric sulphate, lime and chlorine for the pre-treatment of the Berg River water, then these pre-treatment costs would be reduced significantly. Like the experimental results, the preliminary cost

evaluations favour pre-treatment of the Berg River water especially if it includes the MIEX® treatment technology which would result in significant cost savings.

7.8   Evaluation of treatment strategies to determine the best treatment option

The main aim of this study was to determine a treatment strategy for the Berg River water at the Voëlvlei WTP. The experimental results indicate that the Berg River water cannot be effectively treated at the Voëlvlei WTP using the plants treatment parameters, even if it is blended with the Voëlvlei WTP raw water. Therefore, the best treatment strategy for the Berg River water at the Voëlvlei WTP would be pre-treatment of the water before entering the Voëlvlei WTP. Although there are various ways of pre-treating the Berg River water, this study has identified the following possible pre-treatment strategies:

(iv) pre-treatment with ferric sulphate and lime

 (v) pre-treatment with ferric sulphate and lime in conjunction with MIEX® resin

(vi) pre-treatment with MIEX® resin only

Further research and investigation is necessary to determine the best pre-treatment strategy in terms of cost and efficiency. The pre-treated Berg River water would have to pass through the Voëlvlei WTP treatment process (i.e. high coagulation pH) to remove any manganese that might be present in the water.

RECOMMENDATIONS

a) More samples should be taken at various points along the Berg River upstream of the Voëlvlei WTP over a longer period of time to compare the quality of water at these points in the river and also to monitor the effect of various run-off sites, e.g., the Paarl and Wellington wastewater works, agriculture, informal settlements, etc. Although microbiological analyses were not part of this study, it would be advisable to include this important analytical parameter in the monitoring programme. This information would play an important part in finalizing a pre-treatment strategy for the Berg River water.

b) MIEX® resin technology seems to be an effective treatment strategy, in terms of cost and treated water quality, and further research is necessary to see if this technology could be used as a pre-treatment step on its own or in conjunction with a more conventional water treatment process using ferric sulphate, lime and chlorine.

c) A more in-depth investigation is necessary to determine the actual capital and operational costs for the pre-treatment of the Berg River water. A detailed report should be compiled comparing all the costs involved for the proposed pre-treatment strategies.

CHAPTER 8

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CHAPTER 9

APPENDICES

Appendix A   Physical and chemical results for the Voëlvlei WTP raw water

Table A1   Physical and chemical results for the Voëlvlei WTP raw water (May 2008 – October 2008): Part A

Sample Date	Alkalinity	Aluminium	Calcium	Chloride	Colour	Conductivity	Hardness	Iron
	mg/L as CaCO$_3$	mg/L	mg/L	mg/L	mg/L Pt	mS/m	mg/L as CaCO$_3$	mg/L
5/05/08	14.0	0.631	4.3	18.1	40	9.3	21	0.709
12/05/08	13.7	2.744	3.5	18.7	30	9.2	19	1.896
19/05/08	13.8	1.745	3.8	17.0	30	9.2	20	0.751
25/05/08	13.5	1.177	3.7	18.6	40	11.0	20	0.942
2/06/08	13.9	3.248	3.7	18.7	20	9.0	20	2.045
9/06/08	13.6	1.482	3.4	18.1	40	9.1	17	0.839
17/06/08	14.0	0.383	4.0	18.4	10	9.2	20	0.485
23/06/08	13.4	2.047	3.2	18.0	20	8.8	17	2.834
30/06/08	12.7	5.770	3.9	17.9	40	8.7	22	3.620
7/07/08	12.3	5.340	3.2	16.9	20	8.3	18	3.300
14/07/08	6.7	1.070	3.0	16.8	30	8.0	16	0.868
21/07/08	11.0	0.502	2.8	14.1	20	7.7	15	0.573
28/07/08	10.8	0.297	2.6	15.9	20	7.7	14	0.509
4/08/08	10.6	0.420	2.8	15.3	30	7.8	15	0.560
11/08/08	11.5	0.282	3.2	14.8	50	8.0	16	0.708
18/08/08	10.1	0.437	2.5	14.4	30	7.5	14	0.476
25/08/08	10.4	0.471	2.8	14.3	29	7.7	15	0.524
1/09/08	10.3	0.409	2.8	14.8	32	7.8	15	0.537
8/09/08	9.8	0.422	2.6	14.8	17	7.5	15	0.410
15/09/08	9.8	0.375	2.3	15.1	51	7.3	13	0.394
22/09/08	9.7	0.247	2.3	15.5	34	7.3	13	0.376
29/09/08	10.2	0.429	2.6	14.4	32	7.3	14	0.437
6/10/08	9.2	0.408	2.4	13.7	26	7.6	13	0.591
13/10/08	9.7	0.390	2.4	14.6	32	7.3	13	0.436
20/10/08	10.5	0.383	1.9	14.9	38	7.4	11	0.379
27/10/08	10.0	0.371	2.5	13.8	32	7.4	14	0.417

Table A2   Physical and chemical results for the Voëlvlei WTP raw water (May 2008 – October 2008): Part B

Sample Date	Magnesium	Manganese	pH	Potassium	Sulphate	Sodium	Turbidity	UV Absorbance
	mg/L	mg/L		mg/L	mg/L	mg/L	NTU	300 nm / 4 cm
5/05/08	2.6	0.040	7.38	1.00	5.5	10.9	86	0.405
12/05/08	2.4	0.026	7.39	0.91	4.5	10.3	74	0.328
19/05/08	2.5	0.010	7.46	0.93	3.2	9.9	65	0.382
25/05/08	2.5	0.019	7.40	0.88	4.4	10.8	69	0.407
2/06/08	2.6	0.020	7.30	1.11	4.5	9.3	69	0.203
9/06/08	2.0	0.012	7.39	1.01	5.3	8.9	67	0.367
17/06/08	2.4	0.016	7.63	0.75	5.9	9.6	70	0.171
23/06/08	2.1	0.043	7.31	0.86	5.4	9.4	88	0.275
30/06/08	2.9	0.040	7.40	1.41	5.5	10.3	69	0.443
7/07/08	2.5	0.039	7.35	1.19	5.4	8.8	72	0.270
14/07/08	2.1	0.027	5.78	0.84	5.1	8.3	77	0.344
21/07/08	2.0	0.023	7.18	0.80	2.9	8.1	72	0.366
28/07/08	1.9	0.016	7.25	0.63	3.1	7.6	63	0.288
4/08/08	1.9	0.016	7.24	0.77	3.8	7.8	56	0.391
11/08/08	2.0	<0.001	7.52	0.76	3.5	7.7	53	0.429
18/08/08	2.0	0.007	7.17	0.79	3.1	8.8	45	0.374
25/08/08	2.0	0.008	7.30	0.77	3.1	8.9	42	0.345
1/09/08	2.0	0.008	7.56	0.72	4.7	8.7	48	0.360
8/09/08	2.0	0.006	7.18	0.64	–	8.7	46	0.257
15/09/08	1.9	0.011	7.69	0.61	1.5	8.2	41	0.495
22/09/08	1.8	0.011	7.48	0.54	3.7	8.2	44	0.383
29/09/08	1.9	0.015	7.47	0.67	1.6	8.8	45	0.351
6/10/08	1.8	0.017	6.83	80.55	2.1	54.6	35	0.363
13/10/08	1.8	0.015	7.50	0.68	<4.0	7.2	50	0.352
20/10/08	1.6	0.014	9.01	0.67	<4.0	7.5	40	0.401
27/10/08	1.9	0.012	7.56	0.72	<4.0	8.3	41	0.332

Table A3   Physical and chemical results for the Voëlvlei WTP raw water (November 2008 – May 2009): Part A

Sample Date	Alkalinity	Aluminium	Calcium	Chloride	Colour	Conductivity	Hardness	Iron
	mg/L as CaCO$_3$	mg/L	mg/L	mg/L	mg/L Pt	mS/m	mg/L as CaCO$_3$	mg/L
3/11/08	10.0	0.662	2.3	14.9	35	7.5	13	0.600
10/11/08	8.8	2.235	2.7	14.1	41	7.9	16	1.609
17/11/08	9.6	0.295	2.5	14.2	21	7.9	14	0.485
24/11/08	10.5	0.381	2.6	14.2	18	8.0	15	0.541
1/12/08	11.3	0.371	2.6	14.9	39	8.0	15	0.466
8/12/08	10.9	0.380	2.6	15.2	28	8.0	15	0.440
15/12/08	12.5	3.504	2.7	15.4	47	8.2	16	2.219
12/01/09	11.9	1.377	2.5	15.4	30	8.3	15	1.144
19/01/09	11.4	0.39	2.6	15.6	33	8.3	15	0.683
26/01/09	12.2	0.534	2.7	14.8	27	8.7	15	0.655
2/02/09	11.4	2.291	2.8	15.4	14	8.6	17	1.724
9/02/09	12.2	0.497	3.1	16.0	38	8.7	17	0.612
16/02/09	12.2	0.449	3.0	16.0	47	8.7	16	0.628
23/02/09	11.6	2.115	3.0	17.0	52	8.9	17	1.629
2/03/09	11.6	0.607	3.0	17.0	50	8.9	16	0.445
9/03/09	12.3	0.678	3.2	16.0	46	9.5	17	0.692
16/03/09	11.3	0.767	3.2	16.0	47	9.2	17	0.611
23/03/09	12.0	7.067	3.1	16.0	40	8.7	20	4.101
30/03/09	11.8	7.126	3.5	17.0	35	9.1	21	4.205
6/04/09	11.0	0.326	3.1	18.0	39	9.1	17	0.462
14/04/09	9.9	6.835	3.6	17.0	35	9.2	22	4.138
20/04/09	13.1	6.858	4.2	17.0	18	10.8	23	4.211
4/05/09	11.9	7.155	3.3	17.0	46	9.0	21	4.167
11/05/09	12.4	7.302	3.2	17.0	38	9.2	21	4.240
18/05/09	12.5	7.654	3.4	17.0	46	9.1	21	4.494
25/05/09	12.7	6.463	3.5	17.0	43	9.2	21	3.920

Table A4   Physical and chemical results for the Voëlvlei WTP raw water (November 2008 – May 2009): Part B

Sample Date	Magnesium	Manganese	pH	Potassium	Sulphate	Sodium	Turbidity	UV Absorbance
	mg/L	mg/L		mg/L	mg/L	mg/L	NTU	300 nm / 4 cm
3/11/08	1.8	0.019	7.59	0.66	<4.0	7.8	42	0.371
10/11/08	2.1	0.021	6.98	1.18	4.4	7.8	43	0.413
17/11/08	1.9	0.019	9.25	0.88	<4.0	7.8	35	0.269
24/11/08	2.0	0.024	7.94	0.80	4.8	8.3	57	0.241
1/12/08	2.0	0.018	9.17	0.73	3.8	8.3	44	0.387
8/12/08	2.0	0.012	7.17	0.76	3.4	8.4	47	0.310
15/12/08	2.3	0.019	8.68	1.25	4.0	8.6	46	0.455
12/01/09	2.2	0.032	8.33	1.03	3.7	8.4	47	0.315
19/01/09	2.2	0.040	8.39	0.88	4.1	8.0	48	0.348
26/01/09	2.0	0.027	8.16	0.20	3.6	7.9	54	0.371
2/02/09	2.3	0.035	7.37	1.30	3.4	8.8	54	0.173
9/02/09	2.2	0.022	7.62	0.86	3.7	8.8	57	0.367
16/02/09	2.2	0.032	7.72	0.78	3.9	9.6	55	0.452
23/02/09	2.4	0.037	7.76	1.21	7.5	9.4	61	0.493
2/03/09	2.2	0.021	8.03	0.99	3.8	9.2	55	0.471
9/03/09	2.2	0.030	7.65	0.70	3.9	8.9	51	0.451
16/03/09	2.3	0.021	7.36	0.99	3.5	9.6	55	0.445
23/03/09	3.0	0.051	7.57	2.29	3.5	9.5	66	0.409
30/03/09	3.1	0.044	7.17	2.61	3.4	9.6	58	0.363
6/04/09	2.3	0.030	6.90	0.84	3.6	10.3	73	0.379
14/04/09	3.0	0.044	7.12	2.15	4.1	8.7	67	0.333
20/04/09	3.1	0.040	7.34	2.57	4.4	9.9	66	0.411
4/05/09	3.2	0.040	7.16	2.43	3.8	10.2	78	0.446
11/05/09	3.1	0.041	7.22	2.44	3.8	10.0	75	0.377
18/05/09	3.1	0.041	7.25	2.39	3.8	9.9	71	0.428
25/05/09	3.1	0.040	7.36	2.09	4.4	10.0	56	0.416

Table A5 Physical and chemical results for the Voëlvlei WTP raw water (June 2009 – December 2009): Part A

Sample Date	Alkalinity	Aluminium	Calcium	Chloride	Colour	Conductivity	Hardness	Iron
	mg/L as CaCO$_3$	mg/L	mg/L	mg/L	mg/L Pt	mS/m	mg/L as CaCO$_3$	mg/L
1/06/09	12.3	5.812	3.8	18.0	51	9.7	22	3.343
8/06/09	12.0	–	3.3	17.0	60	9.6	18	NA
15/06/09	11.5	5.610	3.1	17.0	59	9.6	19	3.357
22/06/09	11.8	5.564	2.9	17.0	22	9.6	18	3.305
29/06/09	11.5	5.039	2.9	14.0	21	9.4	18	3.082
6/07/09	9.9	4.800	2.6	16.0	25	9.5	17	3.010
13/07/09	10.2	4.390	2.1	15.0	25	8.9	15	2.675
20/07/09	9.6	0.398	2.2	15.0	22	8.5	13	0.408
28/07/09	10.1	3.842	1.1	16.0	23	8.1	12	2.481
3/08/09	9.8	4.052	1.9	16.0	16	8.3	14	2.669
11/08/09	9.8	3.541	2.0	15.0	51	7.8	13	2.243
17/08/09	8.4	3.809	2.2	15.0	26	7.6	14	2.384
24/08/09	8.9	3.438	1.8	15.0	13	7.5	13	2.148
31/08/09	8.4	3.779	2.2	14.0	53	7.5	14	2.327
7/09/09	9.3	3.716	1.7	14.0	18	7.5	13	2.339
14/09/09	9.5	3.680	1.6	15.0	37	7.3	12	2.280
21/09/09	9.7	0.260	1.5	15.0	28	7.4	11	0.403
28/09/09	10.2	3.129	1.9	14.0	18	8.0	13	1.975
5/10/09	9.8	3.913	1.7	15.0	53	7.7	13	2.485
12/10/09	9.7	3.139	1.4	15.0	26	7.6	10	1.919
19/10/09	10.0	3.640	2.0	15.0	28	7.8	13	2.250
26/10/09	10.2	3.412	2.5	15.0	27	7.9	15	2.157
2/11/09	10.5	3.967	2.4	15.0	29	7.7	15	2.418
9/11/09	10.1	3.886	2.6	15.0	28	7.8	15	2.547
16/11/09	10.5	4.211	4.1	15.0	20	7.9	20	2.578
23/11/09	11.1	3.792	2.2	16.0	54	8.3	15	2.425
30/11/09	11.2	4.038	1.6	16.0	31	8.2	14	2.457
7/12/09	10.7	4.509	1.8	16.0	31	8.2	14	2.983
14/12/09	11.2	4.850	2.1	16.0	28	8.2	15	3.006
21/12/09	11.1	4.340	2.8	16.0	32	9.1	17	2.714

Table A6   Physical and chemical results for the Voëlvlei WTP raw water (June 2009 – December 2009): Part B

Sample Date	Magnesium	Manganese	pH	Potassium	Sulphate	Sodium	Turbidity	UV Absorbance
	mg/L	mg/L		mg/L	mg/L	mg/L	NTU	300 nm / 4 cm
1/06/09	2.9	0.025	7.26	2.14	4.2	10.8	54	0.477
8/06/09	2.4	0.011	7.19	–	4.6	10.4	53	0.545
15/06/09	2.7	0.035	7.29	1.75	4.9	9.4	53	0.462
22/06/09	2.7	0.036	7.18	2.46	3.7	9.8	51	0.262
29/06/09	2.5	0.027	7.06	1.91	3.3	9.2	50	0.249
6/07/09	2.5	0.029	7.11	1.85	3.2	9.3	43	0.317
13/07/09	2.3	0.020	7.11	1.56	3.4	8.7	31	0.266
20/07/09	1.9	0.011	7.03	0.77	3.4	8.4	36	0.257
28/07/09	2.2	0.024	7.02	1.39	5.1	7.9	33	0.252
3/08/09	2.2	0.026	7.12	1.41	3.8	7.8	39	0.242
11/08/09	2.0	0.019	7.36	1.32	3.2	8.0	37	0.464
17/08/09	2.1	0.020	7.12	1.45	3.2	8.0	33	0.288
24/08/09	2.1	0.022	7.14	1.34	3.0	7.5	33	0.196
31/08/09	2.1	0.010	7.20	1.44	2.6	8.0	36	0.230
7/09/09	2.0	0.019	7.22	1.48	1.8	7.4	38	0.264
14/09/09	2.0	0.022	7.27	1.26	2.7	7.5	37	0.413
21/09/09	1.7	0.011	7.61	0.76	3.2	7.6	34	0.326
28/09/09	1.9	0.019	9.22	1.00	3.6	7.2	34	0.250
5/10/09	2.0	0.034	9.14	1.33	3.1	7.7	40	0.472
12/10/09	1.7	0.014	9.09	0.73	1.7	7.2	38	0.287
19/10/09	1.9	0.022	7.99	1.17	1.4	7.2	33	0.227
26/10/09	2.0	0.022	7.72	1.24	3.5	8.0	34	0.412
2/11/09	2.1	0.031	7.35	1.30	2.9	8.2	35	0.258
9/11/09	2.1	0.033	7.26	1.29	4.3	7.9	34	0.502
16/11/09	2.3	0.030	7.34	1.37	2.9	9.7	40	0.242
23/11/09	2.2	0.029	8.19	1.19	2.6	8.3	37	0.493
30/11/09	2.4	0.029	7.70	1.15	2.8	8.8	37	0.232
7/12/09	2.3	0.033	7.19	1.79	3.0	8.1	42	0.272
14/12/09	2.3	0.036	7.43	1.43	3.1	9.0	26	0.448
21/12/09	2.5	0.030	8.09	1.25	1.1	9.2	43	0.454

Appendix B Physical and chemical results for the Voëlvlei WTP raw water as a function of time

Table B1 Aluminium and iron concentration of the Voëlvlei WTP raw water as a function of time

Date	Al (mg/L)	Fe (mg/L)	Date	Al (mg/L)	Fe (mg/L)	Date	Al (mg/L)	Fe (mg/L)
5/05/08	0.631	0.709	3/11/08	0.662	0.600	1/06/09	5.812	3.343
12/05/08	2.744	1.896	10/11/08	2.235	1.609	15/06/09	5.610	3.357
19/05/08	1.745	0.751	17/11/08	0.295	0.485	22/06/09	5.564	3.305
25/05/08	1.177	0.942	24/11/08	0.381	0.541	29/06/09	5.039	3.082
2/06/08	3.248	2.045	1/12/08	0.371	0.466	6/07/09	4.800	3.010
9/06/08	1.482	0.839	8/12/08	0.380	0.440	13/07/09	4.390	2.675
17/06/08	0.383	0.485	15/12/08	3.504	2.219	20/07/09	0.398	0.408
23/06/08	2.047	2.834	12/01/09	1.377	1.144	28/07/09	3.842	2.481
30/06/08	5.770	3.620	19/01/09	0.390	0.683	3/08/09	4.052	2.669
7/07/08	5.340	3.300	26/01/09	0.534	0.655	11/08/09	3.541	2.243
14/07/08	1.070	0.868	2/02/09	2.291	1.724	17/08/09	3.809	2.384
21/07/08	0.502	0.573	9/02/09	0.497	0.612	24/08/09	3.438	2.148
28/07/08	0.297	0.509	16/02/09	0.449	0.628	31/08/09	3.779	2.327
4/08/08	0.420	0.560	23/02/09	2.115	1.629	7/09/09	3.716	2.339
11/08/08	0.282	0.708	2/03/09	0.607	0.445	14/09/09	3.680	2.280
18/08/08	0.437	0.476	9/03/09	0.678	0.692	21/09/09	0.260	0.403
25/08/08	0.471	0.524	16/03/09	0.767	0.611	2/11/09	3.967	2.418
1/09/08	0.409	0.537	23/03/09	7.067	4.101	9/11/09	3.886	2.547
8/09/08	0.422	0.410	30/03/09	7.126	4.205	16/11/09	4.211	2.578
15/09/08	0.375	0.394	6/04/09	0.326	0.462	23/11/09	3.792	2.425
22/09/08	0.247	0.376	14/04/09	6.835	4.138	30/11/09	4.038	2.457
29/09/08	0.429	0.437	20/04/09	6.858	4.211	7/12/09	4.509	2.983
6/10/08	0.408	0.591	4/05/09	7.155	4.167	14/12/09	4.850	3.006
13/10/08	0.390	0.436	11/05/09	7.302	4.240	21/12/09	4.340	2.714
20/10/08	0.383	0.379	18/05/09	7.654	4.494	–	–	–
27/10/08	0.371	0.417	25/05/09	6.463	3.920	–	–	–

Table B2 pH and turbidity of the Voëlvlei WTP raw water as a function of time

Date	pH	Turb (NTU)	Date	pH	Turb (NTU)	Date	pH	Turb (NTU)
5/05/08	7.38	86	24/11/08	7.94	57	22/06/09	7.18	51
12/05/08	7.39	74	1/12/08	9.17	44	29/06/09	7.06	50
19/05/08	7.46	65	8/12/08	7.17	47	6/07/09	7.11	43
25/05/08	7.40	69	15/12/08	8.68	46	13/07/09	7.11	31
2/06/08	7.30	69	22/12/08	6.97	42	20/07/09	7.03	36
9/06/08	7.39	67	5/01/09	7.84	44	28/07/09	7.02	33
17/06/08	7.63	70	12/01/09	8.33	47	3/08/09	7.12	39
23/06/08	7.31	88	19/01/09	8.39	48	11/08/09	7.36	37
30/06/08	7.40	69	26/01/09	8.16	54	17/08/09	7.12	33
7/07/08	7.35	72	2/02/09	7.37	54	24/08/09	7.14	33
14/07/08	5.78	77	9/02/09	7.62	57	31/08/09	7.20	36
21/07/08	7.18	72	16/02/09	7.72	55	7/09/09	7.22	38
28/07/08	7.25	63	23/02/09	7.76	61	14/09/09	7.27	37
4/08/08	7.24	56	2/03/09	8.03	55	21/09/09	7.61	34
11/08/08	7.52	53	9/03/09	7.65	51	28/09/09	9.22	34
18/08/08	7.17	45	16/03/09	7.36	55	5/10/09	9.14	40
25/08/08	7.30	42	23/03/09	7.57	66	12/10/09	9.09	38
1/09/08	7.56	48	30/03/09	7.17	58	19/10/09	7.99	33
8/09/08	7.18	46	6/04/09	6.90	73	26/10/09	7.72	34
15/09/08	7.69	41	14/04/09	7.12	67	2/11/09	7.35	35
22/09/08	7.48	44	20/04/09	7.34	66	9/11/09	7.26	34
29/09/08	7.47	45	28/04/09	7.36	78	16/11/09	7.34	40
6/10/08	6.83	35	4/05/09	7.16	78	23/11/09	8.19	37
13/10/08	7.50	50	11/05/09	7.22	75	30/11/09	7.70	37
20/10/08	9.01	40	18/05/09	7.25	71	7/12/09	7.19	42
27/10/08	7.56	41	25/05/09	7.36	56	14/12/09	7.43	26
3/11/08	7.59	42	1/06/09	7.26	54	21/12/09	8.09	43
10/11/08	6.98	43	8/06/09	7.19	53	28/12/09	8.43	45
17/11/08	9.25	35	15/06/09	7.29	53	–	–	–

Table B3 UV Absorbance and colour of the Voëlvlei WTP raw water as a function of time

Date	UV Abs 300nm, 4cm	Colour (mg/L Pt)	Date	UV Abs 300nm, 4cm	Colour (mg/L Pt)	Date	UV Abs 300nm, 4cm	Colour (mg/L Pt)
5/05/08	0.405	40	17/11/08	0.269	21	29/06/09	0.249	21
12/05/08	0.328	30	24/11/08	0.241	18	6/07/09	0.317	25
19/05/08	0.382	30	1/12/08	0.387	39	13/07/09	0.266	25
25/05/08	0.407	40	8/12/08	0.310	28	20/07/09	0.257	22
2/06/08	0.203	20	15/12/08	0.455	47	28/07/09	0.252	23
9/06/08	0.367	40	12/01/09	0.315	30	3/08/09	0.242	16
17/06/08	0.171	10	19/01/09	0.348	33	11/08/09	0.464	51
23/06/08	0.275	20	26/01/09	0.371	27	17/08/09	0.288	26
30/06/08	0.443	40	2/02/09	0.173	14	24/08/09	0.196	13
7/07/08	0.270	20	9/02/09	0.367	38	31/08/09	0.230	53
14/07/08	0.344	30	16/02/09	0.452	47	7/09/09	0.264	18
21/07/08	0.366	20	23/02/09	0.493	52	14/09/09	0.413	37
28/07/08	0.288	20	2/03/09	0.471	50	21/09/09	0.326	28
4/08/08	0.391	30	9/03/09	0.451	46	28/09/09	0.250	18
11/08/08	0.429	50	16/03/09	0.445	47	5/10/09	0.472	53
18/08/08	0.374	30	23/03/09	0.409	40	12/10/09	0.287	26
25/08/08	0.345	29	30/03/09	0.363	35	19/10/09	0.227	28
1/09/08	0.360	32	6/04/09	0.379	39	26/10/09	0.412	27
8/09/08	0.257	17	14/04/09	0.333	35	2/11/09	0.258	29
15/09/08	0.495	51	20/04/09	0.411	18	9/11/09	0.502	28
22/09/08	0.383	34	4/05/09	0.446	46	16/11/09	0.242	20
29/09/08	0.351	32	11/05/09	0.377	38	23/11/09	0.493	54
6/10/08	0.363	26	18/05/09	0.428	46	30/11/09	0.232	31
13/10/08	0.352	32	25/05/09	0.416	43	7/12/09	0.272	31
20/10/08	0.401	38	1/06/09	0.477	51	14/12/09	0.448	28
27/10/08	0.332	32	8/06/09	0.545	60	21/12/09	0.454	32
3/11/08	0.371	35	15/06/09	0.462	59	–	–	–
10/11/08	0.413	41	22/06/09	0.262	22	–	–	–

Appendix C   Physical and chemical results for the Berg River water

Table C1   Physical and chemical results for the Berg River water (May 2008 – July 2008)

Date	5/05/08	12/05/08	19/05/08	26/05/08	2/06/08	9/06/08	17/06/08	23/06/08	30/06/08	7/07/08	14/07/08	21/07/08	28/07/08
Conductivity , mS/m	12.0	10.1	19.0	10.2	10.0	16.4	18.2	19.6	18.1	19.2	25.7	29.8	42.0
Turbidity , NTU	24	18.4	26	34	28	62	43	21	66	354	110	42	281
pH	6.58	6.72	6.87	6.90	6.95	6.76	6.53	7.04	6.87	6.54	6.90	6.96	6.74
Total Alkalinity , mg/L CaCO$_3$	15.4	16.0	24.8	17.8	18.6	21.8	22.9	18.9	18.2	16.8	23.6	28.7	37.9
UV Absorbance (300nm / 4cm)	0.412	0.337	0.243	0.402	0.455	0.464	0.412	0.488	0.622	1.103	0.524	0.412	0.785
Colour , mg/L Pt	30	20	10	30	30	40	30	30	50	100	30	20	50
Calcium , mg/L	8.24	7.64	12.9	7.42	7.94	7.66	12.8	13.00	9.88	8.82	12.90	14.82	22.56
Magnesium , mg/L	4.20	2.80	4.98	2.25	2.46	2.31	3.86	6.82	4.22	5.87	7.47	8.12	9.24
Sodium , mg/L	18.24	14.46	28.40	17.46	16.24	14.00	28.22	36.10	21.90	28.40	37.80	38.8	48.14
Potassium , mg/L	3.86	3.21	5.86	3.68	3.67	3.89	5.43	6.51	4.31	7.48	4.92	4.98	6.12
Chloride , mg/L	26.20	18.80	35.60	21.60	19.80	49.74	25.63	37.24	70.00	33.07	52.77	67.35	109.53
Sulphate , mg/L	8.21	10.62	10.88	12.27	12.02	9.36	6.64	8.48	8.72	7.97	6.45	5.81	6.06
Ammonia , mg/L	0.138	0.119	0.070	0.146	0.179	0.166	0.154	0.142	0.168	0.132	0.154	0.004	0.132
Nitrate / Nitrite , mg/L	0.57	1.47	2.74	1.20	1.25	1.87	1.14	1.82	1.64	2.19	2.16	2.12	2.80
Phosphate , mg/L P	0.51	0.36	0.29	0.29	0.28	<0.10	<0.10	0.12	<0.10	0.17	0.15	0.17	0.22
Aluminium , mg/L	0.422	0.312	0.468	0.310	0.643	0.662	0.349	1.640	0.471	0.424	1.120	0.924	1.268
Iron , mg/L	0.654	0.488	0.421	0.560	0.692	0.572	0.594	2.670	0.593	0.566	0.924	0.886	0.994
Manganese , mg/L	0.012	0.021	0.024	0.024	0.021	0.015	0.024	0.043	0.025	0.017	0.046	0.034	0.044
Cadmium , mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.001	0.001	<0.001	<0.001	<0.001
Cobalt , mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	<0.001	<0.001	0.001	0.001	<0.001	<0.001	0.001
Chromium , mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Copper , mg/L	0.001	0.004	0.001	0.001	0.001	<0.001	0.004	0.006	0.010	0.008	0.015	0.001	0.002
Nickel , mg/L	0.001	0.001	0.002	<0.001	0.007	<0.001	<0.001	0.001	0.004	0.001	0.003	0.001	0.004
Lead , mg/L	0.004	0.003	0.001	0.004	0.021	<0.001	<0.001	0.003	0.002	0.002	0.003	0.002	0.002
Strontium , mg/L	0.034	0.043	0.032	0.035	0.039	0.037	0.040	0.084	0.046	0.045	0.084	0.064	0.092
Vanadium , mg/L	0.001	0.001	0.002	0.001	<0.001	0.002	0.001	0.004	<0.001	0.002	<0.001	0.001	0.001
Zinc , mg/L	0.004	0.002	0.003	0.008	0.009	0.006	0.003	0.009	0.001	0.003	0.003	0.004	0.001

Table C2   Physical and chemical results for the Berg River water (August 2008 – October 2008)

Date	4/08/08	11/08/08	18/08/08	25/08/08	1/09/08	8/09/08	15/09/08	22/09/08	29/09/08	6/10/08	13/10/08	20/10/08	27/10/08
Conductivity , mS/m	27.2	28.4	31.0	29.4	16.8	23.8	23.9	19.5	18.3	19.1	17.8	23.2	23.8
Turbidity , NTU	84	32	35	43	168	47	45	41	43	42	29.5	22.4	18.6
pH	7.16	7.54	7.21	6.82	7.13	7.59	6.84	6.79	6.87	6.94	7.92	7.06	8.32
Total Alkalinity , mg/L CaCO$_3$	26.4	26.5	39.5	27.8	15.5	28.4	25.1	21.6	19.4	20.2	21.5	27.1	28.4
UV Absorbance (300nm / 4cm)	0.591	0.358	0.282	0.314	0.904	0.434	0.436	0.442	0.469	0.458	0.340	0.244	0.256
Colour , mg/L Pt	40	20	10	20	80	30	30	30	30	30	20	20	20
Calcium , mg/L	12.86	12.92	14.66	14.24	9.20	10.24	10.42	8.68	7.33	9.24	6.93	8.92	10.01
Magnesium , mg/L	7.44	7.23	4.98	3.86	4.62	4.75	4.66	4.26	4.51	4.18	4.19	5.49	5.68
Sodium , mg/L	28.96	32.12	34.46	28.34	24.64	28.28	28.64	26.80	23.74	26.54	22.04	28.91	30.56
Potassium , mg/L	3.96	4.22	4.76	3.92	2.68	2.59	2.84	2.76	2.36	2.44	2.23	2.87	3.49
Chloride , mg/L	57.09	59.47	67.98	67.14	32.54	47.15	49.38	36.24	34.37	37.05	32.9	42.36	44.1
Sulphate , mg/L	6.32	5.99	7.42	5.74	4.31	2.90	5.25	4.38	4.07	3.66	3.83	1.26	0.65
Ammonia , mg/L	0.151	0.149	0.149	0.179	0.145	0.153	0.187	0.164	0.154	0.148	0.242	0.246	0.214
Nitrate / Nitrite , mg/L	1.51	1.70	2.00	1.79	0.66	1.15	1.07	0.78	0.73	0.77	0.58	0.82	0.76
Phosphate , mg/L P	0.14	0.11	0.13	0.19	0.14	0.12	0.11	0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Aluminium , mg/L	0.766	0.614	0.546	0.344	0.924	0.646	0.562	0.742	0.873	0.764	0.241	0.208	0.189
Iron , mg/L	0.484	0.476	0.592	0.516	0.766	0.742	0.916	0.846	0.886	0.850	0.404	0.386	0.324
Manganese , mg/L	0.022	0.024	0.032	0.028	0.014	0.051	0.032	0.035	0.038	0.044	0.045	0.069	0.085
Cadmium , mg/L	<0.001	<0.001	<0.001	<0.001	0.001	0.002	0.001	0.003	0.003	0.002	0.002	0.002	0.003
Cobalt , mg/L	<0.001	<0.001	0.001	<0.001	0.003	0.003	0.005	0.003	0.004	0.002	0.003	0.003	0.004
Chromium , mg/L	<0.001	0.001	<0.001	<0.001	0.003	0.004	0.002	0.003	0.004	0.003	0.003	0.003	0.008
Copper , mg/L	0.004	0.004	0.008	0.001	0.008	0.005	0.006	0.002	0.006	0.004	0.005	0.005	0.004
Nickel , mg/L	0.002	0.002	0.001	0.001	0.001	0.005	0.004	0.003	0.004	0.006	0.005	0.005	0.010
Lead , mg/L	0.004	0.001	0.004	0.002	0.003	0.001	0.002	0.004	0.006	0.003	0.006	0.007	0.006
Strontium , mg/L	0.056	0.058	0.062	0.052	0.052	0.050	0.046	0.065	0.058	0.058	0.055	0.077	0.091
Vanadium , mg/L	0.002	0.001	0.001	0.001	0.003	0.003	0.002	0.003	0.004	0.003	0.004	0.004	0.004
Zinc , mg/L	0.001	0.006	0.004	0.003	0.010	0.009	0.011	0.010	0.011	0.010	0.008	0.008	0.010

Table C3   Physical and chemical results for the Berg River water (November 2008 – January 2009)

Date	3/11/08	10/11/08	17/11/08	24/11/08	1/12/08	8/12/08	15/12/08	22/12/08	29/12/08	5/01/09	12/01/09	19/01/09	26/01/09
Conductivity , mS/m	27.9	27.6	28.6	24.4	23.4	11.8	19.2	27.2	20.6	18.4	13.8	13.9	17.3
Turbidity , NTU	19.4	21.2	20.8	18.2	20.3	17.4	8.9	10.6	10.2	22.9	6.82	11.6	20.9
pH	8.11	7.86	7.21	7.64	9.92	9.90	9.74	6.62	6.84	6.81	7.68	7.54	8.19
Total Alkalinity , mg/L CaCO$_3$	29.6	30.4	29.2	24.3	20.3	15.4	27.6	29.3	18.3	23.1	19.9	18.1	39.7
UV Absorbance (300nm / 4cm)	0.268	0.320	0.364	0.342	0.244	0.232	0.320	0.200	0.246	0.232	0.312	0.300	0.320
Colour , mg/L Pt	20	20	20	10	50	30	40	10	10	10	10	20	20
Calcium , mg/L	12.42	11.94	12.24	10.64	10.21	6.84	8.96	11.86	9.43	8.24	4.84	4.46	7.85
Magnesium , mg/L	5.92	5.62	4.96	4.14	4.88	3.92	4.12	5.14	5.63	2.87	2.12	2.34	2.89
Sodium , mg/L	34.42	33.16	32.86	29.46	28.85	22.12	27.64	38.16	28.56	26.46	22.42	23.16	25.96
Potassium , mg/L	3.64	3.89	3.56	2.86	2.94	2.16	2.88	3.65	3.11	2.96	2.54	2.57	2.86
Chloride , mg/L	34.17	35.71	22.03	27.11	33.25	45.31	37.33	41.95	49.4	24.8	22.82	22.9	34.86
Sulphate , mg/L	6.25	6.05	7.08	8.52	12.22	10.55	11.11	1.58	1.07	1.08	1.34	1.12	1.53
Ammonia , mg/L	0.058	0.052	0.067	0.067	0.076	0.076	0.142	0.112	0.077	0.081	0.062	0.118	0.183
Nitrate / Nitrite , mg/L	1.18	0.98	0.60	1.50	0.79	1.91	1.66	1.24	0.13	0.21	0.15	0.14	0.16
Phosphate , mg/L P	0.12	0.18	0.14	0.12	0.14	<0.10	0.11	0.14	0.12	<0.10	0.11	0.12	0.18
Aluminium , mg/L	0.432	0.412	0.396	0.286	0.296	0.182	0.304	0.396	0.287	0.432	0.312	0.246	0.414
Iron , mg/L	0.343	0.334	0.292	0.304	0.344	0.224	0.316	0.456	0.321	0.521	0.489	0.420	0.564
Manganese , mg/L	0.034	0.056	0.046	0.031	0.029	0.012	0.033	0.056	0.024	0.021	0.014	0.018	0.042
Cadmium , mg/L	<0.001	0.001	0.001	<0.001	0.003	0.003	<0.001	0.001	0.001	<0.001	0.002	0.002	0.001
Cobalt , mg/L	0.002	0.004	0.004	0.001	<0.001	0.003	0.003	<0.001	<0.001	<0.001	0.001	0.001	<0.001
Chromium , mg/L	0.001	0.001	<0.001	0.002	0.004	0.001	<0.001	0.002	0.001	0.001	0.002	0.001	0.001
Copper , mg/L	0.002	0.005	0.004	0.004	0.001	0.004	0.003	0.004	0.001	0.012	0.006	0.005	0.002
Nickel , mg/L	0.006	0.004	0.002	0.004	0.003	0.001	0.001	0.003	0.002	0.004	0.001	0.001	0.003
Lead , mg/L	0.005	0.001	0.002	0.003	0.003	0.003	0.006	0.001	0.002	0.008	0.001	0.001	0.005
Strontium , mg/L	0.084	0.076	0.088	0.068	0.054	0.032	0.054	0.074	0.051	0.042	0.034	0.033	0.049
Vanadium , mg/L	0.002	0.004	0.004	0.003	0.001	0.001	0.002	0.003	0.003	0.001	0.001	0.006	0.004
Zinc , mg/L	0.008	0.006	0.008	0.010	0.012	0.012	0.006	0.010	0.009	0.008	0.009	0.004	0.005

Table C4   Physical and chemical results for the Berg River water (February 2009 – April 2009)

Date	2/02/09	9/02/09	16/02/09	23/02/09	2/03/09	9/03/09	16/03/09	23/03/09	30/03/09	6/04/09	13/04/09	20/04/09	27/04/09
Conductivity , mS/m	16.4	14.2	9.2	12.2	16.8	16.9	15.4	12.8	14.4	16.1	14.2	14.3	13.8
Turbidity , NTU	22.8	3.64	36.2	7.4	5.78	21.2	18.6	16.3	14.4	12.1	16.4	12.7	14.4
pH	7.28	7.39	6.72	6.76	6.68	6.81	6.97	6.82	6.67	6.69	6.75	7.14	7.91
Total Alkalinity , mg/L CaCO$_3$	18.7	17.6	11.8	18.4	27.2	17.8	19.7	18.4	20.8	22.8	20.6	22.1	24.7
UV Absorbance (300nm / 4cm)	0.280	0.344	0.336	0.412	0.464	0.456	0.412	0.386	0.369	0.387	0.424	0.441	0.427
Colour , mg/L Pt	20	30	10	30	30	40	30	20	20	20	30	30	40
Calcium , mg/L	7.62	6.64	3.12	5.89	7.98	8.12	3.70	3.40	3.86	6.24	4.96	4.72	4.34
Magnesium , mg/L	2.87	2.56	2.06	2.54	2.92	2.87	2.27	1.96	2.38	2.98	2.78	2.73	2.65
Sodium , mg/L	24.89	22.85	18.68	21.64	28.63	27.69	21.04	22.28	24.28	28.12	24.16	23.57	22.12
Potassium , mg/L	2.64	2.32	1.85	2.44	2.81	2.77	1.83	1.66	1.82	2.43	1.95	1.87	1.77
Chloride , mg/L	26.8	24.24	18.42	21.22	28.42	26.53	22.44	20.96	21.43	26.54	23.43	22.85	21.04
Sulphate , mg/L	4.24	2.84	1.26	1.98	2.04	1.87	2.97	2.64	2.85	3.12	2.43	2.24	2.12
Ammonia , mg/L	0.104	0.072	0.124	0.064	0.086	0.122	0.546	0.244	0.212	0.218	0.345	0.196	0.128
Nitrate / Nitrite , mg/L	0.14	0.13	0.36	0.22	0.16	0.14	0.12	0.14	0.23	0.28	0.18	0.16	0.12
Phosphate , mg/L P	0.12	<0.10	<0.10	<0.10	0.12	0.12	0.10	0.14	0.13	<0.10	0.12	<0.10	<0.10
Aluminium , mg/L	0.388	0.292	0.122	0.341	0.485	0.423	0.552	0.390	0.491	0.542	0.421	0.396	0.354
Iron , mg/L	0.522	0.413	0.331	0.545	0.589	0.554	0.717	0.581	0.724	0.874	0.633	0.616	0.414
Manganese , mg/L	0.044	0.032	0.018	0.028	0.044	0.049	0.040	0.021	0.048	0.034	0.023	0.028	0.022
Cadmium , mg/L	0.001	<0.001	<0.001	<0.001	0.001	0.001	<0.001	<0.001	<0.001	0.001	0.001	<0.001	<0.001
Cobalt , mg/L	<0.001	0.002	0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	0.001
Chromium , mg/L	<0.001	<0.001	0.001	0.001	<0.001	<0.001	<0.001	<0.001	0.003	<0.001	0.002	<0.001	0.001
Copper , mg/L	0.004	0.010	0.001	0.012	0.008	0.004	0.002	0.002	0.003	0.001	0.006	0.004	0.002
Nickel , mg/L	0.001	<0.001	<0.001	0.004	0.001	0.002	<0.001	<0.001	<0.001	0.001	0.001	<0.001	<0.001
Lead , mg/L	<0.001	<0.001	<0.001	0.004	0.001	0.001	0.001	0.001	0.006	0.001	0.002	0.002	0.004
Strontium , mg/L	0.052	0.041	0.029	0.036	0.054	0.051	0.046	0.046	0.038	0.056	0.048	0.046	0.031
Vanadium , mg/L	0.003	0.003	0.001	0.001	0.003	0.002	<0.001	<0.001	<0.001	0.001	0.001	<0.001	0.001
Zinc , mg/L	0.003	0.008	0.001	0.004	0.004	0.003	0.001	0.001	<0.001	0.001	0.002	0.001	0.001

Table C5 Physical and chemical results for the Berg River water (May 2009 – July 2009)

Date	4/05/09	11/05/09	18/05/09	25/05/09	1/06/09	8/06/09	15/06/09	22/06/09	29/06/09	6/07/09	13/07/09	20/07/09	27/07/09
Conductivity , mS/m	12.8	15.2	16.6	18.6	14.9	16.7	19.4	20.4	21.1	29.4	40.0	32.0	30.0
Turbidity , NTU	33	41.0	31	46	24	41	32	25	43	78	46	47.1	49
pH	6.94	6.72	6.91	7.21	6.83	7.04	6.78	6.76	6.89	6.64	6.54	7.34	6.99
Total Alkalinity , mg/L CaCO$_3$	18.6	23.4	25.2	29.4	20.9	24.3	23.8	20.9	28.9	27.6	33.9	40.8	37.9
UV Absorbance (300nm / 4cm)	0.531	0.480	0.392	0.512	0.436	0.488	0.449	0.396	0.542	0.714	0.642	0.584	0.572
Colour , mg/L Pt	40	40	30	40	30	40	40	30	40	70	50	50	50
Calcium , mg/L	11.4	12.2	10.9	11.8	8.4	8.6	12.6	12.90	12.8	11.4	18.56	18.24	21.2
Magnesium , mg/L	4.75	4.14	4.24	3.80	2.76	2.56	3.98	5.78	4.86	5.23	8.42	8.1	9.02
Sodium , mg/L	16.90	17.60	24.60	22.12	18.74	18.40	27.64	34.20	29.94	30.80	46.80	41.32	47.15
Potassium , mg/L	3.76	3.86	4.12	3.98	3.42	3.76	4.92	5.43	4.88	7.14	4.92	4.76	5.14
Chloride , mg/L	32.90	34,12	34.98	30.90	22.65	36.40	29.80	41.14	48.42	47.82	82.70	77.90	68.90
Sulphate , mg/L	9.40	11.40	11.94	11.40	10.23	9.88	8.23	9.04	9.40	8.56	9.44	9.21	9.04
Ammonia , mg/L	0.33	0.28	0.140	0.114	0.152	0.14	0.16	0.12	0.15	0.12	–	–	–
Nitrate / Nitrite , mg/L	0.76	0.94	1.46	1.41	1.04	1.65	1.34	1.46	1.34	1.64	–	–	–
Phosphate , mg/L P	0.34	0.18	0.43	0.33	0.24	0.12	0.18	0.11	0.12	0.15	–	–	–
Aluminium , mg/L	0.576	0.464	0.392	0.380	0.488	0.382	0.320	0.540	0.452	0.562	0.743	0.654	0.602
Iron , mg/L	0.720	0.578	0.402	0.514	0.548	0.378	0.489	0.712	0.614	0.523	0.890	0.712	0.689
Manganese , mg/L	0.034	0.019	0.044	0.029	0.031	0.020	0.034	0.040	0.034	0.028	0.060	0.039	0.035
Cadmium , mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.001	0.001	<0.001	<0.001	<0.001
Cobalt , mg/L	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.001	<0.001	0.001	<0.001	<0.001	<0.001	0.001
Chromium , mg/L	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
Copper , mg/L	0.002	0.003	0.002	0.002	0.001	0.001	0.002	0.004	0.006	0.009	0.009	0.001	0.002
Nickel , mg/L	0.001	0.001	0.001	0.001	0.002	<0.001	0.001	0.001	0.004	0.001	0.001	0.001	0.001
Lead , mg/L	0.002	0.003	0.001	0.002	0.007	0.002	0.001	0.002	0.001	0.002	0.002	0.003	0.002
Strontium , mg/L	0.056	0.067	0.064	0.063	0.056	0.061	0.056	0.091	0.074	0.083	0.087	0.077	0.089
Vanadium , mg/L	0.002	0.001	0.001	0.001	<0.001	0.002	0.001	0.003	0.001	0.002	<0.001	0.001	0.001
Zinc , mg/L	0.003	0.001	0.001	0.003	0.006	0.001	0.002	0.004	0.001	0.001	0.004	0.002	0.001

Table C6 Physical and chemical results for the Berg River water (August 2009 – December 2009)

Date	3/08/09	10/08/09	31/08/09	7/09/09	21/09/09	28/09/09	12/10/09	26/10/09	2/11/09	16/11/09	23/11/09	7/12/09	14/12/09
Conductivity , mS/m	27.0	39.0	32.0	24.0	20.0	22.1	19.0	20.0	20.0	20.6	21.2	17.2	18.8
Turbidity , NTU	47.5	17.6	30.3	37.9	22.3	38.5	21	24.4	27.2	24.3	16.9	15.9	12.8
pH	7.67	7.04	7.14	7.58	7.33	7.20	7.40	7.32	7.06	7.12	7.54	7.91	7.76
Total Alkalinity , mg/L CaCO$_3$	30.0	42.4	40.1	28.7	25.7	29.6	30.1	27.1	29.8	28.2	26.5	18.3	19.8
UV Absorbance (300nm / 4cm)	0.516	0.349	0.432	0.418	0.372	0.412	0.386	0.364	0.354	0.325	0.322	0.256	0.314
Colour , mg/L Pt	40	20	40	40	30	30	30	30	30	20	20	20	30
Calcium , mg/L	20.8	17.65	16.46	18.12	14.86	14.24	15.24	14.44	13.21	12.56	11.64	10.98	12.21
Magnesium , mg/L	8.94	7.89	7.41	6.43	5.94	6.04	5.68	5.98	5.98	5.12	4.89	4.14	4.23
Sodium , mg/L	44.78	40.8	47.60	38.76	29.94	28.64	26.62	29.62	32.88	30.63	27.89	23.98	25.57
Potassium , mg/L	4.97	4.42	3.98	2.94	2.93	2.87	2.58	3.32	3.54	3.16	2.95	2.67	2.79
Chloride , mg/L	61.00	73.90	84.8	58.4	48.6	49.2	44	49.2	44.6	38.37	30.56	24.88	25.41
Sulphate , mg/L	9.23	7.32	8.52	6.12	6.34	7.06	6.88	6.55	6.37	6.63	7.34	7.13	6.79
Ammonia , mg/L	–	–	–	–	–	–	–	–	–	–	–	–	–
Nitrate / Nitrite , mg/L	–	–	–	–	–	–	–	–	–	–	–	–	–
Phosphate , mg/L P	–	–	–	–	–	–	–	–	–	–	–	–	–
Aluminium , mg/L	0.654	0.568	0.533	0.456	0.396	0.446	0.362	0.334	0.332	0.317	0.284	0.246	0.249
Iron , mg/L	0.561	0.498	0.506	0.517	0.678	0.594	0.385	0.396	0.312	0.319	0.301	0.287	0.259
Manganese , mg/L	0.028	0.023	0.034	0.044	0.029	0.028	0.032	0.054	0.029	0.037	0.033	0.019	0.016
Cadmium , mg/L	<0.001	<0.001	0.001	0.002	0.001	0.003	0.002	0.003	<0.001	0.001	<0.001	0.003	<0.001
Cobalt , mg/L	<0.001	<0.001	0.001	0.001	0.001	0.002	0.002	0.001	0.002	0.004	0.001	0.001	0.003
Chromium , mg/L	<0.001	0.001	0.001	0.002	0.002	0.003	0.001	0.002	0.001	<0.001	0.002	0.001	0.001
Copper , mg/L	0.003	0.003	0.006	0.005	0.002	0.005	0.005	0.004	0.004	0.006	0.002	0.008	0.003
Nickel , mg/L	0.002	0.002	0.001	0.002	0.004	0.001	0.003	0.006	0.002	0.003	0.002	0.001	0.002
Lead , mg/L	0.002	0.001	0.001	0.001	0.002	0.003	0.001	0.003	0.002	0.002	0.003	0.002	0.003
Strontium , mg/L	0.073	0.067	0.067	0.061	0.073	0.067	0.059	0.082	0.081	0.089	0.068	0.054	0.059
Vanadium , mg/L	0.002	0.001	0.003	0.003	0.002	0.002	0.003	0.004	0.002	0.004	0.003	0.001	0.002
Zinc , mg/L	0.001	0.003	0.002	0.004	0.010	0.006	0.009	0.012	0.008	0.003	0.012	0.009	0.002

Appendix D   Physical and chemical results for the Berg River water as a function of time

Table D1   Aluminium and iron concentration of the Berg River water as a function of time

Date	Al (mg/L)	Fe (mg/L)	Date	Al (mg/L)	Fe (mg/L)	Date	Al (mg/L)	Fe (mg/L)
5/05/08	0.422	0.654	27/10/08	0.189	0.324	18/05/09	0.392	0.402
12/05/08	0.312	0.488	3/11/08	0.432	0.343	25/05/09	0.380	0.514
19/05/08	0.468	0.421	10/11/08	0.412	0.334	1/06/09	0.488	0.548
26/05/08	0.310	0.560	17/11/08	0.396	0.292	15/06/09	0.320	0.489
2/06/08	0.643	0.692	24/11/08	0.286	0.304	22/06/09	0.540	0.712
9/06/08	0.662	0.572	1/12/08	0.296	0.344	29/06/09	0.452	0.614
17/06/08	0.349	0.594	8/12/08	0.182	0.224	6/07/09	0.562	0.523
23/06/08	1.640	2.670	15/12/08	0.304	0.316	13/07/09	0.743	0.890
30/06/08	0.471	0.593	12/01/09	0.312	0.489	20/07/09	0.654	0.712
7/07/08	0.424	0.566	19/01/09	0.246	0.420	27/07/09	0.602	0.689
14/07/08	1.120	0.924	26/01/09	0.414	0.564	3/08/09	0.654	0.561
21/07/08	0.924	0.886	2/02/09	0.388	0.522	10/08/09	0.568	0.498
28/07/08	1.268	0.994	9/02/09	0.292	0.413	31/08/09	0.533	0.506
4/08/08	0.766	0.484	16/02/09	0.122	0.331	7/09/09	0.456	0.517
11/08/08	0.614	0.476	23/02/09	0.341	0.545	21/09/09	0.396	0.678
18/08/08	0.546	0.592	2/03/09	0.485	0.589	28/09/09	0.446	0.594
25/08/08	0.344	0.516	9/03/09	0.423	0.554	12/10/09	0.362	0.385
1/09/08	0.924	0.766	16/03/09	0.552	0.717	26/10/09	0.334	0.396
8/09/08	0.646	0.742	23/03/09	0.390	0.581	2/11/09	0.332	0.312
15/09/08	0.562	0.916	30/03/09	0.491	0.724	16/11/09	0.317	0.319
22/09/08	0.742	0.846	6/04/09	0.542	0.874	23/11/09	0.284	0.301
29/09/08	0.873	0.886	13/04/09	0.421	0.633	7/12/09	0.246	0.287
6/10/08	0.764	0.850	20/04/09	0.396	0.616	14/12/09	0.249	0.259
13/10/08	0.241	0.404	4/05/09	0.576	0.720	–	–	–
20/10/08	0.208	0.386	11/05/09	0.464	0.578	–	–	–

Table D2   pH and turbidity of the Berg River water as a function of time

Date	pH	Turb (NTU)	Date	pH	Turb (NTU)	Date	pH	Turb (NTU)
5/05/08	6.58	24	27/10/08	8.32	19	18/05/09	6.91	31
12/05/08	6.72	18	3/11/08	8.11	19	25/05/09	7.21	46
19/05/08	6.87	26	10/11/08	7.86	21	1/06/09	6.83	24
26/05/08	6.90	34	17/11/08	7.21	21	15/06/09	6.78	32
2/06/08	6.95	28	24/11/08	7.64	18	22/06/09	6.76	25
9/06/08	6.76	62	1/12/08	9.92	20	29/06/09	6.89	43
17/06/08	6.53	43	8/12/08	9.90	17	6/07/09	6.64	78
23/06/08	7.04	21	15/12/08	9.74	9	13/07/09	6.54	46
30/06/08	6.87	66	12/01/09	7.68	7	20/07/09	7.34	47
7/07/08	6.54	354	19/01/09	7.54	12	27/07/09	6.99	49
14/07/08	6.90	110	26/01/09	8.19	21	3/08/09	7.67	48
21/07/08	6.96	42	2/02/09	7.28	23	10/08/09	7.04	18
28/07/08	6.74	281	9/02/09	7.39	4	31/08/09	7.14	30
4/08/08	7.16	84	16/02/09	6.72	36	7/09/09	7.58	38
11/08/08	7.54	32	23/02/09	6.76	7	21/09/09	7.33	22
18/08/08	7.21	35	2/03/09	6.68	6	28/09/09	7.20	39
25/08/08	6.82	43	9/03/09	6.81	21	12/10/09	7.40	21
1/09/08	7.13	168	16/03/09	6.97	19	26/10/09	7.32	24
8/09/08	7.59	47	23/03/09	6.82	16	2/11/09	7.06	27
15/09/08	6.84	45	30/03/09	6.67	14	16/11/09	7.12	24
22/09/08	6.79	41	6/04/09	6.69	12	23/11/09	7.54	17
29/09/08	6.87	43	13/04/09	6.75	16	7/12/09	7.91	16
6/10/08	6.94	42	20/04/09	7.14	13	14/12/09	7.76	13
13/10/08	7.92	30	4/05/09	6.94	33	–	–	–
20/10/08	7.06	22	11/05/09	6.72	41	–	–	–

Table D3   UV Absorbance and colour of the Berg River water as a function of time

Date	UV Abs 300nm, 4cm	Colour (mg/L Pt)	Date	UV Abs 300nm, 4cm	Colour (mg/L Pt)	Date	UV Abs 300nm, 4cm	Colour (mg/L Pt)
5/05/08	0.412	30	27/10/08	0.256	20	18/05/09	0.392	30
12/05/08	0.337	20	3/11/08	0.268	20	25/05/09	0.512	40
19/05/08	0.243	10	10/11/08	0.320	20	1/06/09	0.436	30
26/05/08	0.402	30	17/11/08	0.364	20	15/06/09	0.449	40
2/06/08	0.455	30	24/11/08	0.342	10	22/06/09	0.396	30
9/06/08	0.464	40	1/12/08	0.244	50	29/06/09	0.542	40
17/06/08	0.412	30	8/12/08	0.232	30	6/07/09	0.714	70
23/06/08	0.488	30	15/12/08	0.320	40	13/07/09	0.642	50
30/06/08	0.622	50	12/01/09	0.312	10	20/07/09	0.584	50
7/07/08	1.103	100	19/01/09	0.300	20	27/07/09	0.572	50
14/07/08	0.524	30	26/01/09	0.320	20	3/08/09	0.516	40
21/07/08	0.412	20	2/02/09	0.280	20	10/08/09	0.349	20
28/07/08	0.785	50	9/02/09	0.344	30	31/08/09	0.432	40
4/08/08	0.591	40	16/02/09	0.336	10	7/09/09	0.418	40
11/08/08	0.358	20	23/02/09	0.412	30	21/09/09	0.372	30
18/08/08	0.282	10	2/03/09	0.464	30	28/09/09	0.412	30
25/08/08	0.314	20	9/03/09	0.456	40	12/10/09	0.386	30
1/09/08	0.904	80	16/03/09	0.412	30	26/10/09	0.364	30
8/09/08	0.434	30	23/03/09	0.386	20	2/11/09	0.354	30
15/09/08	0.436	30	30/03/09	0.369	20	16/11/09	0.325	20
22/09/08	0.442	30	6/04/09	0.387	20	23/11/09	0.322	20
29/09/08	0.469	30	13/04/09	0.424	30	7/12/09	0.256	20
6/10/08	0.458	30	20/04/09	0.441	30	14/12/09	0.314	30
13/10/08	0.340	20	4/05/09	0.531	40	–	–	–
20/10/08	0.244	20	11/05/09	0.480	40	–	–	–

Appendix E   Jar test results for the Voëlvlei WTP raw water – optimum dose

Table E1   Jar test results for the Voëlvlei WTP raw water – optimum ferric dose

Jar test results for the Voëlvlei WTP raw water – to determine the optimum coagulant dose using ferric sulphate (at a constant pH of 9.2)

Fe^{3+} Dosage Concentration (mg/L)	pH	Turbidity (NTU)	UV Absorbance (300nm / 4cm)
[Raw Water]	[7.23]	32.00	0.406
2.0	9.2	1.41	0.106
3.0	9.2	0.99	0.088
4.0	9.2	0.63	0.085
5.0	9.2	0.61	0.083
6.0	9.2	0.52	0.077

Table E2   Jar test results for the Voëlvlei WTP raw water – optimum aluminium dose

Jar test results for the Voëlvlei WTP raw water – to determine the optimum coagulant dose using aluminium sulphate (at a constant pH of 6.5)

Al^{3+} Dosage Concentration (mg/L)	pH	Turbidity (NTU)	UV Absorbance (300nm / 4cm)
[Raw Water]	[7.20]	38.00	0.432
0.5	6.5	16.50	0.192
1.0	6.5	2.10	0.070
1.5	6.5	1.90	0.057
2.0	6.5	1.09	0.062
2.5	6.5	0.54	0.062
3.0	6.5	0.43	0.056

Appendix F   Jar test results for the Voëlvlei WTP raw water – optimum pH

Table F1   Jar test results for the Voëlvlei WTP raw water – optimum pH (ferric sulphate)

Jar test results for the Voëlvlei WTP raw water – to determine the optimum coagulation pH using ferric sulphate (at a dosage concentration of 4.0 mg/L as Fe^{3+})

Fe^{3+} Dosage Concentration	pH	Turbidity	UV Absorbance
(mg/L)		(NTU)	(300nm / 4cm)
[Raw Water]	[7.23]	37.0	0.455
4.0	3.96	7.80	0.040
4.0	5.01	7.40	0.030
4.0	5.52	3.40	0.037
4.0	6.02	1.70	0.047
4.0	6.56	0.99	0.059
4.0	7.02	0.86	0.074
4.0	8.05	0.74	0.087
4.0	8.51	0.73	0.086
4.0	9.03	0.71	0.088
4.0	9.48	0.55	0.088

Table F2   Jar test results for the Voëlvlei WTP raw water – optimum pH (aluminium sulphate)

Jar test results for the Voëlvlei WTP raw water – to determine the optimum coagulation pH using aluminium sulphate (at a dosage concentration of 3.0 mg/L as Al^{3+})

Al^{3+} Dosage Concentration	pH	Turbidity	UV Absorbance
(mg/L)		(NTU)	(300nm / 4cm)
[Raw Water]	[7.20]	38.00	0.432
3.0	4.46	2.40	0.073
3.0	5.34	2.20	0.038
3.0	6.07	0.71	0.046
3.0	6.55	0.22	0.056
3.0	7.07	0.33	0.078
3.0	7.97	0.97	0.132
3.0	8.80	9.10	0.180
3.0	9.49	21.00	0.199

Appendix G   Jar test results for the Berg River water – optimum dose

Table G1   Jar test results for the Berg River water – optimum ferric dose

Jar test results for the Berg River water – to determine the optimum coagulant
dose using ferric sulphate (at a constant pH of 5.0)

Fe^{3+} Concentration (mg/L)	pH	Turbidity (NTU)	UV Absorbance (300nm, 4cm)	Al (mg/L)	Fe (mg/L)	Ca (mg/L)
		22.40	0.244			
2.0	5.0	1.34	0.031	0.017	0.598	3.12
4.0	5.0	0.93	0.034	0.019	1.123	6.78
6.0	5.0	0.89	0.027	0.014	1.240	9.92
8.0	5.0	0.51	0.026	0.019	0.596	13.34
10.0	5.0	0.49	0.026	0.021	0.614	15.96
12.0	5.0	0.32	0.035	0.014	0.608	19.45

Table G2   Jar test results for the Berg River water – optimum aluminium dose

Jar test results for the Berg River water – to determine the optimum coagulant
dose using aluminium sulphate (at a constant pH of 6.0)

Al^{3+} Concentration (mg/L)	pH	Turbidity (NTU)	UV Absorbance (300nm, 4cm)	Al (mg/L)	Fe (mg/L)	Ca (mg/L)
		22.40	0.244			
1.0	6.0	3.57	0.086	0.742	0.056	3.25
2.0	6.0	2.94	0.066	0.813	0.049	5.69
3.0	6.0	1.53	0.058	0.786	0.066	8.55
4.0	6.0	1.29	0.036	0.754	0.013	11.37
5.0	6.0	0.46	0.033	0.844	0.021	13.49
6.0	6.0	0.29	0.025	0.680	0.014	16.23

Appendix H   Jar test results for the Berg River water – optimum pH

Table H1   Jar test results for the Berg River water – optimum pH (ferric sulphate)

Jar test results for the Berg River water – to determine the optimum coagulation pH using ferric sulphate (at a dosage concentration of 4.0 mg/L as Fe^{3+})

Fe^{3+} Concentration (mg/L)	pH	Turbidity (NTU)	UV Absorbance (300nm, 4cm)	Al (mg/L)	Fe (mg/L)	Ca (mg/L)	SO$_4$ (mg/L)	Colour (mg/L Pt)
		22.40	0.244					
4.0	3.5	7.14	0.098	0.039	2.870	0.92	10.94	4.2
4.0	4.0	4.12	0.045	0.065	2.231	5.13	11.26	3.1
4.0	6.0	0.39	0.029	0.012	0.403	7.89	11.34	0.9
4.0	8.0	0.47	0.033	0.008	0.798	8.32	11.27	1.4
4.0	10.0	0.40	0.059	0.042	0.434	10.16	11.16	1.3
4.0	12.0	9.67	0.062	0.069	0.381	143.20	13.95	0.8

Table H2   Jar test results for the Berg River water – optimum pH (aluminium sulphate)

Jar test results for the Berg River water – to determine the optimum coagulation pH using aluminium sulphate (at a dosage concentration of 5.0 mg/L as Al^{3+})

Al^{3+} Concentration (mg/L)	pH	Turbidity (NTU)	UV Absorbance (300nm, 4cm)	Al (mg/L)	Fe (mg/L)	Ca (mg/L)
		22.40	0.244			
5.0	4.0	0.89	0.075	3.786	0.091	0.65
5.0	5.0	0.76	0.034	3.614	0.076	7.07
5.0	6.0	0.38	0.023	0.431	0.003	7.90
5.0	7.0	0.45	0.029	0.564	0.012	12.68
5.0	8.0	0.52	0.046	1.554	0.029	10.55
5.0	9.0	0.96	0.073	4.712	0.031	16.92